HVAC Fans and Dampers Maintenance Guide

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HVAC Fans and Dampers Maintenance Guide

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REPORT SUMMARY

Heating, ventilation, and air conditioning (HVAC) systems serve an important function in nuclear power plants because these systems are responsible for maintaining many environmental conditions throughout the facility. Failure of these components can induce undesirable radiological conditions and stressful working conditions, and can compromise the life of qualified equipment. Some HVAC fan and damper failures are preventable by monitoring operating parameters and performing recommended maintenance activities.

Background

Fan and damper function is critical to achieving adequate HVAC system performance. Industry experience indicates that failure of these components and systems occurs frequently. The severity of observed failures ranges from total failure to degraded performance. Enhanced maintenance of fans and dampers can improve system performance and reduce replacement equipment costs.

Objectives

- To provide guidance on basic fan and damper applications in nuclear power generating stations and to suggest guidelines for the investigation of failures observed.
- To provide guidance on predictive and preventive maintenance in order to reduce equipment failures.

Approach

A survey was distributed by EPRI to member plants. Information supplied by respondents was reviewed to identify common failure modes of fans and dampers. This maintenance guide was then developed to provide recommendations for the reduction of common mode failures identified by the survey.

Results

This document provides a general background on fan and damper applications in nuclear HVAC systems. Vibration has been determined to be the primary cause of failure for these components. This guide provides maintenance recommendations and guidelines to determine root causes of vibration-related failures.

EPRI Perspective

This guide can assist utilities in establishing general guidelines for preventing fan and damper failure, improving HVAC system performance and reliability, and investigating the root cause of observed failures. Individual attributes of U.S. nuclear facilities preclude the establishment of generic HVAC system details. However, common features and universally applicable functions of HVAC systems and components are provided as a base for understanding a specific plant configuration.

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ABSTRACT

The Nuclear Maintenance Applications Center (NMAC) Heating Ventilation and Air Conditioning (HVAC) Fan and Damper Maintenance Guide is sponsored by EPRI to assist member facilities in improving the performance and reliability of fans and dampers in plant ventilation systems. Gross failures and degraded conditions of these components can be responsible for a wide range of detrimental effects. The resulting impact on HVAC system performance can compromise utility radiation exposure reduction programs (such as ALARA), reduce the qualified life of components, and cause forced outages in extreme circumstances. Plant ventilation systems are often found in less than optimal condition. As these systems are not typically attributed to the direct generation of power, temporary repairs are frequently applied in an attempt to maintain minimal acceptance of plant environmental conditions. At some point, due to reconfigurations of other plant systems, component failures, or increased service requirements, the system can become taxed such that all plant operational functions cannot be performed. System failure or poor performance is often attributed to the malfunction of fans and dampers.

This guide provides basic information on fans and dampers. Additionally, descriptions of the fundamental requirements for typical HVAC systems in nuclear power plants is provided. Recommended maintenance practices and guidelines for failure investigations are included with an emphasis on vibration, which can be attributed to many fan failures.

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1
INTRODUCTION

1.1 Background

Heating Ventilation and Air Conditioning (HVAC) systems provide control for environmental conditions throughout nuclear power plant facilities. The nature of the service provided by HVAC systems typically found in nuclear power plants varies widely, from simple low-volume exhaust subsystems to crucial pressure and temperature controls required to meet plant operating design bases. Regardless of the system functions, fans and dampers are required to deliver and control air movement as determined by design for a given application. Several types and styles of fans are available for selection by the design engineer, each with unique operating characteristics that can optimize the performance of a system if properly selected and maintained. Similarly, dampers are available in various designs, with each type conducive to specific airflow control functions.

Traditionally, HVAC systems have been considered as support systems without directly contributing to the generation of power. However, the consequences of fan and/or damper failures to nuclear power plant facilities can be significant, especially for systems that are designed for radiological control, or to maintain conditions credited for equipment environmental qualification. HVAC systems can be considered the primary safeguard in controlling the spread of potential contamination by ensuring airflow direction is maintained from areas of low contamination toward areas of higher contamination. Failure of a fan or critical damper could result in an uncontrolled spread of contamination, contributing to plant personnel radiological exposure. Additionally, if sufficient airflow supply is not maintained to areas that contain environmentally qualified equipment, design life could be compromised, necessitating costly equipment replacement or reanalysis.

HVAC systems at nuclear power plant facilities perform typical, as well as specialized, environmental functions. The general parameters that power plant HVAC systems are implemented to control are:

- Heating
- Cooling
- Air quality
- Pressurization (positive or negative)
- Filtration (air cleaning)
- Isolation

Temperature control is important to maintain suitable personnel working environments and the ambient conditions required for operation of mechanical and electric equipment. The American Society of Heating Refrigeration and Air Conditioning Engineers (ASHRAE) has established Standard 62 [1], which specifies minimum ventilation rates and indoor air quality that is acceptable in minimizing adverse health effects to human occupants.

The HVAC design engineer will determine the direction and quantity of airflow transferred between areas within a system, based on environmental and radiological conditions throughout the area served. This room-to-room transfer is accomplished through pressure differentials induced by the ventilation system across room boundaries. The system will rely upon proper fan performance and damper operation to achieve the desired flow.

Airborne contaminants also have physiological and equipment reliability ramifications if not evaluated and appropriately controlled.

The majority of the failure modes described in the EPRI member survey (Appendix A) indicated that vibration analysis would have detected nearly all of the failures. The failure modes of HVAC equipment are primarily directed at rotating components. Predictive maintenance techniques, and especially vibration analysis, are particularly effective at detecting these failure modes. The failure modes included problems with alignment, balance, bearings, shafts, hubs and impellers/wheels, couplings, belts, sheaves, foot and foundation problems, motor rotors and stators, and flow. Trending of vibration data can help to detect incipient failures and to provide Maintenance with a means to plan corrective actions and prevent the abrupt or catastrophic loss of availability of the monitored equipment. This technology is, therefore, the primary focus of attention in this guide.

1.2 Purpose of this Guide

The purpose of this guide is to provide useful information to personnel of all disciplines and skills associated with the maintenance of HVAC systems, planning for their maintenance, and monitoring/evaluating their performance. This guide can provide new insight to experienced personnel and basic information, guidance, and instruction to personnel recently assigned responsibility for the maintenance of HVAC systems. Training departments can use this guide for developing training material related to training of system engineers, component engineers, and maintenance personnel.

1.3 Organization of this Guide

This guide is organized into nine sections as follows:

Section 1 introduces the purpose and content of this guide by briefly identifying the importance of the role fans and dampers play in power plant operation.

Section 2 provides a list of definitions for terminology used in the fan and damper industry.

Section 3 describes typical ventilation systems found in both PWR and BWR nuclear power plants.

Section 4 identifies primary types of fans typically used in power plant applications.

Section 5 discusses the different types of dampers used in power plant applications.

Section 6 discusses some potential effects that fans and dampers can have on related environmental systems. Additionally, inspection guidelines and suggested maintenance checklists are also provided.

Section 7 addresses results from surveys sent to member plants requesting fan and damper application at their facilities.

Section 8 discusses training for individuals desiring to specialize in HVAC systems.

Section 9 lists the references used to write this guide.

Appendix A lists the EPRI member survey results.

2
DEFINITIONS AND ACRONYMS

2.1 Definitions

Acceleration – A vector quantity measuring the time rate of change of velocity.

Acoustic – Relating to, producing or containing sound, usually in the frequency range audible to the human ear.

Aerodynamic – Pertaining to the forces acting on a body or system as a result of its motion with respect to a flowing fluid, or due to the motion of a fluid with respect to a body or system.

Air gap – The space between a rotor and the stator in a motor.

Anti-friction bearing – Any bearing having the capability of reducing friction.

Axial – Along an axis; usually refers to the long axis of a machine, in the direction of the shaft.

Back Draft Damper – A back draft damper is a counter-weighted damper that only permits flow in one direction in the system.

Bladepass – The frequency generated by a rotating machine that is the multiple of the rotational speed (RPM) of the machine times the number of blades or vanes on a fan disk or pump impeller. See *vanepass*.

Centrifugal Fan – A fan rotor or wheel within a scroll-type housing and including driving mechanism supports for either belt drive or direct connection.

Control/Modulation Damper – A damper installed in a duct system to control the amount of air that the system will handle.

Couple unbalance – Unbalance in two or more planes, and in different radial directions with respect to the center, of a rotating body or system.

Critical speed – The speed of a rotating system that corresponds to a natural frequency of the system.

Cycle – The full sequence of a periodic motion that occurs in one period.

Damper – A device used to vary the volume of air passing through an air outlet, air inlet, or duct.

Damping – Dissipation of energy from a dynamic system over time, due to internal effects, viscous effects, friction or external resistance to motion.

Displacement – A vector quantity that specifies the change in position of an object. Displacement is often measured from a position of rest, or from a reference position.

Eccentricity – The distance that the center of rotation of a rotating body or system is displaced from the geometric center.

Fan – Any device that produces a current of air by the movement of a broad surface can be called a fan. There are several types: Centrifugal, Axial, Propeller, Tubeaxial, and Vaneaxial. Fans are also called compressors, ventilators, exhausters, and blowers.

Fan blades – The blades are the principal working surfaces of the impeller.

Fire Damper – A device, installed in an air distribution system, designed to close automatically upon detection of heat, to interrupt migratory airflow, and to restrict the passage of flame. A combination fire and smoke damper shall meet the requirements of both.

Force imbalance – Simple imbalance of one rotating mass, in one plane and in one radial direction.

Frequency spectrum – A description of the frequency and amplitude content of a signal that resolves the signal into its individual frequency components.

Harmonic – An integer multiple of any given frequency. The third multiple would be the third harmonic, and so on.

HEPA Filter – High Efficiency Particulate Air Filter – A throwaway extended media, dry-type filter in a rigid frame, having a minimum particulate-collection efficiency of 99.97% for 0.3 micron thermally generated dioctyl phthalate (D.O.P.) or acceptable alternative particles, and a maximum clean-filter pressure drop of 1.0 inch (2.54 cm) water gauge, when tested at rated airflow capacity.

Hertz – A unit of frequency measurement the same as one cycle per second. Thus, 60 Hertz (Hz) equals 60 cycles per second (CPS) or 3600 cycles or revolutions per minute (CPM or RPM).

Housing – The housing for a fan is the stationary element that guides the air or gas before and after the impeller. A housing can also be called a casing, a stator, a scroll, a panel, a ring, or a volute. For fans, housing, casing, and stator are the preferred general terms.

Hub – Hubs are used to support the blades directly or through a shroud to the shaft. A hub can also be called a boss or a disk.

Hub ratio - Ratio of hub diameter to overall fan diameter.

Impact – A single, rapid, transient transfer of mechanical energy from one body or part of a system to another. A sharp hammer blow, for example. See *shock*.

Impeller – The impeller is the rotating element that transfers energy to the fluid. It is also called a wheel, a rotor, a squirrel cage, a propeller, or a runner. Squirrel cage is restricted to forward curved-blade centrifugal fans, while propeller is restricted to certain simple axial fans.

Inlet – The inlet is the opening through which air enters the fan. It is also called the eye or the suction. A stationary inlet piece can be called an inlet cone, an inlet bell, an inlet nozzle, or a venturi.

Isolation Damper – A damper installed in a system that is capable of stopping or diverting flow from one portion of the system to another.

Journal bearing – A cylindrical bearing.

Mil – One thousandth (0.001) of an inch (2.54×10^{-5}m).

Misalignment – The amount of angularity and/or non-parallelism between the shafts of two or more machines in a machine pair, train, or combination.

Natural frequency – Any frequency of free oscillation or vibration of an object or system.

Orbit – Any closed path followed by a (rotating) body or system. A Lissajous pattern is a representation of an orbit.

Outlet – The outlet is the opening through which air leaves the fan. It can also be called the discharge. A diffuser can be provided to transform kinetic energy to pressure energy. It can be called a discharge cone.

Parameter – A measure or value of a quantity or other descriptive term. For example, velocity and frequency can be parameters of vibration.

Periodic – An oscillation that recurs at specific intervals and increments for an independent variable.

Phase –The difference in time or position between forces or motion as measured in a specific direction from a reference point. Phase is expressed as an angular quantity, and the reference position and/or direction of rotation should also be expressed.

Predictive Maintenance (PdM) - Tracking and trending of equipment operation to assess condition.

Propeller Fan – A propeller or disk-type wheel within a mounting ring or plate and including driving mechanism supports for either belt drive or direct connection.

Proximity probe – A device used to measure displacement between the reference mounting location of the probe and a moving surface.

Pulley –A wheel attached to a shaft, which carries a belt or chain. See *sheave*.

Radial – Directed from or diverging from the center.

Resonance – Forced vibration at a natural frequency.

Response – The motion or other output from a system resulting from external excitation.

Rolling Element bearing – A bearing containing balls or rollers between inner and outer rings (or races), which aid in the reduction of friction.

Rotor – Generally, any rotating body or device.

Secondary Containment - Secondary Containment is a system that is only present in Boiling Water Reactor (BWR) systems. It is considered to be the parts of the Reactor Building that surround the drywell and suppression pool (Primary Containment). Pressurized Water Reactor facilities have only the Containment Building, which serves as both primary and secondary containment.

Seismic Transducer – A vibration transducer that converts mechanical energy to a voltage signal proportional to the velocity of an internal inertial mass moving in a coil, with reference to the base of the transducer.

Sheave - A wheel attached to a shaft, which carries a belt or chain. See *pulley*.

Shock – A single, rapid, transient transfer of mechanical energy from one body or part of a system to another. A sharp hammer blow, for example. See *impact*.

Shrouds – Shrouds are used to support the blades. A shroud is also called a cover, a disk, a rim, a flange, an inlet plate, a back plate, or a center plate. Shroud is the preferred name but cover and disk are also used.

Stator vanes – Stator vanes are stationary vanes used to guide flow. Stator vanes used upstream of the impeller can be called prerotation vanes or inlet guide vanes. Stator vanes used downstream of the impeller can be called straightening vanes or discharge guide vanes.

System – A series of ducts, conduits, elbows, branch piping, etc., designed to guide the flow of air, gas, or vapor to and from one or more locations. A fan provides the necessary energy to overcome the resistance to flow of the system and causes air or gas to flow through the system. Some components of a typical system are louvers, grilles, diffusers, filters, heating and cooling coils, air pollution control devices, burner assemblies, volume flow control dampers, mixing boxes, sound attenuators, the ductwork and related fittings.

Signature – A characteristic pattern of a frequency spectrum or of a time waveform.

Sinusoidal – Referring to simple harmonic motion that would appear, when plotted or graphed, as a sine wave.

Sleeve bearing – A bearing that carries lubricant for the shaft rotating within it. Often used synonymously with Journal bearing.

Stator – The stationary part of a machine within which or about which the rotor turns.

Stiffness – The measure of resistance to motion that is the ratio of force over displacement or deflection.

Synchronous – Related by frequency, periodicity, or phase.

Tachometer – A device for measuring rotational speed and/or frequency.

Time waveform –The representation of a wave by a voltage or mechanical signal. See *waveform*.

Thermal Comfort – Thermal Comfort is defined as a condition of the mind that results in satisfaction for the thermal environment.

Torque – Rotational moment about an axis.

Torsion –Twisting deformation of a body or system about an axis. Torsional.

Tubeaxial Fan – A propeller or disk-type wheel within a cylinder and including drive mechanism supports for either belt drive or direct connection.

Turbulence – Fluid motion in which local velocities and pressures vary rapidly and irregularly in a random manner.

Ultrasonic – Relating to signals that occur above the normal range of human hearing, that is, greater than 20,000 cycles per second. Formerly supersonic.

Vaneaxial Fan – A disk-type wheel within a cylinder; a set of air guide vanes located either before or after the wheel and including driving mechanism supports for either belt drive or direct connection.

Vanepass - The frequency generated by a rotating machine that is the multiple of the rotational speed (RPM) of the machine times the number of blades or vanes on a fan disk or pump impeller. See bladepass.

Vibration – The oscillation or alternating mechanical motion of an object or system.

Vortex – A mass of fluid swirling about a central axis, where the axis itself might also be free to move in space.

Wave – A disturbance that propagates through a medium so that its position can be quantified proportional to time and at an amplitude proportional to position.

Waveform – The representation of a wave by a voltage or mechanical signal. See *time waveform*.

2.2 Acronyms

ACAD - Designation for an I.N.P.O. Academy Document

ALARA - As Low As Reasonably Achievable

AMCA - Air Moving and Conditioning Association

ANSI - American National Standards Institute

ANS - American Nuclear Society

API - American Petroleum Institute

ARI - American Refrigerant Institute

ASHRAE - American Society of Heating Refrigeration and Air Conditioning Engineers

ASME - American Society of Mechanical Engineers

BWR - Boiling Water Reactor

ECCS - Emergency Core Cooling Systems

HVAC - Heating Ventilation and Air Conditioning

IEEE - Institute of Electrical and Electronics Engineers, Inc.

INPO - Institute of Nuclear Power Operations

ISO - International Standards Organization

LEL - Lower Explosive Limit

LOCA - Loss Of Coolant Accident

LOOP - Loss-Of-Off-Site Electrical Power

MVAR - Megavar

MW - Megawatt

NRC - Nuclear Regulatory Commission

NSSS - Nuclear Steam Supply System

OSHA - Occupational Safety and Health Association

PWR - Pressurized Water Reactor

RPM - Revolutions Per Minute

SAR - Safety Analysis Report

SGTS - Standby Gas Treatment System

SCR - Spectrum for Current Readings

SRP - Standard Review Plans

TSC - Technical Support Center

3
HVAC SYSTEM DESCRIPTIONS

There are two types of commercial light-water power reactor designs used in the United States today, the pressurized water reactor (PWR) and the boiling water reactor (BWR). For both types of reactors, the main objective of HVAC systems is to protect operating personnel and the general public from airborne radioactive contamination (during normal and emergency modes of plant operation) and to maintain environment for personnel comfort and/or reliable equipment operation. The Nuclear Regulatory Commission (NRC) code 10CFR20 [2] sets forth the requirements for maintaining radiation exposure as low as reasonably achievable (ALARA). The ALARA concept is one of the design objectives of the HVAC system. In no case is the radiological dose allowed to exceed the limits as defined in NRC codes 10CFR50 [3] and 10CFR100 [4].

The NRC has developed regulatory guides (RGs) that delineate techniques for evaluating specific HVAC problems and provide information concerning NRC reviews and requirements. Four regulatory guides that directly impact HVAC system design are RG 1.52 [5], RG 1.78 [6], RG 1.95 [7], and RG 1.140 [8]. Deviations from RG criteria must be justified by the owner and approved by the NRC.

The design of the critical HVAC systems for a nuclear power generating station must ultimately be approved by the NRC staff, in accordance with Appendix A of 10CFR50 [3]. The NRC developed standard review plans (SRPs) as part of Regulatory Report NUREG-0800 [9] to provide an orderly and thorough review. The SRP provides a good basis or checklist for the preparation of a safety analysis report (SAR). The safety evaluation report is based primarily on the information provided by an applicant in a SAR as required by Section 50.34 of 10CFR50 [3a]. Technical specifications for nuclear power plant systems are developed by the owner and approved by the NRC as outlined in Section 50.36 of 10CFR50 [3b]. Technical specifications define safety thresholds, limiting conditions for operation, and surveillance requirements for all systems important to plant safety.

For any new construction, the minimum requirements for performance, design, construction, acceptance testing, and quality assurance of the equipment used in safety-related air and gas treatment systems of nuclear facilities, are found in ANSI/ASME AG-1 [10]. For existing installations, ANSI/ASME N509 [11] and/or N510 [12] are applicable.

HVAC systems are represented schematically by single line drawings commonly referred to as HVAC P&IDs or airflow diagrams. For illustration purposes, a simplified example of a control room HVAC system is shown in Figure 3-1.

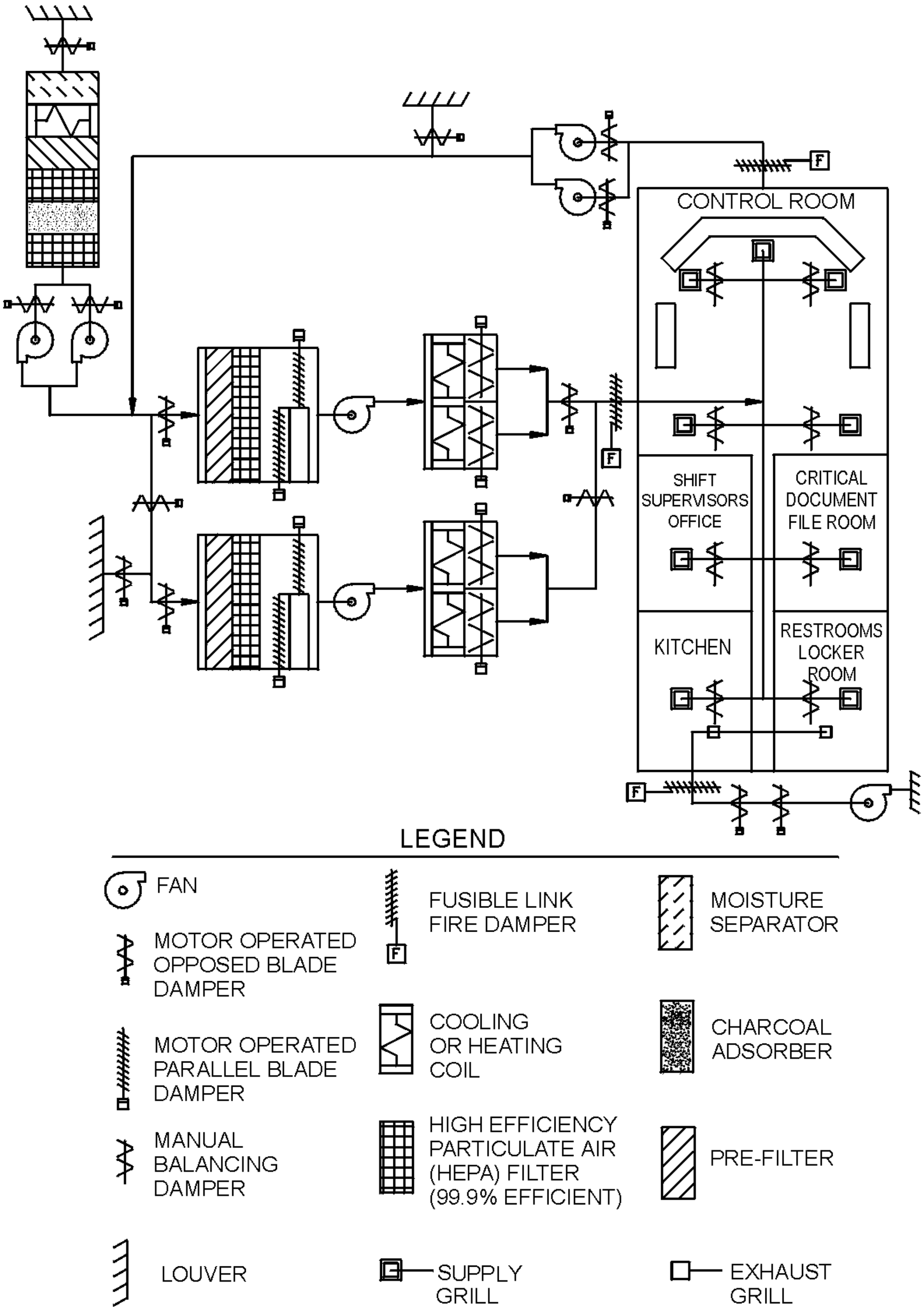


Figure 3-1
Control Room HVAC System Diagram

3.1 Unique Pressurized Water Reactor (PWR) HVAC Systems

3.1.1 Reactor Containment Building

The containment building houses the reactor in a nuclear power plant. The temperature and humidity conditions are dictated by the Nuclear Steam Supply System (NSSS). These conditions are generally specified for many scenarios including normal operation, refueling operation, loss of coolant accident (LOCA), and main steam line break condition. General design requirements are contained in ANSI/ANS 56.6 [13].

The following are typical descriptions for systems employed for containment cooling:

- **Reactor Containment Coolers** - While the reactor containment coolers remove most of the heat load in containment, they can also be used to provide both general and specific equipment cooling inside containment such as for reactor coolant pump motors. The distribution of the air supply depends on the containment layout and the location of the major heat sources.
- **Reactor Cavity Air-Handling Units or Fans** - These units are usually transfer fans (without associated cooling coils) that provide cool air to the reactor cavity. They provide cooling to the neutron detectors that measure reactor power and prevent overheating of the concrete that surrounds the reactor vessel.
- **Control Rod or Control Element Drive Mechanism (CRDM or CEDM) Air-Handling Units** - The CRDM and CEDM are usually cooled by an induced draft system using exhaust fans. Booster fans can be employed to provide supply air for cooling. Because the flow rates, pressure drops, and heat loads are generally high, it is desirable to cool the air before it is returned to the containment atmosphere.
- **Reactor Building Ductwork and Other System Considerations** - The containment air-cooling system, or a part of it, is normally designed to provide cooling after a postulated design basis accident. The system must be capable of performing at high temperature, high pressure, high humidity, and a high level of radioactivity. The heat load is removed by cooling coils that are provided with essential service water. When performing maintenance, it is important to consider these factors to avoid reducing the system's capability to perform its intended function.
- **System Design for Normal and Accident Conditions** - The ductwork must be able to endure the rapid pressure buildup associated with accident conditions. Fan motors and impellers must be sized to handle the high-density air associated with accident conditions. Cooling coils and demisters/moisture separators are located at the suction of the fans to reduce the load on the motors and fans.

Airborne radioactivity is controlled by the following means:

- **Essential Containment Air Filtration Units** - Some older power plants rely on redundant filter units powered by two Class IE buses to reduce the amount of post-LOCA airborne radioactivity. The system can consist of some or all of the following components: a demister, a heater, a High Efficiency Particulate Filter Absorber (HEPA) filter, a decay heat fan, and a charcoal adsorber followed by a second HEPA filter. The electric heater is designed to reduce the relative humidity from 100% to less than 70% at the design inlet air temperature. All of the components are located inside containment and must be designed and manufactured to meet the requirements of a LOCA environment. These filtration units might also be used to maintain the containment atmosphere suitable for containment entry at power.

- **Decay Heat Fan** - In the case of a LOCA and the subsequent operation of the filter train, the charcoal becomes loaded with radioactive iodine. If the primary fan stops, a secondary fan maintains a minimum airflow through the charcoal bed to remove the heat generated by the radioactive decay, thus reducing the possibility for autoignition of the charcoal. The decay heat fan is powered by Class IE power supply. The filtration units are located inside the containment.

- **Containment Power Access Purge or Mini-Purge** - It is necessary to ventilate during normal operation to control containment pressure (or the level of airborne radioactivity within the containment). When the reactor is under pressure, containment integrity is required.

  The system consists of a supply fan, double containment isolation valves in each of the containment wall penetrations (supply and exhaust), and an exhaust filtration unit with a fan. The filtration unit contains a HEPA filter and a charcoal adsorber, followed by a second HEPA filter.

  Some facilities use a containment pressure and vacuum relief system, which uses the differential pressure between containment and the outside atmosphere to maintain proper containment pressure.

  This system should not be connected to any duct system inside the containment. It should include a debris screen within the containment over the inlet and outlet ducts so the containment isolation valves can close, even if blocked by debris or collapsed ducts.

- **Containment Refueling Purge** - Ventilation is required to control the level of airborne radioactivity during refueling. Since the reactor is not under pressure in cold shutdown during refueling, there are no restrictions on the size of the penetrations through the containment boundary. Large openings of 42 to 48 inches (106.68 cm to 121.92 cm) are protected by double containment isolation valves. These valves close automatically on a high radiation signal in the event of a fuel handling accident inside containment. The required ventilation rate is typically based on one air change per hour.

  The system consists of a supply air-handling unit, double containment isolation valves at each supply and exhaust containment penetration, and an exhaust fan. Filters are recommended.

- **Containment Combustible Gas Control** - In an accident scenario there are several possible modes of hydrogen generation. Hydrogen recombiners are used to reduce the hydrogen concentration in the containment atmosphere. This helps reduce the chances of a hydrogen explosion. Redundant hydrogen recombiners are needed to remove the hydrogen from the containment atmosphere. The hydrogen recombiners are normally located in containment and mix hydrogen with oxygen in a reaction chamber to form water. The units consist of a heater, reaction chamber, fan and cooler, recombining the hydrogen with the oxygen and returning the air to the containment. The recombiners might be backed up by special exhaust filtration trains.

3.1.2 Turbine Building HVAC System

The steam supplied to the turbine in a PWR is not contaminated (radioactive). Therefore, turbine building ventilation systems typically take advantage of natural cooling provided by large volumes of outdoor air, ventilating the space through open windows. In temperate or warmer climates, turbines can actually be installed outdoors.

3.2 Unique Boiling Water Reactor (BWR) HVAC Systems

3.2.1 Primary Containment HVAC System

A BWR's primary containment is a low leakage, pressure-retaining structure that surrounds the reactor pressure vessel and related piping. Sometimes referred to as the drywell, it is designed to withstand, with minimum leakage, the high temperature and pressure caused by a major reactor coolant line break. General design requirements are found in ANSI/ANS 56.7 [14].

The primary containment HVAC system is normally a recirculation system utilizing a ducted general distribution system supplemented with multiple fan/coil area coolers. The system normally recirculates and cools the primary containment air to maintain the environmental conditions specified by the NSSS supplier. In an accident, the system performs the function of recirculating the air to prevent stratification of any hydrogen that might be generated. The cooling function and recirculation function might or might not be safety-related, depending on the specific plant design.

Total required fan pressures for ducted primary containment systems can be significant due to the convoluted duct routings resulting from minimal installation space. Often, these systems discharge from a main supply branch into one or two common ring headers. This configuration can result in unusual and non-uniform airflow patterns for which pressure drop calculation and measurement is difficult. The desired air distribution is achieved through backdraft dampers and manual adjustment of balancing dampers.

Temperature problems have been experienced in many BWR primary containments due to temperature stratification effects and the under-estimation of heat loads. The ductwork should adequately mix the air to prevent stratification. Heat load calculations should include a sufficient safety factor to allow for deficiencies in insulation. When performing maintenance, it is important to ensure these adverse conditions are avoided.

3.2.2 Reactor Building HVAC System

The reactor building completely encloses the primary containment, auxiliary equipment, and refueling area, called secondary containment. Under normal conditions, the reactor building HVAC system maintains the design space conditions and minimizes the release of radioactivity to the environment. The HVAC system consists of a 100% outside air cooling system. Outside air is filtered, heated, or cooled as required prior to being distributed throughout the various building areas. The exhaust airflows from areas with the least potential of contamination to the areas of most potential contamination. Prior to exhausting out to the environment, potentially contaminated air might be filtered with HEPA filters and charcoal adsorbers, with all exhaust air being monitored for radioactivity. To ensure that no unmonitored exfiltration occurs during normal operations, the ventilation systems maintain the reactor building at a negative pressure relative to the atmosphere.

High capacity fans are required due to the large load and vastness of the Reactor Building. Modulation dampers might control supply and exhaust airflows to ensure a slight negative pressure is achieved. Some systems might be designed with exhaust fans of greater capacity than the supply fans to ensure the slight negative pressure in the reactor building. The pressure is controlled by system flow balance. Additionally, redundant, bubble tight or low leakage isolation dampers are sometimes installed in any ducts that penetrate the secondary containment boundary. Upon detection of abnormal plant conditions, such as a line break, high radiation in the ventilation exhaust, or loss of negative pressure, the HVAC systems' safety-related function is to isolate the reactor building. This serves as a secondary containment boundary. This boundary is designed to contain any leakage from the primary containment or refueling area following an accident.

Once the secondary containment is isolated, pressure rises due to the loss of the normal ventilation system and the thermal expansion of the confined air. A safety-related exhaust system, the standby gas treatment system (SGTS), is started to reduce and maintain the building's negative pressure. The SGTS exhausts air from the secondary containment to the environment through HEPA filters and charcoal adsorbers. The capacity of the SGTS is based on the amount of exhaust air needed to reduce the pressure in the secondary containment and maintain it at the design level, given the containment leakage rates and required drawdown times.

In addition to the SGTS, some designs include safety-related recirculating air systems within the secondary containment to mix, cool, and/or treat the air during accident conditions. These recirculation systems use portions of the normal ventilation system ductwork; therefore, the ductwork must be classified as "safety-related". Some recirculation systems are independent of normal ventilation system ductwork to provide dedicated space cooling for equipment.

If the isolated secondary containment area is not cooled during accident conditions, it is necessary to determine the maximum temperatures that could be reached during an accident. All safety-related components in the secondary containment must be environmentally qualified to operate at these temperatures. In most plant designs, safety-related unit coolers handle the high heat release with emergency core cooling system (ECCS) pumps.

3.2.3 Turbine Building HVAC System

A BWR supplies radioactively contaminated steam directly to the turbine. Areas of the BWR turbine building, where release of airborne radioactivity is a possibility, should be enclosed. These areas must be ventilated and the exhaust must be monitored for radioactivity. The exhaust can be filtered to reduce the potential radioactive release rates. Filtration trains consist of a pre-filter, a HEPA filter, and a charcoal adsorber followed by a second HEPA filter. Filtration requirements are based on the plant and site configuration. Since heat loads in the turbine building are significant, large volumes of ventilation air are typically used for these systems. The turbine building is usually maintained at negative pressures with respect to surrounding areas and the outdoor atmosphere. Some turbine building ventilation systems might contain heating or cooling coils, or evaporative or swamp air coolers.

3.3 Common Nuclear Power Plant HVAC Systems

3.3.1 Auxiliary Building

The auxiliary building contains a large amount of support equipment, much of which handles potentially radioactive material. The building can be air conditioned for equipment protection and/or personnel comfort, and the exhaust can be filtered to reduce the release rate of potential airborne radioactivity. The filtration trains consist of a pre-filter, HEPA filter, and a charcoal adsorber followed by a second HEPA filter. The general airflow path is from areas of lower containment to areas of higher containment.

The HVAC system is a once-through system, as needed for general cooling. Ventilation is augmented by local recirculation air-handling units located in the individual equipment rooms that require additional cooling due to localized heat loads. The building is maintained at a negative pressure relative to the outside.

If the equipment within rooms in the building is not safety-related, the area is cooled by normal air conditioning units. If it is safety-related, the area is cooled by safety-related or essential air-handling units powered from the same Class IE (ANSI/IEEE 323) [15] power as the equipment in the room.

The normal and essential functions can be performed by one unit having both a normal and an essential cooling coil and a safety-related fan served from a Class IE bus. The normal coil is served with chilled water from a normal chilled water system and the essential coil operates with chilled water from a safety-related chilled water system.

3.3.2 Control Room

The Control Room HVAC system provides the control room with conditioned air to maintain the area comfortably for the operators and compatible with the equipment located there. During abnormal conditions, such as a safety injection actuation or high control room radiation alarm, the control room HVAC shifts to an accident mode of operation. Under these conditions, the make-up and/or recirculation air to the control room passes through filtration units to minimize the radiation dose received by the operators. In many control room designs, filtered make-up air provides the control room with a positive pressure as compared to the surrounding areas. This positive pressure prevents infiltration of hazardous material into the Control Room. The control room charcoal filters can also remove toxic gases from make-up air and can be used to force smoke away from the control room in the event of a fire.

In addition to filter systems, control rooms are also equipped with isolation dampers to prevent the infiltration of unwanted contaminants from the outside environment. These dampers are tested at the manufacturer for a specified leak tightness. The isolation dampers are often installed with two dampers in series to afford extra protection against failure. The control room isolation dampers are used to isolate the make-up system and the rest of the control room to prevent the infiltration of contaminants, such as toxic gases, into the control room envelope.

The Control Room HVAC system serves the control room habitability zone—those spaces that must be habitable following a postulated accident to allow the orderly shutdown of the reactor—and performs the following functions:

- Controls indoor environmental conditions
- Provides pressurization to prevent infiltration
- Reduces the radioactivity of the influent
- Protects the zone from hazardous chemical fume intrusion
- Protects the zone from fire
- Removes noxious fumes, such as smoke

The design requirements are described in detail in SRP 6.4 [16] and SRP 9.4.1 [17]. Regulatory guides that directly affect control room design are RG 1.52 [5], RG 1.78 [6], and RG 1.95 [7]. NUREG-CR-3786 [18] provides a summary of the documents affecting control room system design. ANSI/ASME N509 [11] also provides guidance for the design of control room habitability systems and methods of analyzing pressure boundary leakage effects.

3.3.3 Control Cable Spreading Rooms

Control Cable Spreading Rooms contain many cables that must enter the control room and are located directly above and/or below the control room. They are usually served by the same air-handling units that serve the electric switchgear room or the control room. If a fire were to occur in these areas, they are isolated by dampers to prevent spreading. The HVAC system provides conditions to prevent deterioration of the cables in these rooms.

3.3.4 Diesel Generator Building

Nuclear power plants have auxiliary power supplies to generate electric power for all essential and safety-related equipment in the event of loss-of-off-site electrical power (LOOP). The auxiliary power plant typically consists of at least two independent diesel generators, each sized to meet the emergency power load. Most of the heat generated by the diesel engine is removed by the essential service water system. The heat released by the diesel generator and associated auxiliary systems in the room is normally removed through outside air ventilation. A cooling fan starts whenever the emergency diesel starts to maintain the room within acceptable temperature limits to protect equipment.

3.3.5 Emergency Electrical Switchgear Rooms

Emergency Electrical Switchgear Rooms house the electrical switchgear that controls essential or safety-related equipment. The switchgear located in these rooms must be protected from excessive temperatures to ensure that its useful life, as determined by environmental qualification, is not reduced and to prevent the loss of power circuits required for proper operation of the plant, especially its safety-related equipment.

3.3.6 Battery Rooms

Upon loss-of-off-site power, the DC control power system must rely on backup station batteries. The minimum room design temperature should be taken into account in determining battery size.

Batteries produce hydrogen gas during charging periods. The minimum number of room air changes to prevent a dangerous buildup of hydrogen gas is five per hour. As hydrogen is lighter than air, the system exhaust duct inlet openings should be located on the top side of the duct to prevent hydrogen pockets from forming at the ceiling. If the ceiling is supported by structural beams, there should be an exhaust air opening in each beam pocket.

The HVAC system must be designed to limit the hydrogen concentration to the lowest of the levels specified by IEEE 484 [19], OSHA, and the lower explosive limit (LEL), while maintaining the batteries at a temperature that will provide optimum capacity during a loss-of-off-site power.

3.3.7 Fuel-Handling Building

New and spent fuel is stored in the Fuel-Handling Building. The building is air conditioned for equipment protection and ventilated with a once-through air system to control potential airborne radioactivity. Normally, the level of airborne radioactivity is so low that the exhaust need not be filtered, although it should be monitored. If significant airborne radioactivity is detected, the building is sealed, filters are aligned to the building exhaust, and fans start to keep the building under negative pressure. These filtration trains are powered by Class IE buses.

3.3.8 Personnel Facilities

For nuclear power plants, personnel facility areas usually include decontamination facilities, laboratories, and medical treatment rooms. These areas are usually located in the Auxiliary Building, consequently their HVAC systems are subsystems of the auxiliary building ventilation system. It is important to note that the ventilation hoods in the laboratories must be able to draw a vacuum in excess of that in the general auxiliary building, otherwise the airflow will be out of, not into, the hood.

3.3.9 Pump Houses

Cooling water pumps are protected by houses that are often ventilated by fans to remove the heat from the pump motors. The buildings are supplied with heat to protect the equipment during cold weather. The HVAC system maintains the pumps within a specified temperature band to ensure their operable status. If the pumps are essential or safety-related, the supporting ventilation equipment must also be considered safety-related, if the ventilation system supports equipment operability.

3.3.10 Radwaste Building

Radioactive waste, other than spent fuel, is stored, shredded, baled, or packaged for disposal in this building. The building is air conditioned for equipment protection and ventilated to control potential airborne radioactivity. The air might require filtration through HEPA filters and/or charcoal adsorbers prior to atmospheric release.

3.3.11 Technical Support Center

The Technical Support Center (TSC) is an outside facility located close to the Control Room and used by plant management and technical support personnel to provide assistance to control room operators under accident conditions.

In case of an accident, the TSC HVAC system must provide the same comfort and radiological habitability conditions maintained in the control room. The system is generally designed to commercial HVAC standards. An outside air filtration system (HEPA-charcoal-HEPA) pressurizes the facility with filtered outside air during emergency conditions. The TSC HVAC system does not have to be designed to safety-related standards.

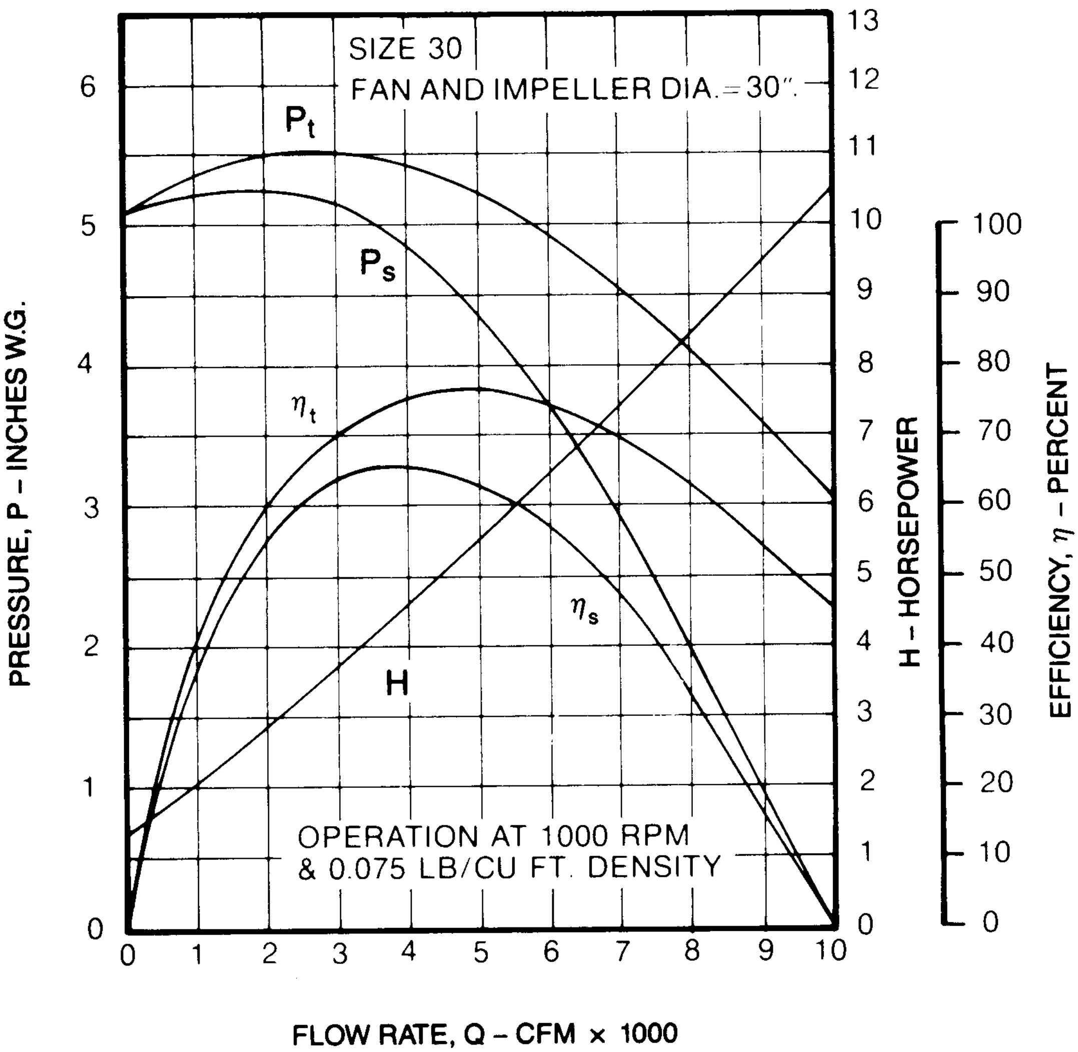
4
FANS

The primary mechanical component in a ventilation system is the fan. Some industrial applications require fans to move not only air, but dispersed quantities of solid materials as well. In nuclear power plant applications, fan systems are typically designed for "clean-air" service. This allows the system designer to select from almost any of the basic fan types. ASHRAE HVAC Systems and Equipment Manual, Chapter 18 (1996), Table 18.2 describes the essential characteristics of various fan types.

A suitable type of fan can be selected such that the conditions and requirements unique to a given application can usually be accommodated. Of all fans available for selection by the designer, there are three basic types:

- Centrifugal
- Vaneaxial
- Propeller

Regardless of the type of fan, performance and selection criteria are described by airflow quantity and developed pressure. For a given fan speed and size, the airflow quantity delivered is directly related to the pressure loss imparted between the fan inlet and outlet. These performance parameters are plotted on a graph and result in a curve that describes how much flow a fan can deliver at a given pressure (fan curve, see Figure 4-1). Additional information available on typical fan curves can include required horsepower and efficiency throughout the operational range of flows and pressures described by the curve.



Legend: **P_t = Total Pressure** **P_s = Static Pressure**
η_t = Total Efficiency **η_s = Static Efficiency**

Figure 4-1
Typical Fan Performance Curve (Courtesy: AMCA Publication 201-90)

Relative to flow control, in addition to methods directly related to the fan, dampers in ducted systems can also be adjusted to effectively increase or decrease flow within the limits of the fan curve. This can be accomplished automatically or manually. Many ducted systems incorporate flow-sensing devices that provide a control signal to a damper actuator that adjusts damper position as required to deliver the desired flow. Also, manual balancing dampers are positioned to establish the initial system flow conditions, and are adjusted as necessary to selectively deliver flow to the various areas served by the ducted fan system. In either case, damper adjustments alter the system’s pressure characteristics, thereby defining the operational point on the fan curve.

Ventilation systems most frequently include ductwork to distribute and direct airflow throughout the desired spaces and areas that they serve. Ducted systems also provide the designer with additional flow control options because they accommodate modulating or manual balancing dampers. System design should include an evaluation of the length of straight duct sections connected directly to the discharge of the fan. If insufficient straight duct is installed on the fan's discharge, performance is compromised due to the additional pressure losses imparted. This "system effect" is due to the flow profile at various distances from the discharge of each type of fan (see Figure 4-2). For vaneaxial fans, the minimum effective duct length is determined by the fan diameter and the resulting air velocity at design flow. For centrifugal fans, the minimum effective duct length is determined by the ratio of blast area and outlet area in conjunction with the orientation of the first fitting attached to the straight duct. The longer the straight section attached to the fan discharge, the less the resulting pressure loss. For proper application of system effect factors to a specific ducted configuration, see reference [20], the Air Movement and Control Association (AMCA) Publication 201, Fans and Systems.

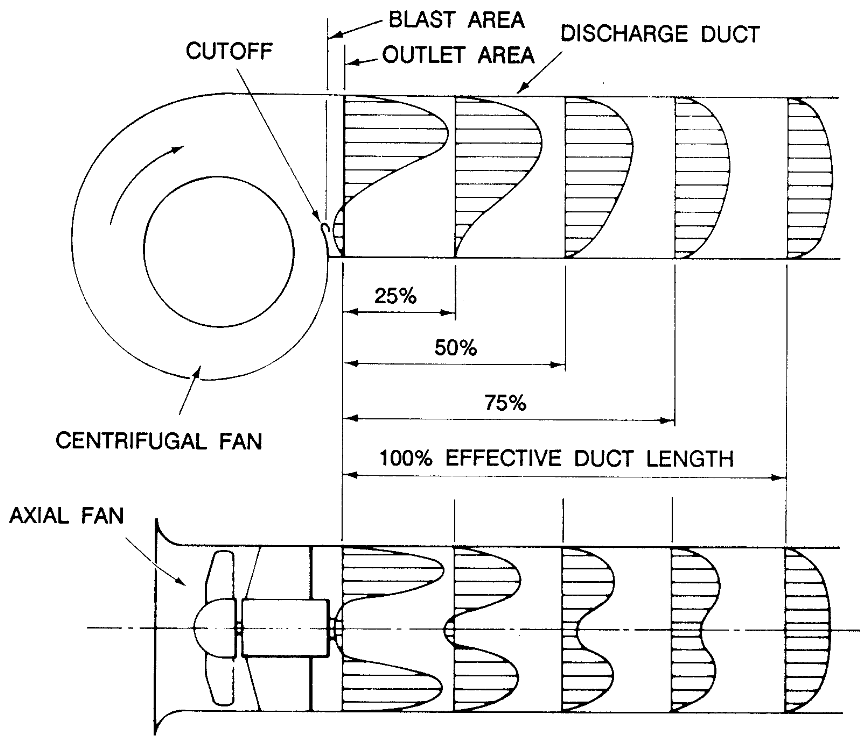


Figure 4-2
Fan Outlet Velocity Profiles (Courtesy: AMCA Publication 201-90)

Although nuclear power plant facilities have large equipment rooms and service areas, the primary ventilation system fans are typically large and, therefore, require long straight discharge ducts to minimize system effect pressure loss and to maximize performance. This is frequently difficult to accommodate, resulting in flow patterns that tax the prescribed capabilities of the specified fan.

Un-ducted ventilation systems are used in applications that are designed to transfer air between two spaces. Wall-mounted propeller fans and roof-mounted propeller or centrifugal fans are representative examples of un-ducted ventilation systems.

4.1 Types of Fans

4.1.1 Centrifugal Fans

Centrifugal fans are the most widely used due to their efficiency in moving large and small quantities of air over a wide pressure range (see Figure 4-3 and 4-4a). The fan operates by using a rotating impeller mounted inside of a scroll-type housing to impart energy to the air. For a given set of performance requirements (airflow quantity, developed pressure), centrifugal fans are typically larger than their vaneaxial counterparts. Flexibility in performance characteristics can be achieved, in part by selecting from the available impeller styles. The impeller blades can be forward-curved, backward-curved, air-foil, or radial. For greatest efficiency, backward curved airfoil shaped blades are usually preferred. Some space saving might be realized with forward curved impeller wheel design. Standard configurations also include single or double-width impellers and inlets [20]. There is one drawback to a double-width, dual-inlet centrifugal fan. In dual-inlet systems with inlet vane damper control, there are potential implications for bearing damage if one of the inlet dampers fails to open or close. In this case, with one inlet damper open and the other closed, there is an unbalanced force on the impeller of the fan. This will cause excess thrust wear on the impeller bearings. This thrust wear can limit bearing life and result in unnecessary maintenance or equipment unavailability, if the problem goes unresolved. The consequences of this maintenance issue are normally taken into consideration during the design of the system.

Available drive types include direct and belt drive. Airflow quantity delivered by centrifugal fans can be adjusted by means of “inlet vanes” positioned in line with the air inlet. By adjusting the position of these vanes (partially open and closed), pressure loss is imparted to the air stream, thereby altering the operating point on the fan head-flow curve. As pressure is induced to the air-stream by the inlet vanes, flow decreases as described by the fan curve (Figure 4-1). The speed of the impeller wheel can also be altered on belt-driven fans by means of changing sheave sizes. This alters the speed of the wheel and, thereby, the performance characteristics of the fan. The maximum impeller speed is limited by design and should not be exceeded. However, with this type of alteration, the fan produces new flow and pressure characteristics and thereby operates at flow and pressure conditions different from those described by the original fan curve. As can be seen in Figure 4-3, the discharge of a centrifugal fan can be slightly obstructed by the lip of the scroll housing. The reduced cross-sectional area of the discharge that results from this obstruction is called the “blast area,” and is considered when determining the configuration of ductwork attached to the discharge of a centrifugal fan.

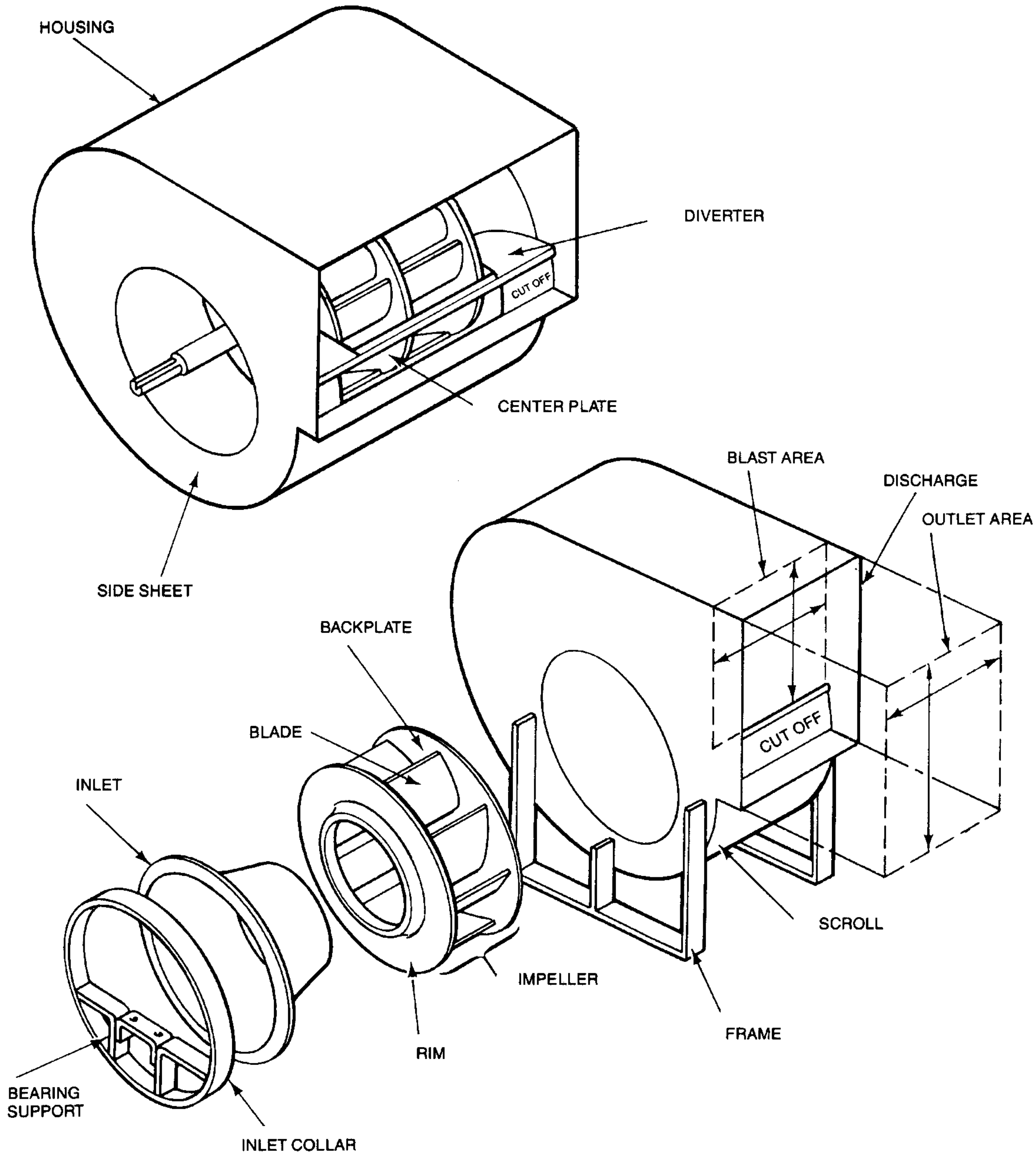


Figure 4-3
Terminology for Centrifugal Fan Components (Courtesy: AMCA Publication 201-90)

4.1.2 Vaneaxial Fans

The designation of vaneaxial fans refers to the industrial configuration of the general axial flow fan category (see Figure 4-4c). In general, fans in the axial-flow category tend to be smaller and less expensive than a centrifugal fan with comparable capacity. However, a notable unique characteristic of this type of fan is an increased level of noise. Silencers can be installed to compensate for this effect, but an additional resistance is imparted to the system with this device. In this fan, as in all axial flow fans, air flows parallel to the fan shaft. Additionally, the fan hub and propeller blades are placed within a cylindrical housing. Guide vanes are used before and after the blades in order to reduce air stream rotation. The "hub ratio" in these types of fans is typically high with fairly large hub diameters. The blades extend radially from the hub outward toward the housing, with the blade tips in fairly close tolerance with the inside of the housing surface. Flow can be controlled in vaneaxial fans by adjusting the pitch of the blades. Stamped marks are provided on the blade shafts, which can be rotated to produce different performance characteristics. Also, templates can be obtained from the fan manufacturer that provide for more accurate positioning of the blades. As with centrifugal fans, vaneaxial fans can be configured with either direct or belt drives. For belt drives, sheave sizes can be changed to alter the fan's performance characteristics.

Table 4-1 provides a general characterization of fan types.

Table 4-1
General Fan and Centrifugal Fan Attributes

General Fan Attributes

Fan Attribute	Centrifugal	Axial
Cost	Less expensive	More costly
Volumetric Flow	High	Lower
Static Pressure Rise	Lower	Higher
Size vs. Flow Capacity	Smaller	Larger
Design Complexity	Simpler	More complex

Centrifugal Fan Attributes

Fan Attribute	Radial	Forward Swept	Back Swept	Airfoil Back Swept
Flow Stability	Stable	Less Stable	Most stable	Most Stable
Pressure Rise	Moderate	Higher	Moderate	Higher
Design Complexity	Simple	Simple	Simple	Complex
Efficiency	Moderate	Moderate	Higher	Highest

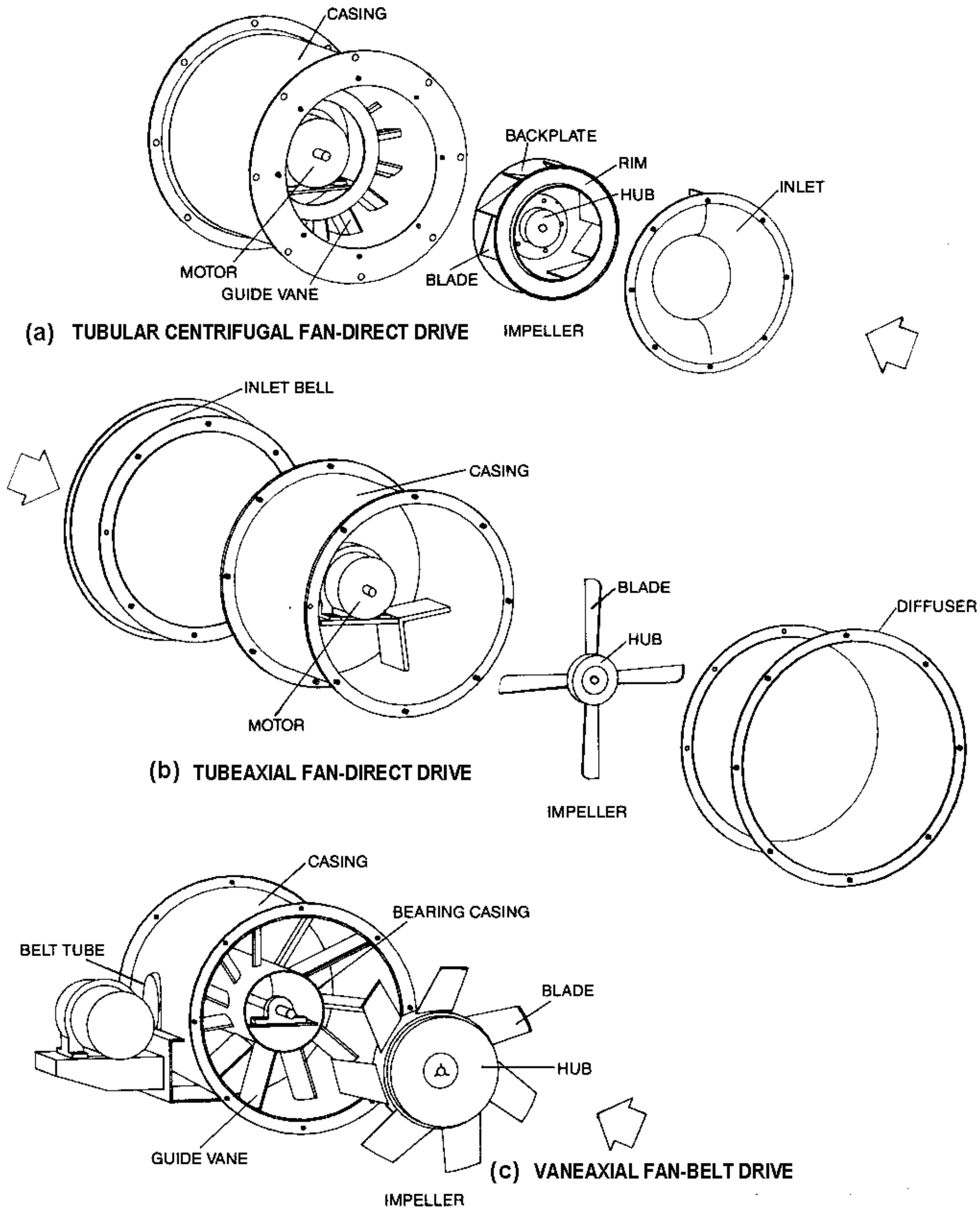


Figure 4-4
Terminology for Axial and Tubular Centrifugal Fans (Courtesy: AMCA Publication 201-90)

4.1.3 Propeller Fans

Propeller fans are usually backward-curved blade-type and can also be categorized as axial flow (Figure 4-4b). However, these fans are distinguishable by their small hub ratios, lack of any substantial housing, and are used in applications that require air to be transferred, un-ducted, between spaces. Large diameter propeller fans can be applied to move significant quantities of air, but developed pressures are lower than those available with centrifugal or vaneaxial fans. They can often be found in roof and wall exhaust applications. Control is possible with belt drive configurations, but is usually not required since pressure variances across the fan do not substantially occur in un-ducted applications.

4.2 Types of Fan Drivers and Drives

Multiple options are available for the selection of the type of drive system used for fan applications. Of the variety available, the two primary methods utilized are belt drive and direct drive. For nuclear installations it should be recognized that fans with external drives have a potential to allow air infiltration through the drive shaft opening and bearing. Care should be exercised when applying this arrangement to potentially contaminated areas. Special attention should be paid in sealing the seams of a drive belt tube in belt drive systems, and in checking for and repairing seal, shaft, and/or bearing leakage in direct drive systems during regular maintenance.

4.2.1 Belt Drive

The most widely used drive method is the belt drive. This application is the most economical and provides for good flexibility in range of application. With this system, the fan-to-motor connection is established with a drive pulley (sheave) on the motor, a drive belt ("V" or cog), and a fan pulley. Fan speeds are determined by both the motor speed and the ratio of the pulleys on the motor and fan. This allows the fan and motor combination to be closely tuned to the service application. Furthermore, if future system changes alter the ventilation demand, a new sheave or pulley can be installed that will change the performance characteristics of the fan. It should be understood that this effectively produces a different fan performance curve. Prior to implementing this type of change, a new system curve should be established and plotted with the new fan curve to ensure operation will not occur in an unstable region of the fan curve.

4.2.2 Direct Drive

Direct drive systems typically require less maintenance than belt drive systems, due to the lack of replaceable belts and pulleys. There is also the expectation that there are fewer losses in the power transmission between the fan and motor. However, the disadvantage with this type of system is the limited range of delivery flows and pressures available with the standard model fan and motor combination. Speeds are limited to available motor speeds. When used with standard model fans, the range of resulting performance curves might not allow for optimum application to the subject system characteristics.

4.2.3 Variable Speed Motor Drive

One variation on the direct drive system is the variable speed drive. This system incorporates an electronic control that sends a variable signal to the motor, which modulates the speed in accordance with the requirements of the system. This type of application is useful when consistent flows must be maintained in systems that have variable conditions. Sensors are placed at critical points in the ventilation system to monitor flow. As conditions change (for example, filters load, fume hoods placed in service) the sensors generate a signal and relay the change to the controller, which in turn modulates the fan speed to re-establish the design flow. These applications are sensitive to the associated installation parameters recommended by the manufacturers and should not be used unless the minimum requirements for location of sensors can be met. Also, the variable speed drive systems are far more expensive than the conventional drives.

4.3 Fan/Motor Condition Assessment

The primary failure modes of fans and dampers are associated with the rotating components, primarily motor, fans, and coupling devices (belts and sheaves).

Early stages of several failure modes can be detected using standard predictive maintenance (PdM) techniques. PdM technologies include vibration analysis, lubrication analysis, infrared thermography, motor testing, acoustics, and others. The major technology focus in this section will be vibration analysis, although motor testing will be discussed briefly.

As with any rotating equipment, some level of vibration of fans and their drivers is unavoidable. Excessive vibration is a symptom of some other problem. The underlying cause(s) of undesirably high levels of vibration should be corrected to prevent loss of service availability, damage to the machine, or an unsafe work environment.

For nuclear safety-related components, or those that could affect plant operations, corrective actions should be taken quickly. Vibration data trending and analysis, as part of a formal plant PdM program, is an effective method of initiating these actions proactively.

As with any tasks in a potentially hazardous environment, the collection of vibration data can present personnel risks. An effective safety program requires awareness of all safety requirements on the part of all participating personnel. A vibration program, with the necessity to perform work in close proximity to rotating components, requires a strong safety “sense”. The importance of safety cannot be overstressed.

Generally, most nuclear safety-related system and equipment evaluations require the use of calibrated equipment. Calibrated equipment and tools are also often required for tasks on peripheral systems that might have a secondary impact on nuclear safety or operability. Vibration test equipment, including, but not limited to, transducers, amplifiers, power supplies, dataloggers and analyzers, should be calibrated. Software codes might require verification. The test program itself might require that measurements and results be subject to checking or independent verification.

Acceptable vibration levels vary for different machines, and often depend on the application and the criticality of the machine. There are a number of references that give limits or ranges for acceptable vibration. Vibration charts, such as a Rathbone Vibration Severity Chart, various types of vibration nomographs, are available. Information from various other organizations such as ISO, API, ASHRAE, and ASME, technical societies, machinery manufacturers, and vibration equipment vendors is also available.

4.3.1 Fan Motor Imbalance

Imbalance is a common problem with rotating machines, especially if balancing is not included in normal machine start-up practices. Imbalance can result from imperfections in castings, construction errors or non-adherence to tolerance limits for built-up machines, either during original manufacture or when rebuilds or repairs are done. It might also result from loss of material due to wear, erosion, or corrosion. Frequently with fans, the source is a build-up of matter deposited on rotating components by the air stream.

Such accretions can build up rapidly and break off randomly, so indicated vibration levels and phase angles might not be consistent. The vibrational evidence of imbalance, however, always occurs at a frequency equal to running speed (1X rpm).

Vibration due to imbalance at 1X rpm usually dominates the spectrum (Figure 4-5). The amplitude varies as the square of the speed. Static imbalance is characterized by vibration predominantly in the radial direction, “in-phase” at both bearings. It can be corrected by one balance weight in one plane, preferably at the center of gravity of the rotor.

Couple imbalance is also at 1X rpm, but phases tend toward 180 degrees out at opposite ends of the same shaft. Amplitude still varies as the square of the speed. There can be high axial vibration as well as radial. Correction of a couple imbalances requires balancing in at least two planes, usually with several weight locations.

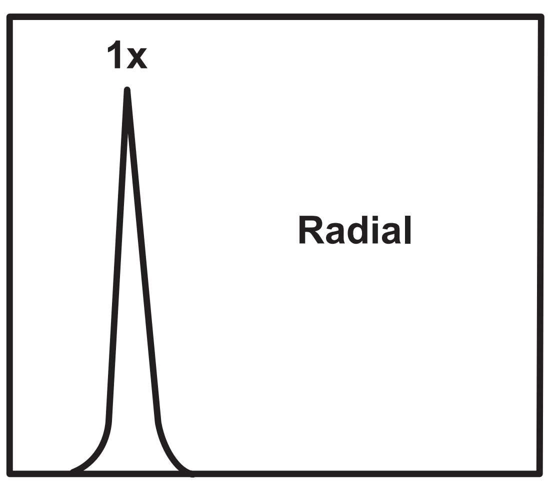


Figure 4-5
Spectrum for Force and Couple Imbalance

In some instances, where imbalance is severe, the limits of the bearing clearances or structural flexibility might be nearly exceeded due to the sizable forces exerted by the rotating imbalance. In some cases, pounding might occur and a multiple of 1X (harmonics) might be visible in the spectra, particularly in the radial directions (Figure 4-6). A balance correction is immediately called for to reduce the levels of vibration to prevent damage to the machine.

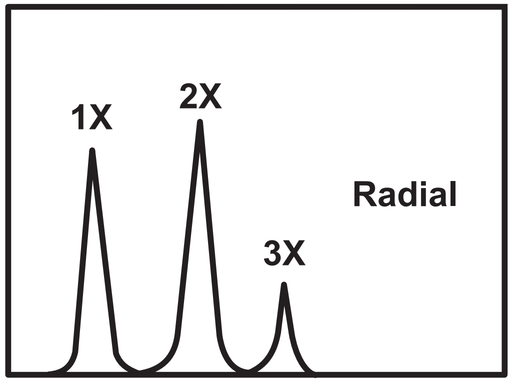


Figure 4-6
Spectrum for Severe Imbalance

Overhung rotors, typical of many fans, experience high 1X vibration in both the radial and axial directions (Figure 4-7). Many times this is a combination of force and couple imbalance, which both require correction.

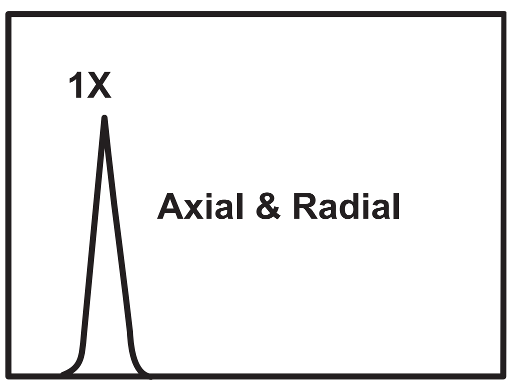


Figure 4-7
Spectrum for Overhung Rotor Imbalance

An eccentric rotor can appear to mimic imbalance vibration due to the offset of the center of rotation from the geometric centerline of the component (for example, a sheave, bearing, gear, motor rotor, or armature). Phase readings in radial directions 90 degrees apart on the same plane of the rotor usually differ by either 0 or 180 degrees. Attempts to balance in one direction often lead to reducing vibration in that direction, while increasing it in another.

In some cases where journal bearings are monitored by displacement probes, the time domain waveform can be useful for analysis. When analyzing signals from proximity probes, it must be remembered that the vibration amplitude is a measure of the relative displacement between the rotating shaft and the mounting location of the probe. As such, the mount must be stable and not resonant, in order for the measurement to be accurate.

Time waveforms due to imbalance are sinusoidal at 1X rpm (Figure 4-8).

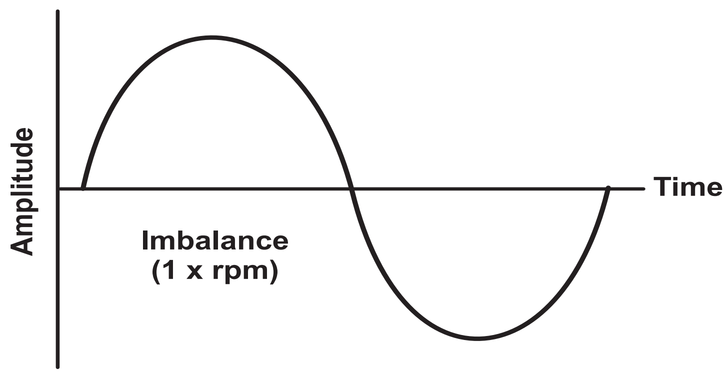
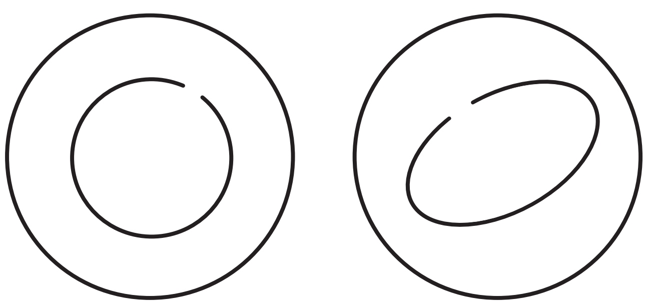


Figure 4-8
Time Waveform for Imbalance

The signals for two displacement probes that are 90 degrees apart (for example, one horizontal, the other vertical) can be displayed in a Lissajous or "orbit" pattern. This is a useful technique with journal bearings. The orbit is a representation of the motion of the shaft centerline with respect to the mounting locations of the probes.

If imbalance is predominant, the orbit will be circular or slightly elliptical (Figure 4-9). The orbit shape should be relatively constant regardless of machine speed but will change in diameter as the square of the rotational speed. A highly elliptical orbit indicates that the operating speed is close to a critical resonance. If the shape of the orbit changes or its orientation flips or shifts drastically with speed changes, another problem such as resonance, is indicated.



Unbalance will typically reveal a circular or slightly elliptical pattern at 1 x rpm

Figure 4-9
Typical Imbalance Orbits

Corrective actions include cleaning or balancing. Cleaning should be performed as a regular maintenance task where accretions are common.

Rudimentary static balancing can be performed by supporting the fan rotor and observing where the “heavy” spot “rolls”. Weight adjustments can be made until the rotor no longer rolls. Matched parts might be required for repairs to built-up fans or blowers.

If possible, the rotor should be balanced in the shop using a balancing stand or machine. In general, the type of balance job to be done requires knowledge of whether the rotor operates “rigidly” or “flexibly” at the balance speed.

Otherwise, a field balance using any of a number of different techniques, such as polar plots and hand calculations, specialized balancing instruments, portable analyzers or dataloggers, can be used.

The ideal balancing job would entail corrections based on measurements from each support or bearing plane. This would account for both static and couple or combination imbalance. This type of technique is often impractical or unachievable due to access, time, or cost constraints. In practice, balancing usually requires measurements and corrections at or near the plane of the bearings. Many fans can be suitably and effectively balanced using single-plane balancing.

Tolerances for balancing, as well as a number of standards for various types of machines, can be obtained from the machine vendor. The residual imbalance indicated by the amplitude of vibration after balancing should be documented, along with the effect coefficients (the vibration reduction corresponding to a certain weight change at a specific location and/or phase angle). Such historical data might be useful for future balance corrections or to use in eliminating balance as the source of vibration when some other problem arises.

4.3.2 Misalignment

Generally, references to alignment refer to the concept that the centerlines of the shafts of the driver and driven machine should be collinear, at least to within the tolerances of the selected coupling.

It is necessary to allow for any positional changes that might occur as a result of thermal growth (from cold to hot condition, or vice versa), due either to heat generated by the machines themselves, due to the fluid being moved internally, or from some external or other source. Thermal changes can also be due to external heating from the air or direct exposure to a heat source (such as the sun). Positional changes can occur as a result of loads that might be exerted on the machines from the foundations on which they are mounted, or by the ducts (or pipes) or structures that are connected to them.

Angular misalignment (Figure 4-10) refers to the angle between the shaft centerlines if they were extended to intersect (if collinear) or overlap in the gap between them. If severe enough, this angle is sometimes referred to as a “dogleg”. Angular misalignment is often characterized by high axial vibration with phases at or almost 180 degrees opposite, in the same measurement direction, across the coupling (Figure 4-11). This high vibration can show in the spectrum as peaks at 1X, 2X, or higher multiples of operating speed (rpm). In the vibration spectrum, frequency peaks at 1X and 2X rpm, often indicate high axial vibration. It is not unusual for higher multiples of rpm to appear, and any of them could be the dominant spectral peak. All of the above symptoms might also indicate coupling problems.

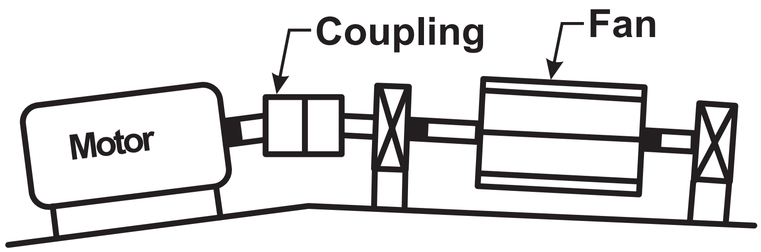


Figure 4-10
Angular Misalignment

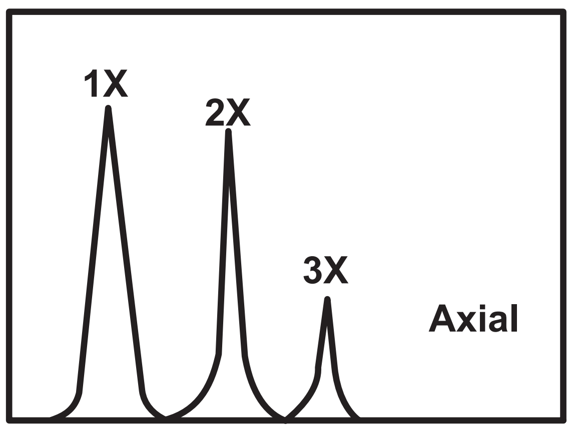


Figure 4-11
Spectrum of Angular Misalignment

Offset or parallel misalignment refers to the non-collinear nature of the shaft centerlines, in any radial direction (Figure 4-12). Typically, when alignment is checked, this type of misalignment will be noted in at least two radial directions 90 degrees apart, such as horizontal and vertical. It is important to remember, however, that the offset might be in any direction and is often accompanied by angular misalignment. The vibration spectrum of offset misalignment typically occurs at 180 degrees out-of-phase, as measured in the same radial direction, across the coupling. The spectrum often shows frequency peaks at 1X and 2X rpm, and might show a string of higher frequency harmonics if the misalignment is severe (this is similar to mechanical looseness, severe imbalance to the limits of mechanical clearances, or some types of impacting) (Figure 4-13). The 2X peak will often dominate and its relative height might be dependent on the type of coupling in use. There might also be axial vibration. The type of coupling in use could have a great deal of influence on the nature of the vibration spectrum and needs to be considered. There is some evidence that the greatest vibration occurs in the direction of the offset misalignment. In other words, if the misalignment is greater in the vertical direction, that will be the direction of greatest vibration amplitude.

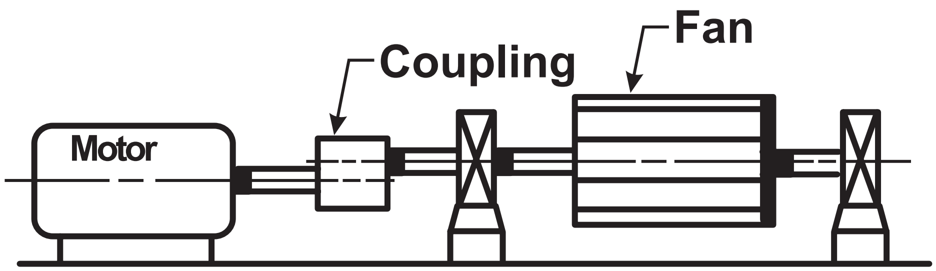


Figure 4-12
Offset Misalignment

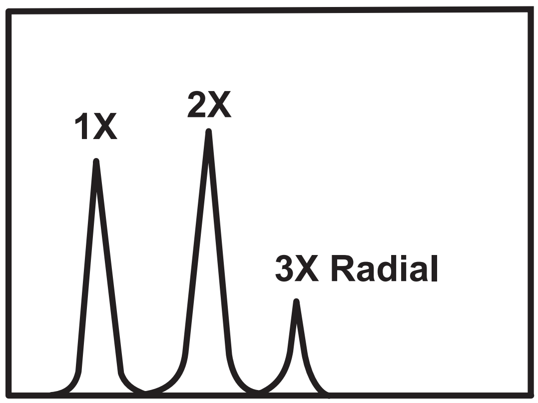


Figure 4-13
Spectrum of Offset Misalignment

If journal bearings are monitored in the radial direction by non-contact displacement probes, the time domain waveform might be useful for analysis of misalignment. In the time domain, the waveform typical for misalignment will appear as all one frequency (sinusoidal), or as a combination of two (or several) frequencies that are harmonically related (sinusoidal, but of varying amplitude) (Figure 4-14).

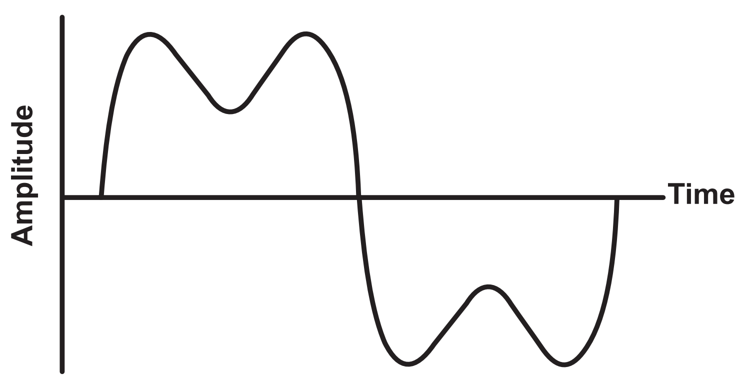


Figure 4-14
Typical Composite Time Waveform for Misalignment

For misaligned conditions, the orbit is often very oblate or flattened and, in cases of severe misalignment, frequently takes the shape of a figure eight (Figure 4-15). The reason for this is the differential stiffness and resistance to the vibrational translation of the shaft within the clearances of the bearing, which results in a second (or higher) harmonic of vibration, thus the 2X in the spectral data.

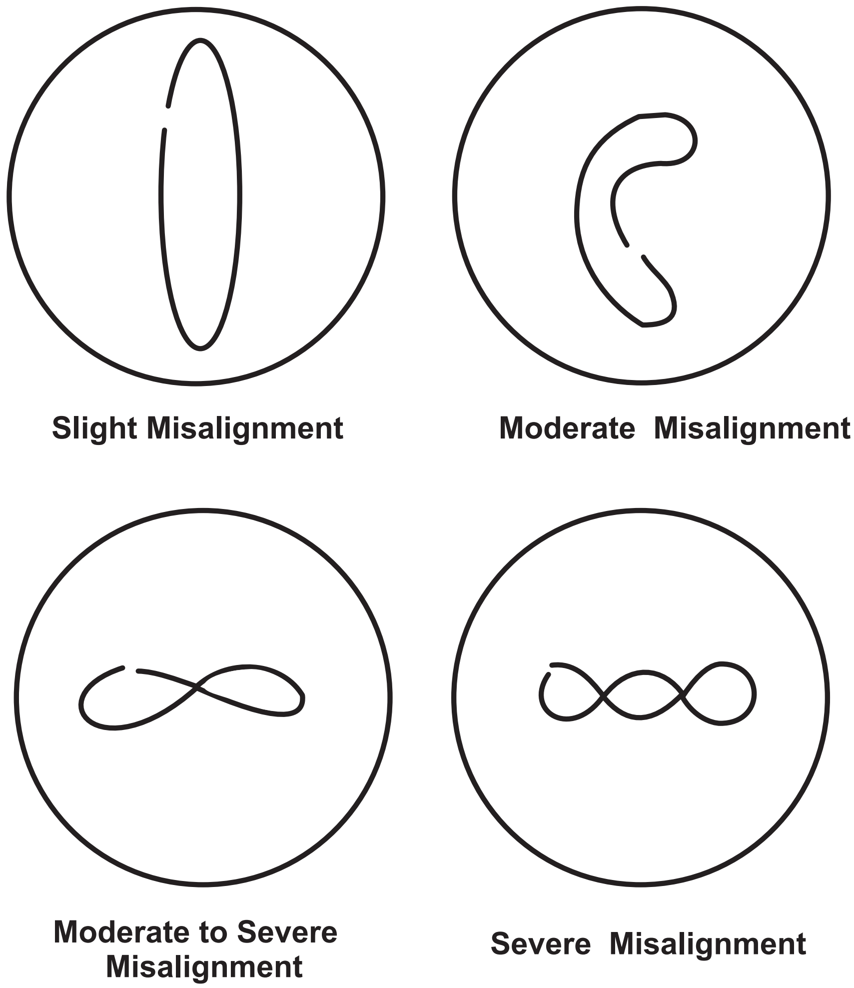


Figure 4-15
Misalignment Orbits

Bearing line-up or cocked bearings will often generate high axial vibration. For journal bearings, this vibration will often appear as 1X and 2X vibration, 180 degrees out-of-phase either axially or radially, measured in the same directions across the coupling. The best measurements for this condition are made with non-contact displacement probes or laser vibrometers. This type of bearing misalignment will only show up if there is also a large residual imbalance forcing the vibration of the shaft close to the bearing clearances.

For rolling element (anti-friction, that is, ball or roller) bearings, the same symptoms of bearing misalignment might appear in the vibration spectrum and might also be accompanied by high peaks at the characteristic bearing frequencies (see Section 4.3.3). Vibration measurements for rolling element bearings are typically made with transducers mounted on the bearing caps. This improper bearing mounting situation often results in high loads in the bearings that can significantly reduce their life. Attempts to correct coupling alignment will not reduce the vibration levels or the evidence in the vibration spectra of a cocked or misaligned bearing condition. The bearing faults must be corrected.

Belt-driven or chain-driven machines are subject to misalignment due to the spatial relationship of their shafts and the sheaves (pulleys) that carry the belts or chains. Correct alignment requires attention to offset (driven end sheaves must be coplanar across their faces) and toe (angular – the shafts must be parallel and the sheaves must not be cocked or loose on the shafts). Correct alignment also requires elimination of twist (the machine shafts must be coplanar through their long axes; that is, the machines cannot be tilted front to rear with respect to each other).

Thermal growth or forced movement must be accounted for, as mentioned above. If one machine gets considerably hotter (or colder) than the other, or if loads from attachments or ducts could result in forces that cause the machine shafts to move with respect to each other, then the best alignment will result when these changes are taken into account. Typically, the goal is to ensure that the machines are in the most desirable configuration, within the tolerances of the coupling (or belts or chains) during operation at normal temperatures and other conditions. A number of vendors offer equipment that can be used to check thermal growth, ranging from relatively simple and inexpensive measurement methods to laser-based computer techniques.

One condition that often mimics misalignment is known as soft foot. The term is often loosely applied to several different possible structural faults and will be discussed further in Section 4.3.10.

A bent shaft can mimic misalignment. A bent shaft is often characterized by high axial vibration with axial phase differences approaching 180 degrees as measured on opposite ends of the same shaft. The dominant frequency of vibration is usually 1X rpm if the bend is near the center of the shaft (similar to shaft thermal bow), but 2X if the bend is closer to the coupling (an abrupt kink in the shaft).

Corrective actions might include a number of alignment techniques. Traditionally, a combination of straight edges, wires or strings, and dial indicators was used. A measurement method resulting in a set of rim and face readings and requiring a series of calculations to determine corrective moves, was time-consuming but effective. In some instances, this method might still be required because of limited accessibility to the coupling area to make measurements. A technique known as the reverse dial indicator method has been in use for many years and is relatively simpler than rim and face techniques. Modern laser alignment sets, although expensive, are generally the simplest to use and offer excellent results, provided that the shafts are accessible for correct mounting of the lasers and measurement targets. These techniques also require that the machines be rotated from 90 to 360 degrees. Care must be taken that the technicians and engineers who use these techniques are properly trained and understand the theory, principles, and practice of machinery alignment.

Tolerances for alignment should be evaluated for each machine, based on the recommendations of the machine, coupling, sheave, belt or chain vendors, and as recommended by various texts and references on alignment.

Misalignment usually makes vibration worse. However, minor misalignment within the tolerances of most couplings does not necessarily result in changes to vibration levels that can be attributed solely to misalignment. In addition, the severity of vibration does not necessarily indicate the severity of misalignment.

There have been several studies done in recent years that attempted to document claims that precise alignment resulted in improved machinery performance and a consequent reduction of energy use (and associated dollar savings). The findings of at least two of these studies failed to show any correlation between power consumption and precision of alignment. The following is a table that summarizes the types and definitions of angular and parallel misalignments along with some characterizations:

Table 4-2
Misalignment Characterization Table (Angular & Parallel Misalignment)

<table>
<tr><th colspan="5">MISALIGNMENT</th></tr>
<tr><th rowspan="2">Type / Definition</th><th colspan="2">Casing Vibration Measurements</th><th colspan="2">Proximity Probes Vibration Measurements (Journal Bearings)</th></tr>
<tr><th>Overall Vibration</th><th>Vibration Spectrum</th><th>Time Waveform</th><th>Shaft Orbit</th></tr>
<tr><td>Angular Misalignment: The angle between the shaft centerlines is greater than acceptable tolerance</td><td>1. High Axial
2. Phases close to 180 degrees opposite in the same measurement across the coupling</td><td>1. High 1X and 2X in the axial vibration spectrum
2. Higher harmonics may be dominant</td><td rowspan="2">Sinusoidal waveform with varying amplitude and high 1X and 2X harmonics with 180 degrees out-of-phase either axially or radially measured in the same direction across the coupling</td><td rowspan="2">1. Orbit is oblate or flattened (ellipse or moon shape)
2. Figure eight if misalignment is severe</td></tr>
<tr><td>Parallel (or Offset) Misalignment: Shaft centerlines are not colinear within tolerance</td><td>1. High vibration in two radial directions 90 degrees apart
2. Phases are 180 degrees opposite in the same radial direction across the coupling
3. Axial vibration might also be present
4. The direction of misalignment might be indicated by the higher vibration</td><td>1. High 1X and 2X in the radial vibration spectrum, the 2X being the dominant
2. A string of higher frequency harmonics might be present if misalignment is severe</td></tr>
<tr><td colspan="5">Notes:
Other conditions that mimic misalignment are soft foot and bent shaft.
Special attention must be given to thermal growth monitoring, bearings, and sheaves mounting.</td></tr>
</table>

4.3.3 Bearing Problems

Journal or sleeve bearings are best analyzed using non-contact displacement probes, although bearing cap measurements might be useful for trending. Fits and tolerances are particularly important for journal bearings, since correct oil film development is crucial to the proper functioning of the bearing. If a sleeve bearing starts to wear, it might not be apparent in the vibration data at first. In the later stages of bearing wear, the vibration spectra might display a long string of harmonics. A wiped bearing might have higher vibration in the more heavily loaded direction. Bearings with excessive clearances might allow a comparatively small residual imbalance or a small misalignment to cause high vibration that would be no cause for concern if the clearances were within tolerance.

Lubrication with the correct oil for the expected loads, temperatures, and operating speeds is crucial. Bearings of the appropriate design that enable proper oil film development are also crucial. If the bearing and the lubricant do not meet the required parameters, several problems might result. Changes in oil viscosity, lube oil pressure, and external preloads might also affect vibration.

Oil whirl is a somewhat uncommon problem with journal bearings, due to improved bearing designs. The vibration is caused by the instability of the oil film wedge in the bearing due to minor variations in operating conditions, and the resulting variable load in varying directions causes the shaft to whirl (precess) within the clearances of the bearing. Additional instability might result if the whirl frequency corresponds to a shaft system dynamic natural frequency (critical). In spite of improvements in bearing design, in older machines with plain bearing designs, this fault might still occur and is characterized by a vibration just under 0.5X (Figure 4-16). Oil whirl can be very severe, and is considered excessive if the amplitude of the whirl vibration is greater than half the bearing clearance. Displacement measurements are, therefore, required.

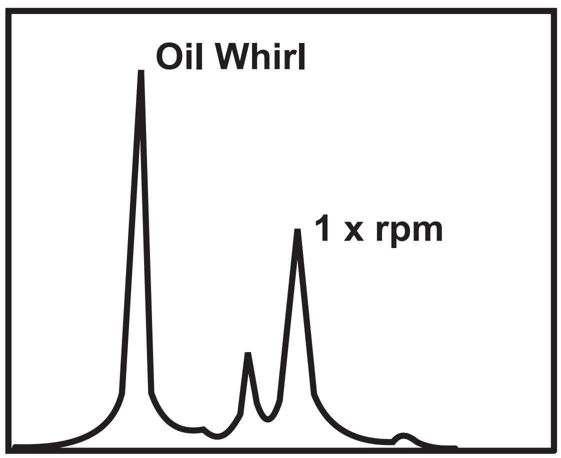


Figure 4-16
Spectrum of Oil Whirl

In the time domain, the whirl orbit is either circular or elliptical and usually has an internal loop that rotates or precesses with respect to the main orbit (Figure 4-17).

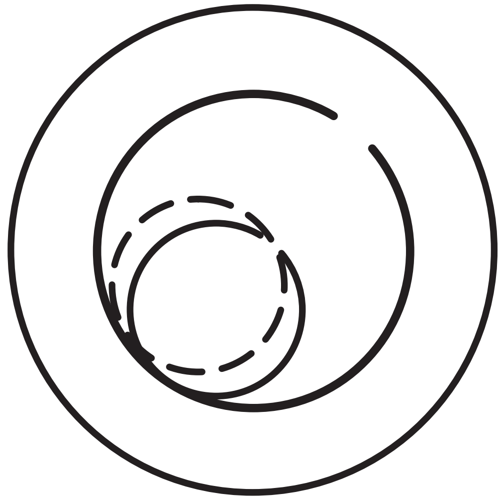


Figure 4-17
Oil Whirl Orbit

Oil whip is a rare whirl problem that might occur on machines that operate at or above twice the first shaft dynamic natural frequency or critical speed.

Anti-friction (rolling element) bearings, if used, are possibly the most precisely manufactured component in most machines. Consequently, it is important to handle and store them correctly. If bearings are damaged in handling or are incorrectly installed, they might fail well in advance of their projected life expectancy. Proper lubrication is also very important. An improperly lubricated ball or roller bearing can be damaged and progress to failure very rapidly.

Looseness, fits, and tolerances are just as important for ball and roller bearings as they are for journal or sleeve bearings. Looseness can result in high vibration, as can rubs due to incorrect fits. As mentioned above, cocked bearing conditions can mimic misalignment.

Spectral indications of rolling element bearing problems are easily identified in many cases, because the characteristics are based on calculated frequencies that depend on machine speed and bearing construction. The frequencies can be calculated for both ball and roller bearings alike. These frequencies are commonly referred to by names that indicate the part of the bearing in which the defect is present (Figure 4-18):

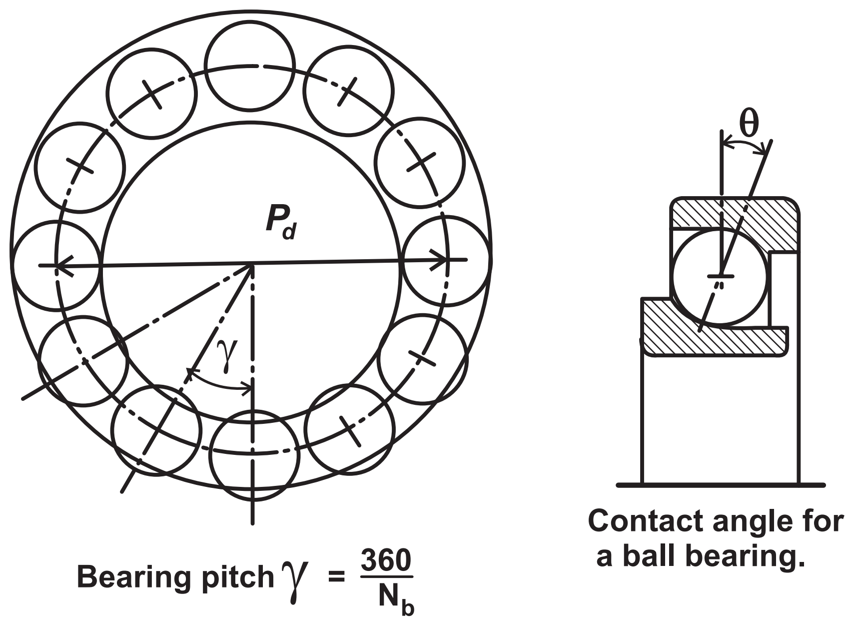


Figure 4-18
Contact Angle and Bearing Pitch

Fundamental Train Frequency (FTF) equation:

$$FTF = \frac{1}{2}\left(1 - \frac{B_d}{P_d}\cos\theta\right) \times rpm \qquad \text{(eq. 4-1)}$$

Ball Spin Frequency (BSF) equation:

$$BSF = \frac{P_d}{2B_d}\left(1 - \left(\frac{B_d}{P_d}\right)^2 (\cos\theta)^2\right) \times rpm \qquad \text{(eq. 4-2)}$$

Ball Pass Frequency, Inner Race (BPFI) equation:

$$BPFI = \frac{N_b}{2}\left(1 + \frac{B_d}{P_d}\cos\theta\right) \times rpm \qquad \text{(eq. 4-3)}$$

Ball Pass Frequency, Outer Race (BPFO) equation:

$$BPFO = \frac{N_b}{2}\left(1 - \frac{B_d}{P_d}\cos\theta\right) \times rpm \qquad \text{(eq. 4-4)}$$

Where: N_b = Number of balls

B_d = Ball or Roller diameter (in.)

P_d = Bearing Pitch diameter

θ = Contact Angle (Degrees)

The information required for specific bearings can be obtained from vendor reference materials. The frequency calculations can be done manually but most data collection software for vibration dataloggers and analyzers, or for use in predictive maintenance applications, contain calculator programs that use these or similar equations.

In addition, the small impacts from internal defects excite bearing natural frequencies, which might show up in the spectral data as non-synchronous frequencies that have no relationship to the above characteristic frequencies.

Bearing problems generally occur in progressive stages (Figure 4-19). In the first stage, defects are generally small and do not result in much change in vibration amplitude of measurements made on the external surface of the bearing cap in either the radial or axial directions. For this reason, incipient bearing faults often go undetected using transducers like accelerometers, which are commonly used in many vibration programs. However, even minor defects will generate noise and vibration in the ultrasonic (greater than 100,000 cycles per second) or very high mechanical frequencies. Use of an ultrasonic detector or a high frequency technique such as High Frequency Detection (HFD and demodulation, Computational Systems, Inc.), Spectral Energy Enveloping (SEE, SKF Condition Monitoring), Spike Energy (ENTEK/IRD), or Shock Pulse Monitoring (SPM, SPM Corporation) can be beneficial to analysis.

In the second stage of bearing defect development, the high frequency noise usually continues to increase in amplitude and bearing natural frequencies begin to appear. These are also relatively high frequencies, often higher than 30,000 cycles per second, and might even approach the ultrasonic. As the bearing degrades through this stage, sidebands begin to appear in the spectral data on both sides of the natural frequency peaks. Vibration usually occurs radially and axially.

In the next stage of bearing defect development, the bearing characteristic frequencies begin to be very visible in the spectra. Harmonics of these frequencies begin to appear and sidebands grow on both sides of the main and harmonic peaks. Vibration usually occurs radially and axially. The high frequency noise continues to increase. If the bearing was disassembled at this stage, the defect(s) would be plainly visible. It is generally agreed that this is the stage at which to replace the bearings.

As the bearing defects grow even worse in the fourth stage, the entire frequency spectrum is affected because harmonics and sidebands appear across the frequency band from 1X rpm and up. As the bearing condition worsens, usually rapidly at this stage, the bearing defect, harmonic and sideband frequencies might actually begin to disappear and a random broadband noise floor begins to arise from the noise background of the spectrum. Vibration usually occurs radially and axially. Ultrasonic and high frequency noise might also decrease, but will usually reappear at very high amplitudes just prior to final failure of the bearing.

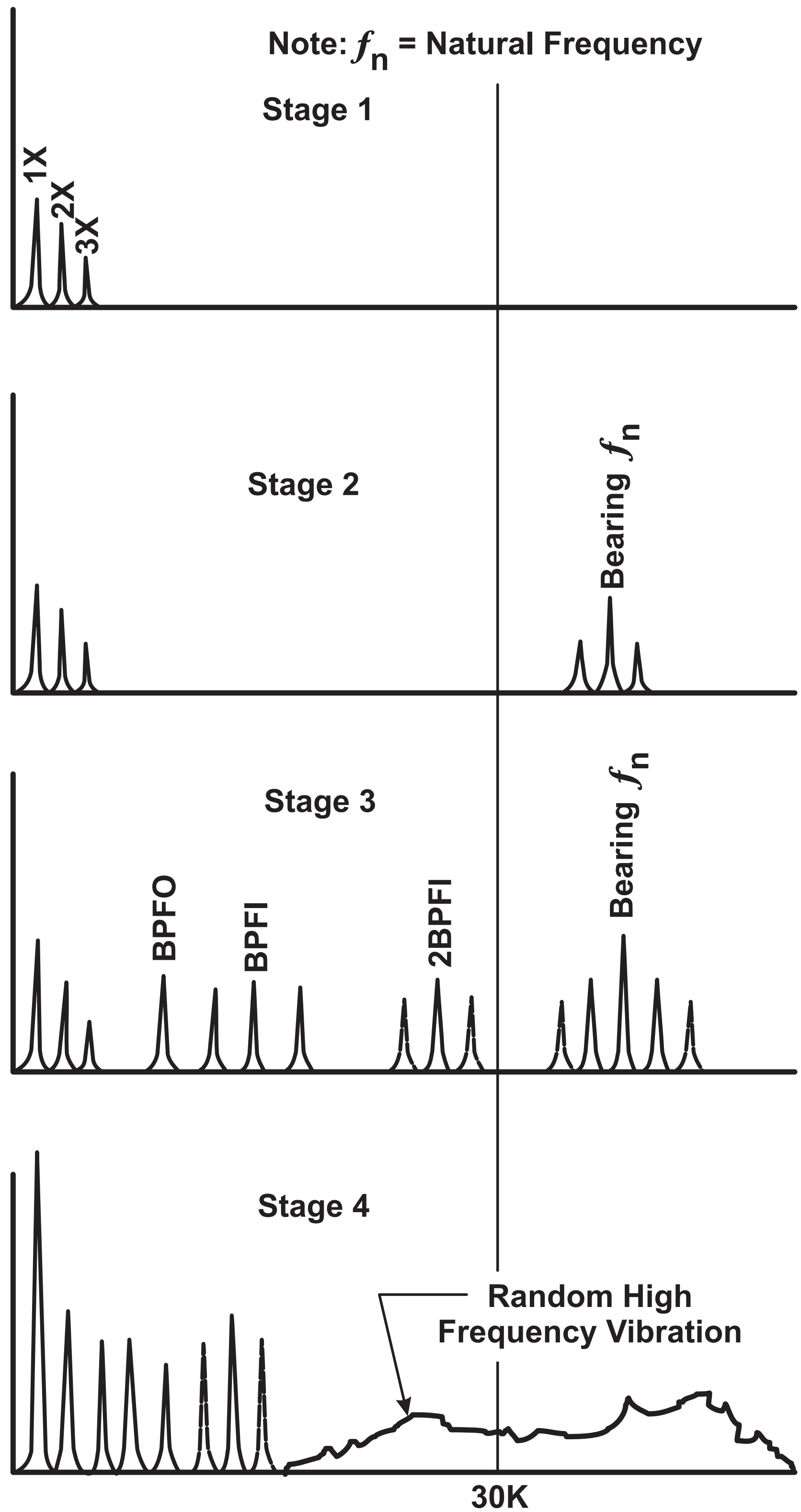


Figure 4-19
Spectral Plots for Phases of Bearing Defects

Time waveform indications of bearing problems are sometimes present but are often not very instructive. Typically, the amplitudes will not increase until the later stages of failure. However, there might be the appearance of "packets" of energy and high frequency noise in the time waveform. These are related to the appearance of the bearing frequencies in the spectral data. Corrective actions include strict attention to proper assembly procedures, ensuring proper lubrication, and bearing replacement at the appropriate stage of defect development.

4.3.4 Mechanical Looseness or Rubbing

Mechanical looseness can occur internally in the machine, at various locations on the external body such as the bearing caps, or at structural interfaces like the feet. Only the first two types are addressed here; the other type is discussed in the section on structural vibration below.

Internal looseness is generally caused by improper fit between component parts. This causes strings of sub and higher multiple harmonics to appear in the spectral data due to the nonlinear response of the loose parts to the dynamic forces acting on them (caused by the rotation of the machine) (Figure 4-20). The time waveform might appear flat-topped or truncated. Common causes are looseness of a journal bearing sleeve or liner inside its cap, excessive clearances in either a journal or rolling element bearing or a loose fan wheel. The phase of vibration with respect to the reference might be very unstable from one start to the next because of shifting of the loose components. The vibration due to looseness might be very direction-dependent, so a survey of vibration in various locations might be necessary and useful in diagnosing the problem.

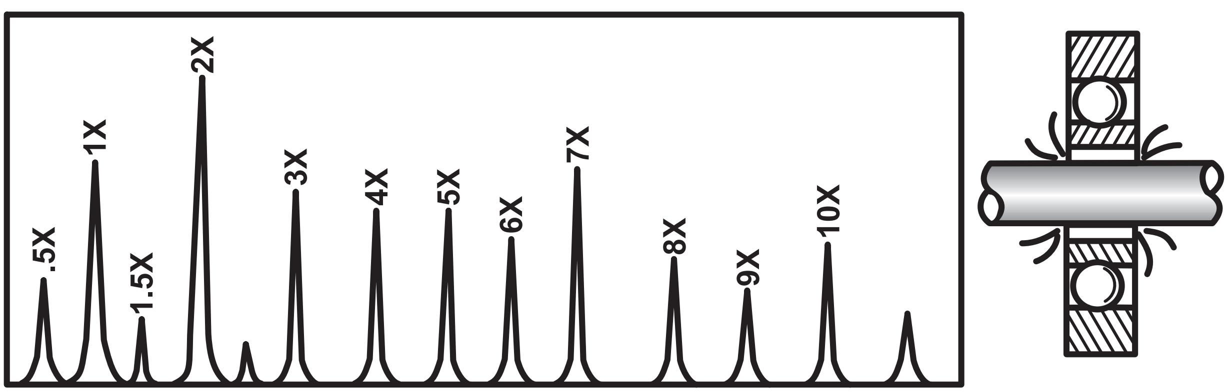


Figure 4-20
Internal Looseness Spectrum and Diagram

External looseness is generally caused by a loose bolt or some variety of "soft foot" (see 4.3.10) conditions, by a loose pillow block bearing mounting, or by cracks in the machine frame or in attachments to the frame (Figure 4-21). Strings of sub and higher harmonics appear in the spectra (Figures 4-22 and 4-23). By measuring the vibration at various locations it is possible to locate the source of looseness. In many cases, visual inspection will reveal the problem location due to water or oil being squeezed out of the loose joint, or by observation of a crack opening and closing due to the dynamic forces from rotation.

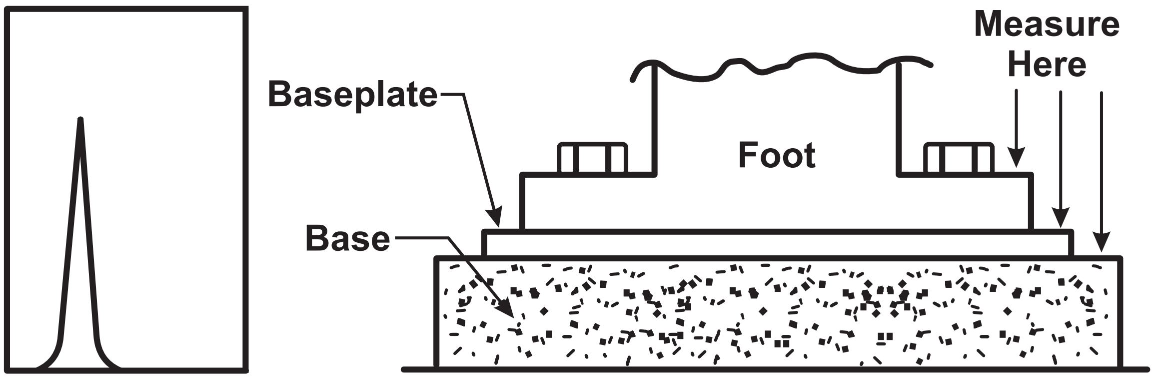


Figure 4-21
External Looseness Spectrum and Picture

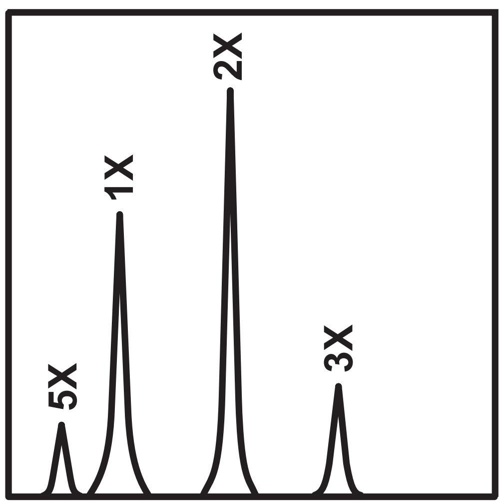


Figure 4-22
External Looseness Spectrum

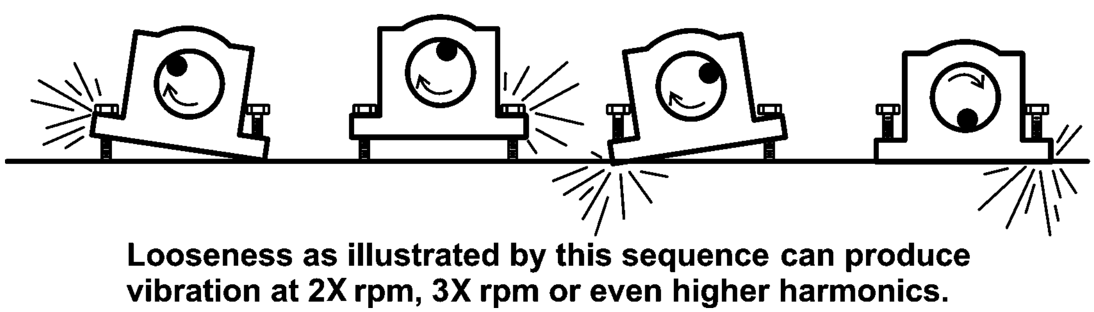


Figure 4-23
External Looseness Picture

Rubs can be due to several conditions. A rotor rub occurs when a rotating part contacts a stationary component. Rubs can occur due to inadequate oil film development or because of mechanical misassembly. Rubs might be partial or slight, or might occur during the entire rotation. In some cases, the rub condition will clear after a brief period of operation. In other cases, the rub condition might cause rapid deterioration and severe damage to the machine. Some rubs cause audible squealing or squeaking. The frequency content in the spectrum of rubs can include sub and higher harmonics and also random non-synchronous and resonance frequencies (Figure 4-24). The excitation of resonances by the rub often results in the appearance of integer subharmonics in the spectrum (1/2, 1/3, 1/4, 1/5 rpm and so on).

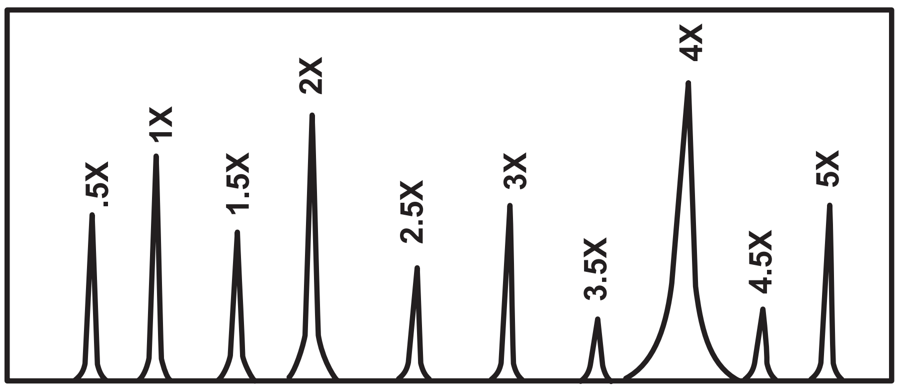


Figure 4-24
Rub Spectrum

In the time domain, truncated waveforms are common (Figure 4-25).

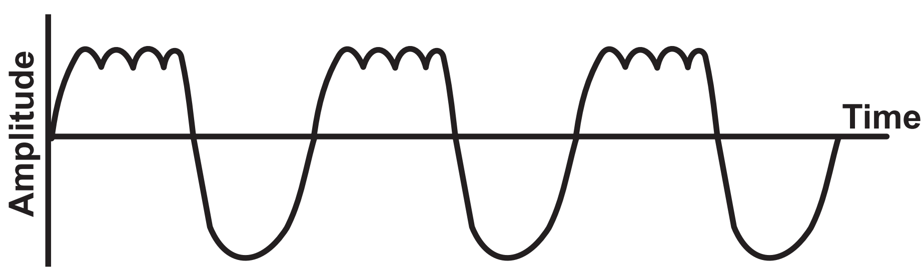


Figure 4-25
Rub Waveform

In the orbit, minor flattening in one segment of the orbit at a stationary location in succeeding orbits, indicates a slight rub. This is because the rotor only slightly touches where the rub occurs. A more severe rub might result in the appearance of an internal loop in the orbit. Unlike the internal loop caused by oil whirl, this loop does not rotate inside or move in orientation with respect to the main orbit. The pattern is referred to as hit-and-bounce. This is what causes the subharmonics in the spectral data. A serious rub might result in bouncing of the shaft at random within the bearing, resulting in a flower-like pattern as multiple orbits or translational motion across the bearing occur, tracing many patterns in the time required for one orbit (Figure 4-26).

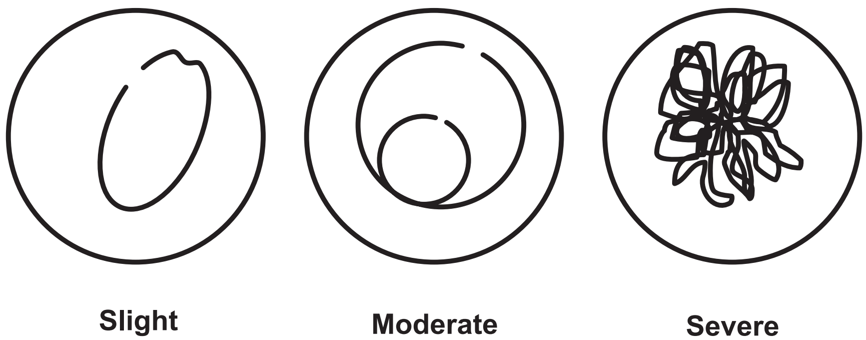


Figure 4-26
Rub Orbits

4.3.5 Belt Problems

Belt driven fans are common, as is vibration due to problems with them. Worn belt condition, incorrect installation, and mismatching bolts are common problems. A strobe light is a valuable tool to use when trying to diagnose belt problems.

Belt length (Figure 4-27) can be calculated by:

$$l = \frac{\pi D}{2} + \frac{\pi d}{2} + 2 \bullet PD \qquad \text{(eq. 4-5)}$$

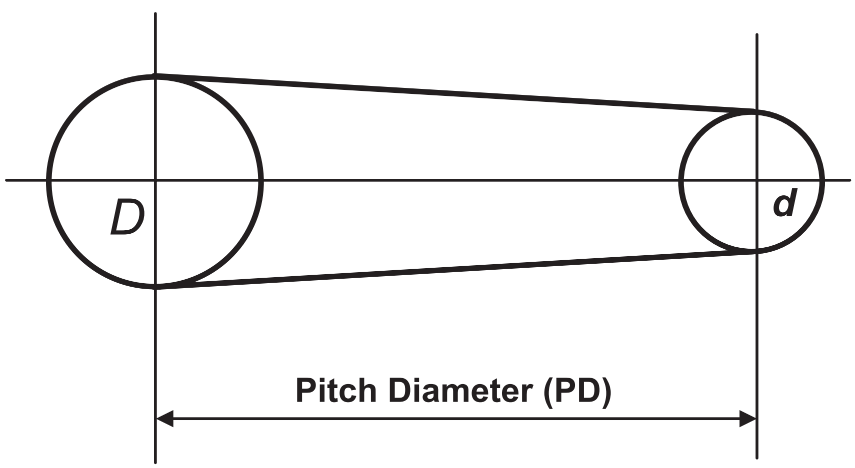


Figure 4-27
Belt Length

Belt frequencies can be calculated by the equation below:

$$\text{Belt Frequency} = \frac{3.142 \text{ x Sheave rpm x Pitch Diameter}}{\text{Belt Length}} \qquad \text{(eq. 4-6)}$$

Belt frequencies are always below the rpm of either machine. Some vibration at belt frequency is to be expected and will always be visible in the spectra.

Worn belts will produce higher multiples, usually up to 3X or 4X of belt frequencies. The 2X is often the dominant frequency of vibration. Amplitudes are often unsteady; beating or pulsation is frequently audible and is observed as spectral peaks that vary in the amplitude or time waveforms that display such amplitude variations.

Similar vibration results from loose belts. Belt tension is important and it is necessary to use a belt-tensioning tool in order to get the best results. It is not desirable to have loose belts because they can slip, wasting energy, or they might flop about causing alternating stresses in bearings and shafts. If loose enough, they might even fly off the sheaves and cause damage or injury. Slipping belts will wear the sheaves causing excessive belt wear. Having belts too tight might result in excessive loads and alternating stresses leading to bearing or shaft failures.

Many machines require more than one belt. For a multi-belt drive equipment it is important that the belts are a matched set, equally tensioned for uniform loading. These belts should be re-tensioned after a suitable run-in period. Re-tensioning of steel cord belts might not be required. Multi V-belts, constructed as a single unit (with a flat belt connecting all the V's) are also less prone to loosening. If the belts run loose, slip between belt and pulley might occur. This can lead to pulley wear, making ridges on the pulley face. This is true for single or multiple drive belts. In such cases, the pulley must be replaced to prevent damage to the new replacement belt.

When replacing belts, the old belts should be closely examined for any abnormal wear. Non-equal wear across all belts will indicate that the belts were not uniformly loaded. Non-uniform wear will indicate mis-alignment or a cracked pulley. If you are replacing belts more frequently than every three to five years, you should look into equipment alignment and belt specification.

Vibration due to loose belts is similar to that from worn ones (Figure 4-28).

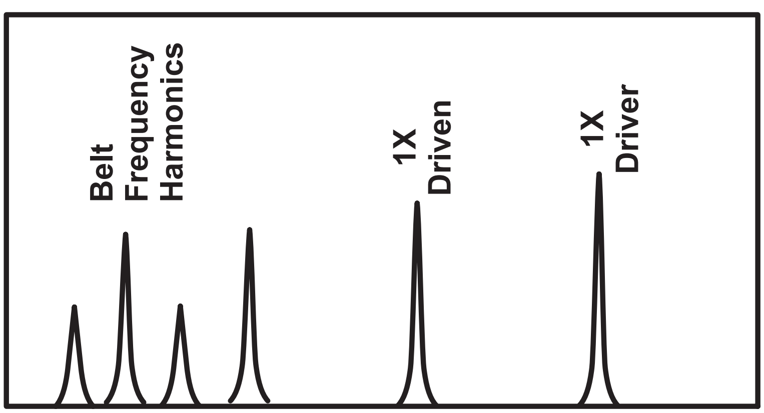


Figure 4-28
Spectrum for Worn, Loose, or Mismatched Belts

Sheave or pulley imbalance, eccentricity, and looseness of mounts all result in vibration characteristics similar to those faults described in sections 4.3.1, 4.3.2, and 4.3.4 of this guide. Sheave or pulley imbalance and eccentricity produce high 1X rpm vibration, which might appear on either machine. However, the 1X rpm data indicates which sheave is the problem. The vibration is usually greatest in line with the belts. Imbalance might be corrected using typical methods, but eccentric sheaves should be reworked or replaced in order to avoid alternating stresses on the shaft.

As mentioned in the section on misalignment, offset, toe, and twist must all be considered when setting up belted machines (Figures 4-29 and 4-30). Vibration due to misalignment of belted machines is usually high in the axial direction, often at fan rpm (Figure 4-31). The amplitude might depend on where the data is taken and the relative masses and foundation stiffnesses of the two machines.

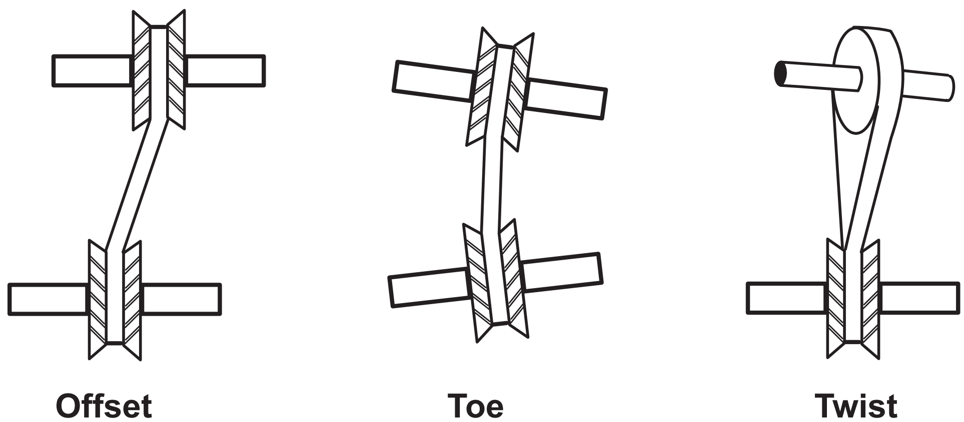


Figure 4-29
Belt/Sheave Misalignment

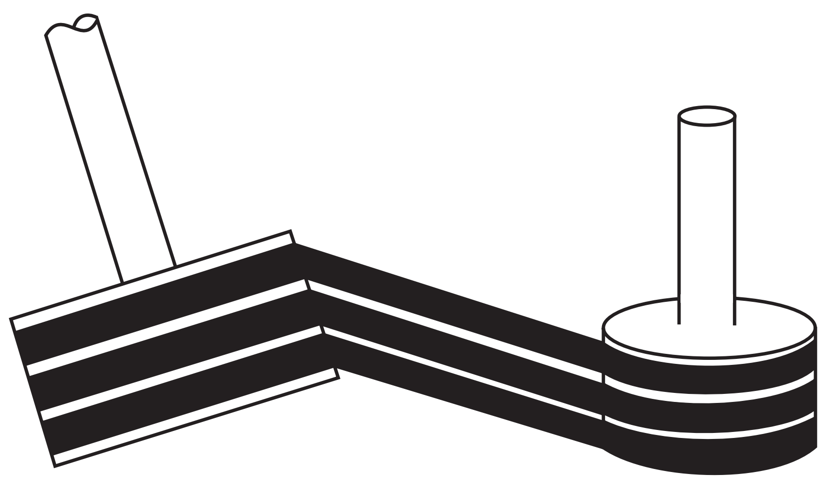


Figure 4-30
Combination of All Three Misalignments, Offset, Toe, and Twist

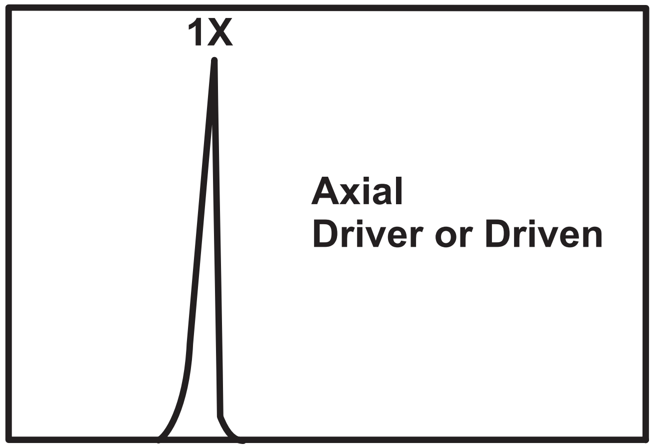


Figure 4-31
Belt Misalignment Spectrum

Belt resonance can cause high vibration if the belt natural frequency coincides with (or is close to) either the motor, fan, or belt rpm (Figure 4-32). Belt resonance vibration is indicated by variable amplitude of the associated spectral peaks as the resonance phase shifts occur (Figure 4-33). This variability will also show in the time waveform. The belt natural frequency can be changed by adjusting belt tension or by changing belt length. The latter might require repositioning of the machines. The resonance situation might be confirmed by plucking the belt (or otherwise abruptly jerking it) while measuring the response on either sheave. If it is possible to easily adjust tension and operate the machine again, it might serve to confirm resonance and fix the problem.

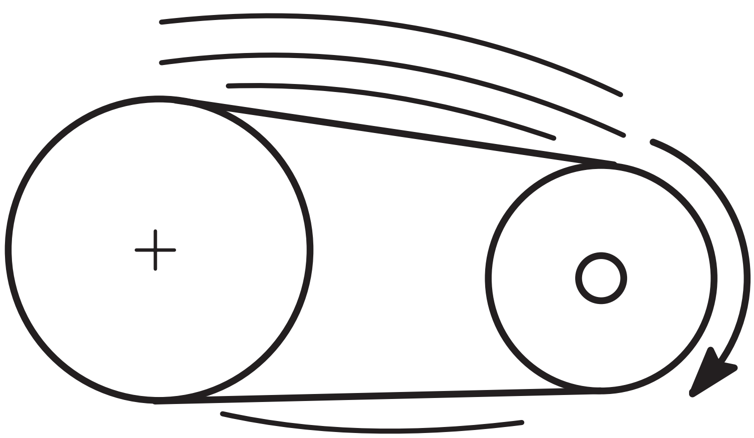


Figure 4-32
Belts Flapping Due to Resonance

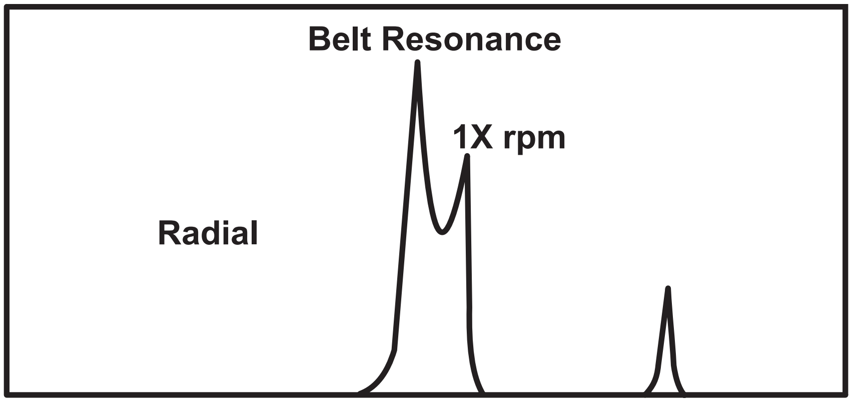


Figure 4-33
Spectrum of Belt Resonance

4.3.6 Chain Drive Problems

Evaluation of chain drive problems should take into account similar considerations as for belts. It is necessary to know the frequencies for the cogged pulleys. Alignment is still critical to reducing vibration and for extending chain life. Chain tension is possibly more crucial due to the need to keep the stresses on linkages within the design tolerances.

4.3.7 Coupling Problems

From a vibration standpoint, coupling problems exhibit the same characteristics as misalignment.

In general, couplings are not the source of most vibration problems. Improperly selected, worn, defective, or improperly maintained flexible couplings can, however, contribute to high vibration.

A gear-type flexible coupling might be subject to torque lock, causing it to behave as a rigid coupling (Figure 4-34). This raises selection and lubrication issues for this type of coupling. A properly sized and lubricated coupling of this type will perform in a normal, non-vibratory manner. If it is undersized or misapplied and improperly lubricated, it might seize and lock up to be non-flexible both radially and axially under torque. This allows any misalignment present to cause excessive vibration. This condition might be detected by variability in phase readings from one start to the next, because the locked condition might be released when the machine is stopped.

Figure 4-34
Gear-Type Coupling

Disk pack flexible couplings lose their flexibility if the disks begin to fail, resulting in high vibration at 1X rpm. Similar vibration results from excessive age and wear of pin and bushing couplings.

4.3.8 Ductwork

Duct mechanical resonance might be excited by the forcing frequencies generated by fan rotation, particularly bladepass (see Figure 4-36). This might result in excessive noise and vibration and might lead to fatigue failures of the duct and/or attachments. Natural frequency tests will reveal frequencies that closely coincide with rotational frequencies, thus, redesign of the duct might be required.

Acoustic resonance might occur and is primarily a function of duct length. The frequencies of resonance do depend somewhat on duct shape and on whether it behaves as if it is open at both ends or closed at one end. This can be a problem when the acoustic frequencies coincide with forcing frequencies from the rotating machine and/or with mechanical natural frequencies of the ducts or components. In some systems, the operation of the fan or blower can result in standing acoustic waves that traverse the duct continuously.

Chamber (Helmholtz) resonance frequencies result when the moving fluid passes over the small opening of a large acoustic cavity. This effect is similar to what happens when one blows over the mouth of an empty soft drink bottle. The cavity has a set of characteristic frequencies that can be excited by the flow past its mouth. These become potential problems when they correspond to mechanical natural frequencies, resulting in resonant response.

4.3.9 Flow-Induced and Flow-Related Effects

The control of noise is an important aspect of fan and duct design and operation. Noise problems can be difficult to diagnose and expensive to correct. Since noise analysis and control are extensive topics for study in themselves, an examination of them is not included in the scope of this module, except as it relates to the recognition and resolution of mechanical or aerodynamic vibration problems.

It is important to remember, however, that fan noise is aerodynamic in origin and the presence and type of noise might point to a specific problem that is manifested by excessive vibration. Noise might increase with flow velocity and turbulence, or the proximity of fan blades to fixed surfaces, or be due to other problems resulting in stall and flow separation. However, the vibrational properties of the fan itself generally have no role in fan noise because the generation of airborne noise is not dependent on the moving surfaces.

Fans and blowers are often installed in systems that require them to operate under variable duty, away from their original and most efficient best operating points. This causes instability, which might result in vibration.

Surging is a common instability fault. The fan repeatedly travels up and down its head/flow curve and, as a result, there is cyclic variation in the flow through the duct. This variation is typically low frequency and is dependent on the duct volume. For large fans it might occur at less than one cycle per second. Surge is most common in forward-swept bladed centrifugal fans and vaneaxial fans operating to the left of their catalog fan curve cutoff. This surge operating location for vaneaxial fans is in the range of a small dip in the performance curve. The intersection of these two curves is very near the catalog cutoff point. If a system is experiencing surge, it should be investigated for possible changes to the system design characteristics that have placed the system in the surge zone.

Internal unstable vortex formation can occur in fans with inlet guide vanes designed to unload the fan. When the guide vanes are closed, the inlet vortex becomes unstable and is no longer parallel to the fan axis. Instead, it curves upward internally toward the backplate of the fan. As the fan rotates, the vortex does also, producing periodic pulsing as it passes the cutoff. The frequency of pulsation can vary from 1X to 3X fan turning speed.

Rotating stall might occur in an axial fan under low flow conditions. A small disturbance in the flow causes stall (loss of the ability to force air through the impeller) on the suction side of one blade. Deflection of the air stream, coupled with rotation of the fan and the variations in pressure, results in the stall moving from one blade to the next, around the fan. The result is large pressure pulsations, usually at a frequency about 2/3 the rpm of the fan, but varying up to 1.5 X rpm if flow is reduced further. Stall can cause severe vibration of the fan and an increase in audible noise.

Even the most perfectly designed fan or blower will generate some turbulence (Figure 4-35). Turbulence might occur in blowers due to variations in pressure or flow velocity of the air in the system as it passes through the fan or duct. These minor disruptions cause random turbulent vibration, which generally appears as broadband noise and vibration, often of significant amplitude and usually at less than 1X rpm of the fan. As the flow velocity is increased, the amount and effect of turbulence is increased.

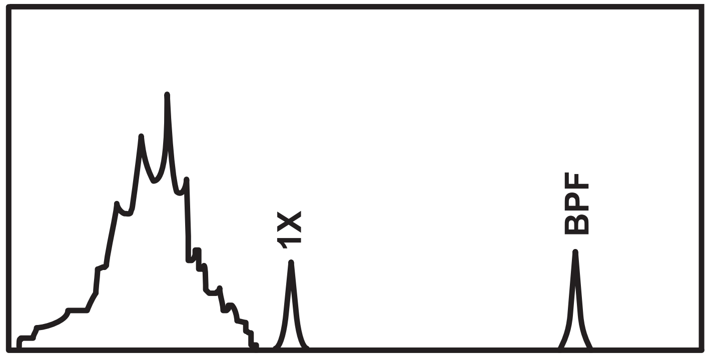


Figure 4-35
Spectrum of Turbulence

Bladepass (or vanepass) (Equation 4-7) is the frequency generated as each rotating fan or blower vane passes a stationary point on the structure surrounding it. It appears in the spectrum at the frequency of the number of vanes multiplied by the turning speed. Good designs of machines (such as keeping the gap between fan wheel and case equal around the circumference) and well-designed/obstacle-free ducts help to minimize the effects of this type of vibration; however, it is nearly impossible to eliminate entirely and usually causes no problems. These frequencies can be problems if they force resonant vibration of some other component or structure (Figure 4-36).

$$\text{Bladepass Frequency} = \text{Number of Blades x rpm} \qquad \text{(eq. 4-7)}$$

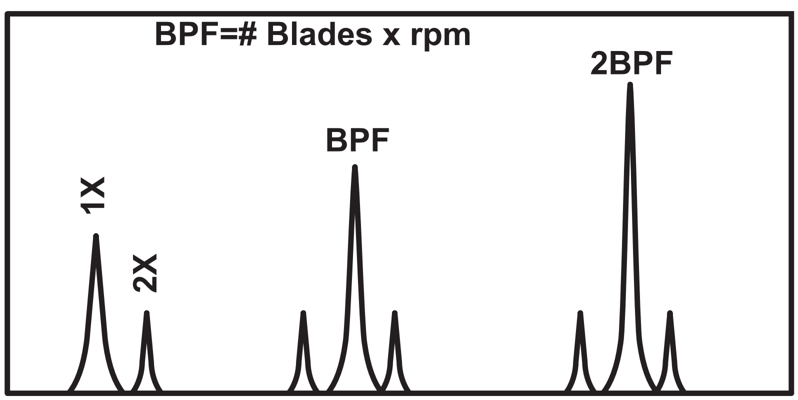


Figure 4-36
Spectrum of Bladepass

Vortex shedding occurs when flow across a body or structural member results in the formation of eddies or whirlwinds (a vortex or vortices) that might attach to and/or trail away upstream from the member. Their formation depends on the velocity of flow across the body and the fluid density, as well as the shape of the body. The characteristic frequencies are called vortex shedding or von Karman frequencies. Vibration analysis depends on calculating these frequencies and comparing them to measured frequencies, which can be difficult. These vortices might cause high vibration themselves but are particularly problematic if they excite resonance vibration of structural natural frequencies. This could cause rapid failure due to fatigue of duct structural members such as internal bracing, guide vanes, or dampers.

4.3.10 Structural Problems

Bases, bedplates or baseplates, machine feet, and mounting bolts are often overlooked as potential sources of vibration problems. However, inadequate or faulty mounting can often lead to problems that manifest themselves as high vibration.

Soft foot is the term loosely applied to several undesirable conditions that might affect the contact and, thus, the mounted stability of the machine at the interface between the machine feet and the base. Soft foot can include structural looseness, deformation, or weakness of the machine feet (they deflect due to static and/or dynamic loads), weakness of the baseplate, a weak, cracked, or deformed foundation. The grout field under the base might be inadequate or deteriorated. The frame, baseplate, or mounting rails might be deformed. A simple case might be loose hold-down bolts; a more complex case might be a combination of several of the listed conditions. Soft foot is a structural problem, although it is frequently considered as an alignment-related problem. In fact, laser alignment tools usually include a technique for soft foot checking as a first step in performing alignment. This ensures a solid base for the machine, at least at the feet and in the static condition. An operating soft foot check, done by measuring vibration at a reference location and noting how it changes as hold-down bolts are loosened and then retorqued, might need to be done to locate the soft foot in the dynamic condition. (Always use a torque wrench and tighten the bolts to the torque value required for the bolt diameter.) The spectral data usually has a dominant peak at 1X rpm although, in some cases, 1/2X will also appear, especially if looseness is part of the problem. Phase analysis might show 180-degree differences in the vertical vibration at different elevations of the bolted and mounting assembly (that is, from the foot to the baseplate to the base).

Attached structural components such as ductwork, piping, seismic restraints and hangers might be poorly installed or adjusted, resulting in unwanted loads on the rotating machines. These loads might distort the machine casing, causing vibration. Thermal changes might cause a machine to vibrate sometimes but not at other times. Ductwork should be isolated from machinery vibration with flexible connectors and joints. Restraints might not be carrying any load, or they could be adding unwanted load. Rigid or semi-rigid attachments might change the natural frequencies of the machine so that they coincide with forcing frequencies due to rotation or bladepass, causing resonant response.

Vibration from adjacent machines might be transmitted through the floor, walls, or other attachments or structures, and can cause problems. For instance, damage to rolling element bearings in stationary machines due to vibration from external sources (false Brinneling) is a common problem.

4.3.11 Structural Resonances

Specific natural frequencies of vibration (eigenvalues) are inherent to all objects and depend on the shape, mass, damping, and stiffness of the structure (Figure 4-37). Because all structures have many natural frequencies (actually, an infinite number), vibration due to resonance at natural frequencies is a common problem. Even though a structure or machine has many natural frequencies, usually only the first few have any significance to vibration analysis. This is because higher frequencies result in vibration in more and more complex shapes (modes shapes) and are progressively more difficult to excite to high amplitudes of vibration. On the other hand, high frequency vibration at resonance can cause rapid fatigue failures and should be assessed and eliminated. Rotating equipment generates many frequencies that can cause natural frequencies to become excited, or resonant. These so-called forcing frequencies might be due to imbalance, bladepass, or other regular synchronous frequencies caused by rotation. Looseness or rubs might also generate them. As long as they do not exactly coincide with a natural frequency of the machine or structure, the situation could be non-problematic or at least manageable. However, if a forcing frequency exactly (or nearly exactly) coincides with a natural frequency, and the machine or structure has little or no damping (which is common), then the resonant vibration is amplified, and vibration might reach destructive levels, followed by rapid, often catastrophic, failure.

Hammer or "ring" tests in the field or shaker tests in a lab can be used to determine natural frequencies of the machines and structures. In addition, test methods are available that result in “pictures” of the shapes that the machine takes at its various natural frequencies or as it vibrates during operation (operating deflection shapes). These techniques can be very useful in analysis of vibration problems, but the tests are sometimes time-consuming and difficult to achieve, and the analytical methods are often complex.

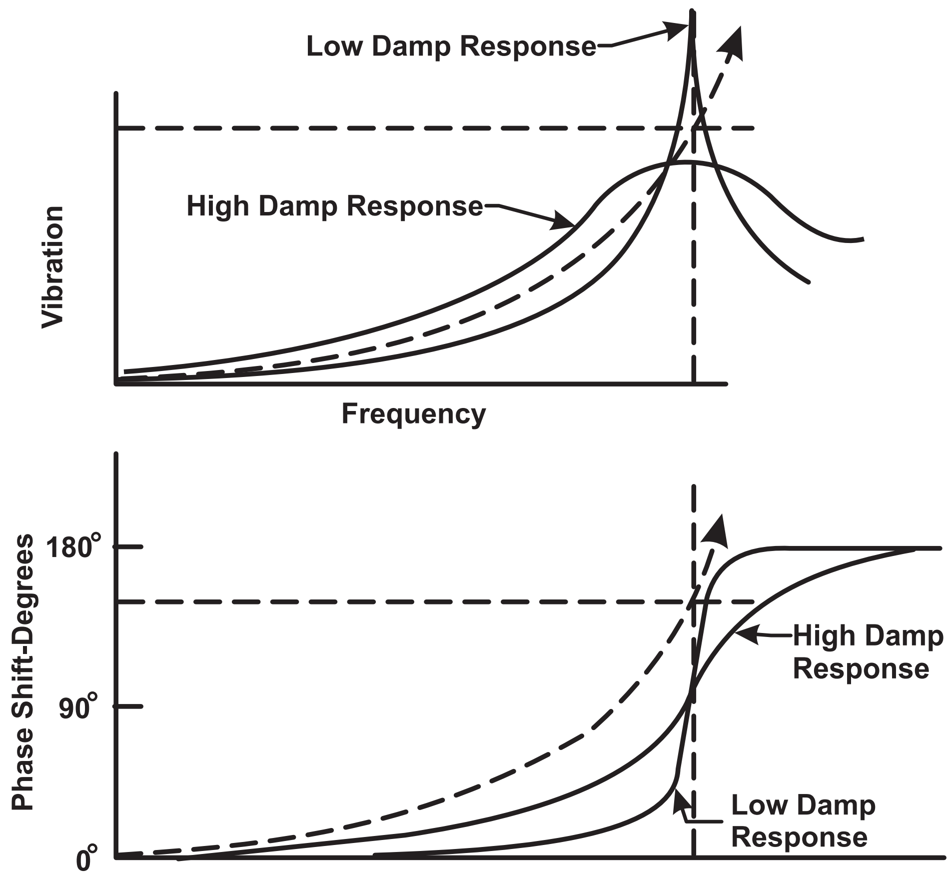


Figure 4-37
Resonance

The top part of Figure 4-37 illustrates vibration at resonance showing how amplitude might vary with dampening. The bottom part of the figure illustrates how phase shift occurs at resonance.

Vibration problems due to resonance at natural frequencies can require extensive analysis and major design changes to correct.

4.3.12 Rotor Critical Speeds

Natural frequencies of the shafts of rotating systems are known as critical speeds. Figure 4-38 shows deflection shape of shaft as a rigid body and at its first and second radial critical speeds. The frequency of the critical speeds depends on the mass, stiffness, and construction of the rotor and the stiffness, construction and mass of the bearing system, including the oil film. Some rotors might be described as rigid, if the shaft rotational speed is lower than the first or bending critical. All rotors that operate above the first (or several) critical are termed flexible. In most cases, the rotors and their support systems are designed to pass safely through the criticals that occur below operating speed, but problems such as cracked shafts, structural defects, or bearing problems can cause vibration at the critical to become problematic. If phase readings are being taken, a shift of 90 degrees will be seen at resonance (Figure 4-39).

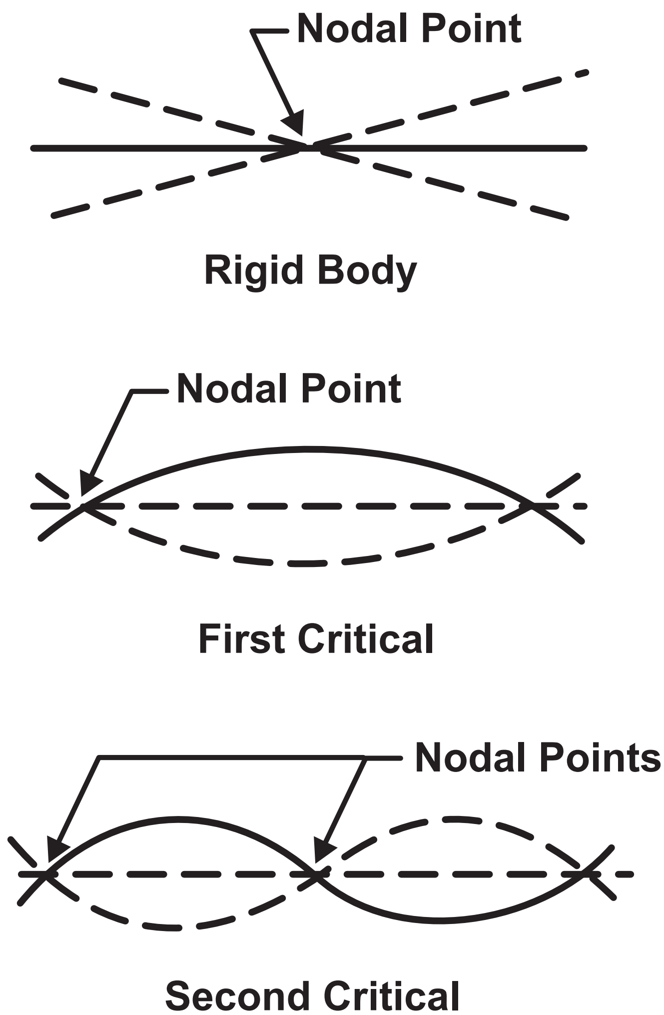


Figure 4-38
Critical Speeds

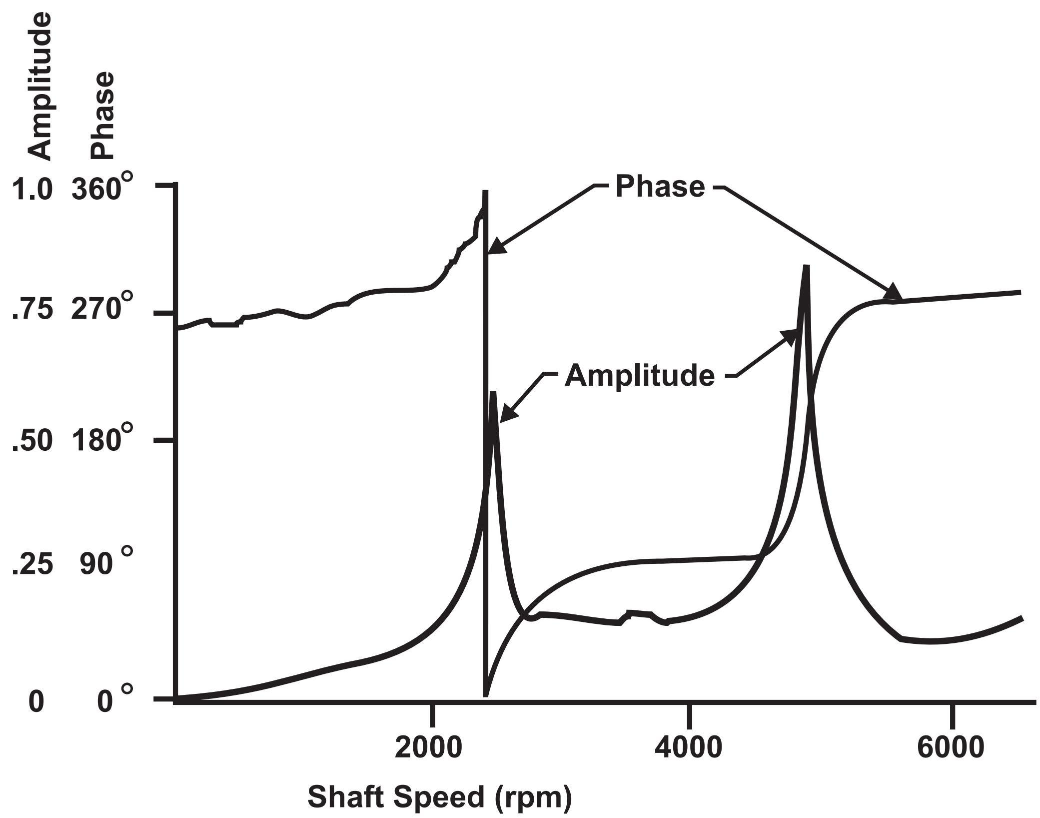


Figure 4-39
Spectrum for Critical Speeds

The radial critical speeds are most often considered. Torsional or twisting modes of vibration rarely cause problems, so little data is ever taken to be able to recognize, let alone evaluate, them. However, there is a growing body of knowledge about torsional criticals and their influence and effects on machinery vibration. Vibration due to torsional modes or other torque problems needs to be considered in evaluating problems with fans, but there is little experiential data to aid in analysis.

4.3.13 Gears and Gearboxes

The most common application of gear drives to fans is probably on cooling tower fans. The drive shaft of this type of fan is typically a long torque tube with a coupling at the motor end and another at the gear drive end. These torque tubes must be balanced, usually in the two planes at the couplings and on overcast days or at night because they are very sensitive to thermal growth in direct sunlight. Alignment should also be done at night for the same reason. Vibration of the supporting structure that spans the cooling tower (often called a torque tee) must also be considered. Pre-loads on shafts must be maintained within the manufacturer's tolerances.

The gearbox can be subject to unwanted loads and subsequent failure if these considerations are not made.

Gearbox vibration can arise from problems with the teeth, the meshing of the gears, the loads on the gears, the amount of slop in the drive train, internal alignment problems or from the bearings in the gearbox (Figure 4-40). See the section on bearings for a discussion of those problems.

One problem due to manufacturing defects or mishandling is called hunting tooth. It is not common but can be problematic if severe. It results from damage or a defect on both the pinion and the gear. The gearbox with this problem will often make an unusual low frequency roaring noise and the spectra will have a low frequency peak (less than 1X rpm) that is not explainable from any other source, such as a bearing defect or known natural frequency.

Gear mesh frequency is the number of teeth on the gear times the rpm of the gear. Thus, each gear in a train has its own characteristic mesh frequency. In order for analysis to be effective, the number of teeth on each gear must be known, as well as all of the rpms of the shafts.

There will always be evidence of the gear mesh frequencies in the spectra of the vibration, along with 1X rpm of the input (motor) shaft and the peak at 1X rpm of the pinion. There might also be sidebands spaced at 1X rpm on both side of the gear mesh. Such frequency peaks, at low amplitude, should be considered normal.

Gear mesh frequency amplitudes often vary with load. It is important to know and trend load along with vibration amplitude, and to pay attention to the characteristic presence and amplitudes of sidebands and harmonics when doing analysis. High amplitudes of overall vibration are not sufficient information to diagnose a fault, nor is the mere variation in amplitude of the gear mesh peak(s).

Gear misalignment usually results in vibration at gear rpm and at gear mesh and harmonics. There will often be sidebands of 1X rpm around all of these other peaks.

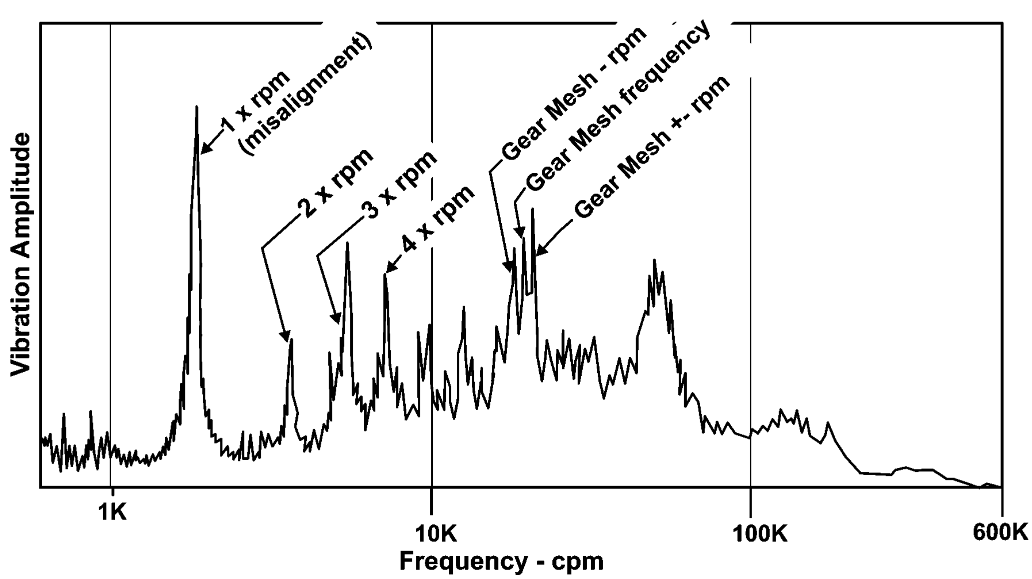


Figure 4-40
Spectrum of Various Gear Frequencies

Internal misalignment, eccentric gears, and backlash often cause sideband amplitudes to increase, in the absence of other problems. This is caused by modulation of gear rpms as they mesh. There might also be minor to large variations in gear mesh frequency amplitudes of the associated gears. Vibration from backlash will sometimes be reduced or disappear when load is increased.

Tooth wear results in increased vibration at gear natural frequencies, which do not correspond to any of the frequencies mentioned above. The natural frequency peak(s) might have sidebands spaced at the rpm of the worn gear. As the wear progresses, the sidebands usually grow in amplitude and might be good indicators to use to trend the condition of the gear.

Overloads, wear, misalignment, and unavoidable incipient defects leading to damage due to fatigue often result in cracked or broken teeth on a gear (Figure 4-41). This condition is recognizable in the spectral data as high vibration at 1X rpm of the damaged gear. The natural frequencies of the damaged gear, and sometimes of the gear(s) it meshes with, will also be present in the spectra. However, in the time waveform, the defect will cause a distinct regularly-spaced spike as the damaged gear passes the mesh point. These impacts are what excites the gear natural frequencies. The time between the spikes corresponds to the 1X rpm of the damaged gear.

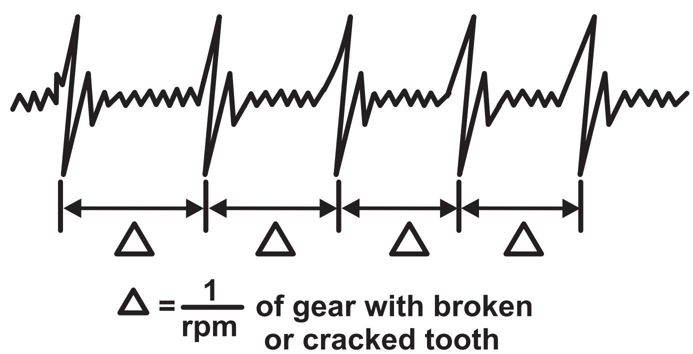


Figure 4-41
Vibration Time Waveform of Cracked or Broken Gear Tooth

4.3.14 Drivers

Turbine-driven fans or blowers are rare in utility applications, and turbines are excluded from the scope of this document. There are numerous references available about turbine vibration that should be consulted if one of these machines is encountered.

Fans and blowers are typically motor-driven. Motors may be AC or DC, and of various types and sizes. The fan can be attached to the motor by a coupling, either rigid or flexible, by a long torque tube and gearbox (cooling tower fans, for example), or it can be mounted on a shaft extension of the motor provided for that purpose. It can also be driven by belts. It is not the intent of this section to provide a full discussion of motors; (for details on motors see Reference [21]) however, the vibration of the motor needs to be considered, since it might be either adversely affected by problems with the fan, or it might be a problem itself.

Special consideration must be given to motors (as well as other machines) in use outdoors, or vibration problems might arise due to bearing faults caused by moisture, or from motor electrical problems due to humidity or dampness.

Motors can be subject to any of the problems discussed previously, and the characteristics of those problems will be the same for motors as for fans. Therefore, the electrical faults that can result in vibration remain to be examined.

It is usually desirable to compare the vibration analysis to an analysis of the motor current signature of all of the electrical phases (if more than one), to try to narrow the possible electrical fault sources to one. This can often be done using a clamp-on current transducer with a voltage output to the same frequency analyzer used for vibration analysis. For large, critical motors that might be expensive to remove from service or to repair, it might be necessary or desirable to perform motor power signature analysis, which requires simultaneous high-speed, high-resolution data collection on all phases of both voltage and current. If on-line tests are not possible or are too risky for personnel or equipment, there are off-line tests such as motor circuit evaluation, surge testing, and other more traditional test techniques that can be used to confirm the assessment begun with vibration data.

This type of analysis requires knowledge of the motor construction, particularly the number of rotor bars, the number of stator slots, and the type of construction, whether it is a built-up or cast rotor.

AC induction motors slow down from their nameplate rpm under load, and varying load on the fan or blower might result in variations in the speed of the machine. The difference between line frequency and rpm is called slip frequency. For vibration analysis, it is necessary to know the pole pass frequency. The number of poles determines the motor rated rpm for a specific line frequency.

To calculate the pole pass frequency:

$$P = \frac{120 f}{N} \qquad \text{(eq. 4-8)}$$

Where: P = Number of poles

f = Frequency, Hz

N = Speed, rpm

Thus, a 2-pole motor at 60 Hz operates at 3600 rpm (no load), a 4-pole at 1800.

Vibration due to electrical faults always occurs in the radial directions. Mechanical faults produce radial vibration, but there might also be axial motion due to out-of-plane forces causing the rotor to shuttle. This is particularly common on 2-pole motors because the axial restoring forces are very low for them.

Rotor problems are those such as loose, cracked or broken rotor bars or shorting rings, bad joints between rotor bars, and shorting rings or shorted rotor laminations. There might also be voids in cast rotors that appear similar to electrical faults in the spectra of vibration or electrical current.

Loose rotor bars can generate high frequency components in the spectrum called rotor bar pass frequencies (RBPF) (Figure 4-42). These frequencies are at rpm times the number of rotor bars and harmonics. There are usually sidebands of twice pole pass around these rotor bar pass peaks. These spectral indications can be very low amplitude at first but grow as the looseness worsens over time. Trending is important.

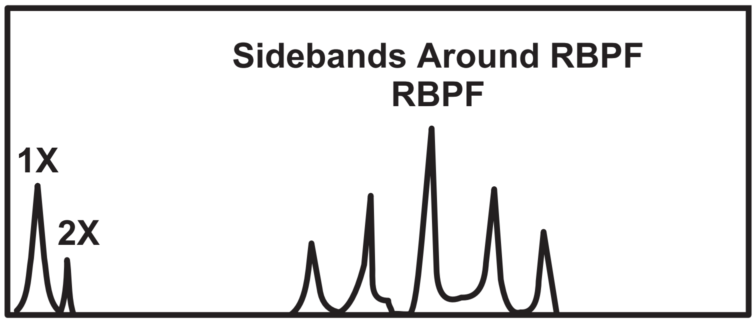


Figure 4-42
Spectrum of a Loose Rotor Bar

Cracked or broken rotor bars cause vibration due to variation in the direction of the magnetic forces between the rotor and stator as the defective rotor spins (Figure 4-43). The vibration from cracks or breaks in the rotor results in a spectral peak at 1X rpm and at exactly line frequency (Figure 4-44). On two-pole motors, it is, therefore, necessary to have vibration data with very high resolution in order to differentiate between the two peaks. Sidebands appear at multiples of pole pass frequency. Harmonics of these groups of peaks might appear, usually up to at least three to four times running speed.

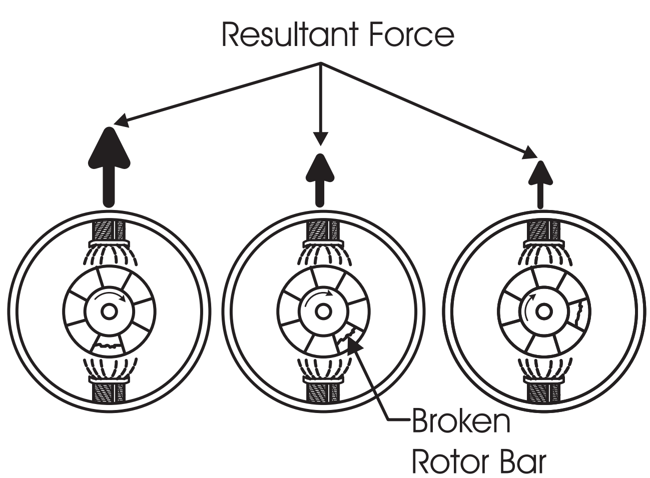


Figure 4-43
Diagram of Cracked/Broken Rotor Bar

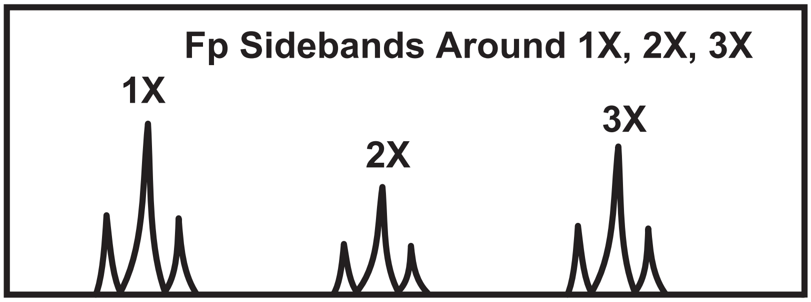


Figure 4-44
Spectrum for Cracked/Broken Rotor Bar

Some faults cause variations in the air gap between the rotor and stator as the motor turns, which results in regular variations in audible noise called beating. Beating is caused by two frequencies very close to each other (for instance 1X rpm of 3580 and line frequency of 3600), coming in and out of phase synchronization with each other. This results in pulsating audible noise and amplitude variation in vibration. One of the peaks in the spectrum usually varies in amplitude, and there is usually amplitude variation in regular fashion in the time waveforms.

An eccentric rotor causes variations in the air gap. Beating will be heard and observed in the vibration spectra and time waveforms (Figures 4-45 and 4-46). Vibration appears in the spectral data as twice line frequency and the closest harmonic of rpm. High resolution of the spectral data is often necessary to see this in the spectrum. Sidebands at pole pass frequencies are usually present around the peak at 1X rpm as well as with the harmonics of line frequency. In the time waveform this appears as regular amplitude variation.

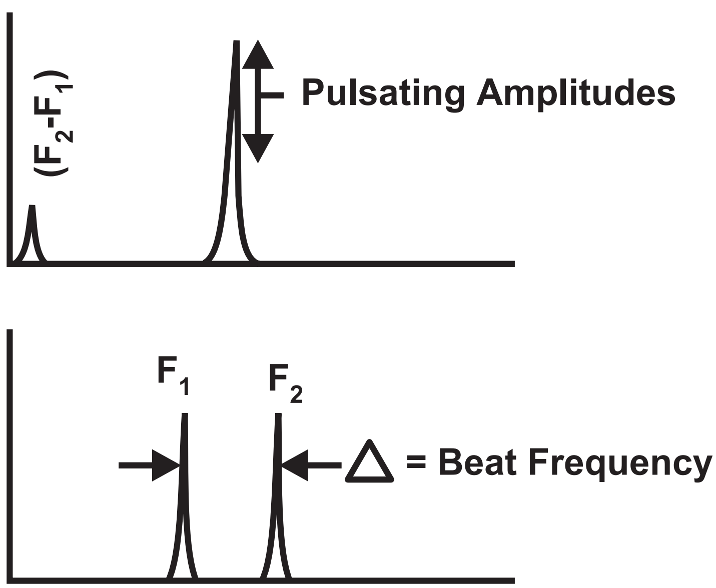


Figure 4-45
Spectrum for Beating

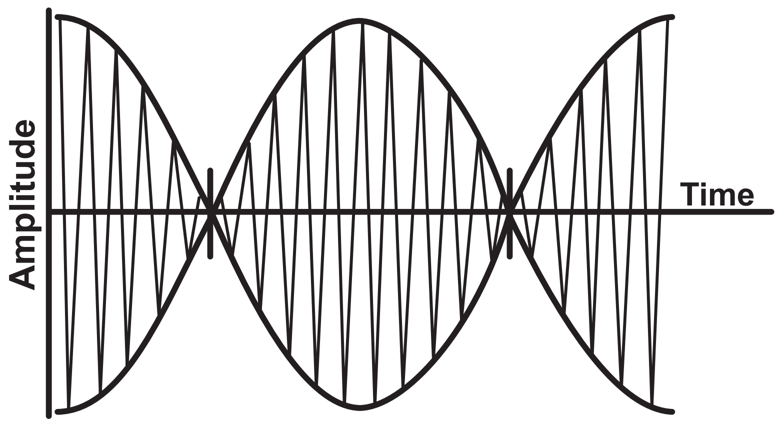


Figure 4-46
Beating Time Waveform

Current readings for rotor problems have strong spectral peaks at 1X line frequency, with pole pass sideband and harmonics (Figure 4-47). The amplitude of the sidebands with respect to the main peak at 1X line frequency is generally an indicator of the severity of the problem. The greater the amplitude of the sidebands, the greater the severity of the fault.

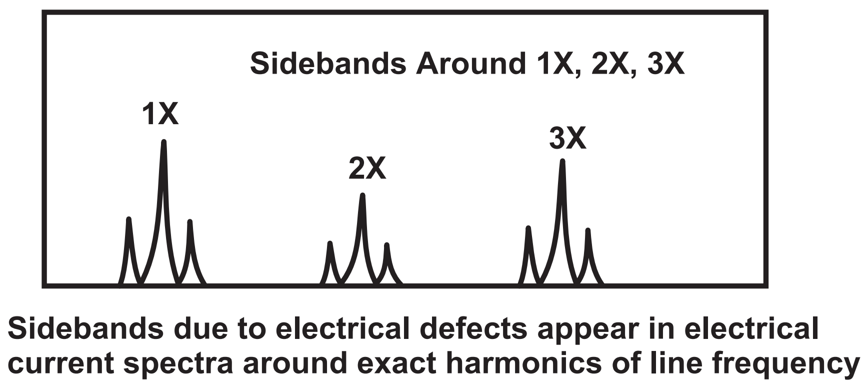


Figure 4-47
Spectrum for Current Readings

Stator problems include loose iron, warping of the case and/or stator itself, and shorted laminations.

Motor casing or stator warping problems are usually indicated by a high vibration at twice line frequency. This is again associated with the uneven air gap that results from the fault. Since the stator is not moving, the vibration tends to be very directional and vibration surveys should be done to determine the direction to help verify this type of fault. Foundation, baseplate, and motor foot problems, or a soft foot condition, can result in warping of the stator (either temporary or permanent), causing similar fault indications. There can also be vibration at stator slot frequencies (number of stator slots times rpm) and harmonics.

Synchronous motors can experience high vibration due to loose stator coils at coil pass frequency (number of coils/pole times number of poles) and harmonics. There are often 1X rpm sidebands accompanying the coil pass frequency peaks in the spectra.

Lamination defects can result in variable heating and result in further damage to the stator, even in accelerated and complete breakdown of the electrical insulation and failure of the stator. Excessive heating can result in thermal bow of the rotor (see above). Thermally-induced vibration might grow over time, at least as long as the rotor is heating due to the fault.

Phase problems, often due to faults such as loose or broken connections, also cause vibration at twice line frequency, and might become more severe over time as the condition worsens. There might be sidebands at 1/3 line frequency (3-phase motors). This type of problem might be intermittent if the connector is subject to variable strain or is rattling, in contact sometimes and not at others. There can also be problems with the incoming electrical service, which would cause similar problems, or the motor might not operate at full speed due to reduced voltage.

DC motors can have vibration problems due to many of the same problems. There is usually a peak at Spectrum Current Readings (SCR) firing frequency (six times line frequency) and its harmonics. Unique DC motor problems include broken, loose, or damaged field windings, loose connections, and bad SCRs. Other problems, such as improperly designed or operating electrical filters, malfunctioning control electronics, loose or blown fuses, can all cause vibration at 1X rpm and harmonics. It is not unusual to have rapid and repeated DC motor failures until these problems are corrected.

Many fans are designed to operate at more than one speed. In most instances, there is a high and low speed, and vibration analysis of problems at either speed can be evaluated using all of the techniques described above. However, some fans operate with variable speed drives and there are some special considerations to be made when doing vibration analysis of these machines.

Variable speed drives that use pulse-type converters cause torsional vibration of the drive system. This can be a particular problem in retrofitting this type of drive to existing fans without redesigning and/or reinforcing the existing foundations, especially if they are still expected to operate over their entire speed range. Torsional excitation is usually not problematic unless it induces resonant torsional response (that lasts for more than about a second) of the driver or the fan. 6-pulse converters generate lower frequency harmonics than do 12-pulse ones. Either type will tend to excite vibration at 1X and 2X rpm plus the 5X and 7X harmonics. (This is because of the square-wave nature of the pulses and the fact that most systems are three-phase electrically). Since many systems might have torsional criticals in their operating speed ranges, or in these higher harmonic ranges, the problem can occur. Solid motor foundations and good shaft alignment help to reduce the magnitude of the problem.

If the driven system has very little damping, torsional vibration can again result in excessive vibration. The use of a resilient coupling with high damping properties will help avoid the problem. In any case, proper design should account for and eliminate the potential for these torsional problems in both new installations and retrofits.

Elimination of unwanted pulsation vibration from variable speed drives depends in part on the sophistication and electrical characteristics of the converter and the control system. The characteristics of the controls and the requirements of the drives should be carefully matched.

4.4 Maintenance Issues and Recommendations

Routine maintenance activities should be prepared, described in work instructions, training or procedures, and consistently implemented by qualified personnel. Where appropriate, results should be documented in a retrievable manner and used as input for performance trending as well as for adjusting the type and schedule of subsequent maintenance.

Various predictive and preventive methods are available and should be considered based on the system and individual component significance, environment, and usage. Non-intrusive predictive techniques, such as Infrared (IR) Thermography, can be very informative while having little or no impact on equipment availability during inspection.

Maintaining good documentation of required corrective maintenance provides important feedback when assessing the effectiveness of the preventive maintenance procedures (PMs). Similarly, having a reasonable working knowledge of the particular HVAC system operation, increases the likelihood of developing more appropriate PMs and inspections. Even basic system knowledge increases the ability to assess a failure for root cause and develop a more complete corrective action plan.

Providing for proper vendor documentation and an accurate Master Equipment List will minimize the chances of incorrect or insufficient PMs based on uncertainty of component type or recommended minimums.

4.4.1 Visual Inspection

Visual inspection is a key to maintaining any type of equipment in a power plant environment. There are many aspects of visual inspection for fans in the ventilation systems. This section contains a breakdown of the various subjects that should be included in a visual inspection. The vendor information for most ventilation equipment contains information on required inspection and suggested inspection. The items contained in the list below can be included or can be used in conjunction with vendor information.

4.4.1.1 Blades/Rotor (Axial Fan) or Wheel (Centrifugal Fan)

When inspecting the rotor or wheel, depending on fan type, it is very important to pay close attention to the state of structural soundness. The measures of structural soundness are indicated by stress cracks in the wheel/rotor, evidence of wheel/rotor rubbing on the housing, and damage to fan blades. In applications where improper design selection has caused unstable fan operation, undue stress can be placed on the rotor, blades, and/or wheel of the fan. Additional causes of blade/rotor failure can be attributed to operating the fan beyond the temperature design range and overspeed operation.

4.4.1.2 Bearings

The results of a bearing visual inspection can provide valuable information on the operation and maintenance attention/abuse that the fans or dampers receive. For example, if the bearing is found to have thick viscous grease leaking from it when it is lubricated by a light weight oil, evidence might have been found that the bearing is overheating and causing the oil to breakdown. This might also represent a system that is located in an environment that is outside of the design ambient conditions. Visual inspection of a bearing can also reveal signs of high vibration, shaft damage, insufficient lubrication, or improper sizing. Mildly damaged, nicked and scratched, rollers in a bearing can indicate that the bearing was insufficiently lubricated. Improperly sized bearings will have caused major damage (for example, smashed, flattened, and flat spotted rollers) to the rollers. The indications of high vibration would be similar to improperly sized bearings. The magnitude of damage should not be great for vibration. All of the previous examples would indicate the possibility for shaft damage as well.

4.4.1.3 Couplings

The visual inspection of couplings usually pertains to checking for proper alignment. Couplings are another location where general system operation and maintenance attention/abuse can be found. Visual evidence of coupling damage can suggest improper sizing, improper startup procedure, coupling damage from adverse environmental conditions, and damage from improperly secured couplings.

4.4.1.4 Shaft

The shaft should be inspected for damage. If damage was found during the inspection of couplings or bearings, there is a high probability that similar damage is apparent on the shaft. Any shafts should also be inspected for structural soundness and ease of rotation.

4.4.1.5 Drive Systems

There are many types of drive systems including coupled shaft, direct shaft, V-Belt drive, and other belt drives. There are specific attributes of each type of drive system that require visual inspection. For all belt drive systems (V-Belt included) there are several generic areas of inspection focus. The fan and motor shafts should be examined for proper axial and horizontal alignment. The shafts should be parallel and the sheaves should be aligned axially. The shafts should be examined for damage such as bending or bearing problems. The sheaves' connections to the shafts should be examined for any potential damage or evidence of improper or loose attachment. The belts should be examined for proper tensioning and belt condition. The proper belt tensioning should be described in the vendor information for the drive. The surface of the belt should be free of cracks. The body of the belt should be flexible and have a matte finish. A shiny or waxy exterior finish is a sign that the belt is aging and in need of replacement. Direct and coupled shaft drives are much less complicated to inspect. The significant areas of inspection are fewer in number. The direct shaft drive only requires examination of the shaft for stress cracks, bending, or other damage. The only further inspection for a coupled shaft drive is the inspection of the coupling device. The coupling should be examined for stress cracks, other possible damage, and loose connection of the shafts. Vendor-specific information might call out other visual inspection needs. In general, the system's vital components are inspected and an overall review is made to determine the system's need for further maintenance.

4.4.1.6 Prime Movers

In most cases for ventilation systems, the prime mover is an electric motor with a drive system. When inspecting electric motors, the main areas of focus are generally on shaft and bearing seals, foundations and mounting, and electrical connections.

4.4.1.7 Seals and Gaskets

The seals and gaskets in a ventilation system are key areas where system leakage could occur. For this reason their visual inspection is very important. Air-streams, heavily laden with abrasive particles, can accelerate degradation of seals and gaskets. Damage and degradation can also occur if the fluid or ambient temperatures exceed the allowable range.

4.4.1.8 Ductwork

The system ductwork is inspected if there is suspected damage or for introduced foreign material removal. This inspection might also be a part of system troubleshooting for suspected or confirmed low flow conditions. It is important to inspect the connection of the ductwork to the fans. This connection is usually made with a flexible fabric that is vulnerable to tears and punctures causing leakage.

4.4.1.9 Foundations and Mounting

Some types of fans and drive systems will require very specific foundations and mounting. The mounting bolts should be inspected for elongation and bending. The foundation should be closely examined to verify that there is no damage from vibration. Damage to the foundation from excessive vibration takes the form of cracks in the foundation structure, chips and cracks in the foundation near the mounting plate, and damage to the mounting plate such as bending of the plate or mounting washers.

4.4.1.10 Filters, Screens, and Filter Housings

Filters and screens should be inspected for damage that could compromise their effectiveness. Screens and filters should be clean to minimize system resistance. The system should be evaluated for bypass of the filters and screens. Filter housing and screen mountings should be inspected to determine adequacy and to ensure adequate support and sealing of the screens and filters.

4.4.1.11 Air Intakes

Air intakes should be treated in a manner similar to screens and filters. Intakes need to be clean, undamaged, and should be configured to minimize the amount of bypass leakage to the fan.

4.4.1.12 Ease of Operation

Part of the inspection program should also include audio and visual inspection of the system while in normal operation. This will permit the identification of such adverse operation characteristics as high vibration, breakdown flow/surge, damaged bearings, improper lubrication, and overheating. The components of the system should be individually operated by hand after the system is shutdown. This provides additional information to identify the adverse characteristics listed above.

4.4.2 General Inspection and Maintenance

The following items are suggested as general issues that could be included in a routine maintenance guide for fan maintenance and inspection activities. See Reference [22], EPRI TR-106857 - Volume 21; PM Basis for HVAC.

4.4.2.1 Routine Mechanical Maintenance

- Check the fan drive mechanism (belts, linkage) for condition, proper tension, and alignment. Adjust or repair if required.
- Inspect the physical condition of the drive mechanism.
- Check fan blades for signs of degradation such as foreign objects, dirt build up, cracks or missing parts. Clean and repair or replace as necessary.
- Check all set screws for tightness.
- Visually inspect expansion joints, seismic mounts, anti-vibration bushings for signs of deterioration. Replace if necessary.
- Visually inspect associated filters for cleanliness, proper type, and installation. Clean or replace as necessary.
- Perform a visual inspection of the inlet plenum and all local duct work. Check for broken welds, cracks, broken bolts, loose parts, and any other structural deficiency.
- Remove the fan shaft bearing covers. Clean out old grease and inspect the condition of the bearing and shaft. Repack the bearing or replace as necessary.
- Giving proper consideration to the vendor-recommended practice and type of lubricant, lubricate bearings as necessary but consistent with an established schedule.

4.4.2.2 Routine Electrical Maintenance

- Baseline amperage and voltage readings; record running loaded amps by phase (as applicable); record volts phase to phase; record on some frequency and after PM.
- Baseline motor and fan rpm readings; record on some frequency, ensuring similar operating conditions while taking data.
- Record vibration readings.

- Baseline and include the thermal signature (via infrared analysis) in some appropriate inspection interval.

4.4.2.3 Mechanical and Electrical Fan Coils (if applicable)

- Visually inspect mechanical fan coils for damage, dirt build up, and debris. Clean coils as necessary.
- Inspect coil drains for leakage, dirt build up, or other obstructions.
- Inspect steam/chilled water control valves for packing/ bonnet leaks and proper operation.
- Perform an operational check of electric heating elements.

4.4.3 Recommended Preventive and Corrective Maintenance Trending Parameters

Parameters selected for trending will vary based on the desired use. Performance assessment parameters might be different than those needed to measure PM effectiveness. The desired outcome should be considered prior to the data-taking exercise to minimize ineffective use of resources and evaluations performed using misleading data.

As with all types of data, quality and usefulness depends on consistency of conditions when the data is taken. The parameters listed are intended to provide a measure of PM effectiveness and possibly support a frequency assessment. Negative trends could indicate some hidden problem or operating condition that might not be detectable by the type or frequency of the PMs performed. Individual system application should always be considered when selecting and assessing trend data.

4.4.3.1 Mechanical

- Number and type of corrective maintenance activities since the last PM set
- Frequency of drive belt replacement, or mechanism adjustment
- Reliability or availability inconsistencies between redundant components
- Excessive component wear or physical damage between PM sets

4.4.3.2 Electrical

- Amperage and voltage readings for similar operating conditions, or following PMs
- Vibration readings when compared to previous sets/baseline
- IR signature when compared to previous similar conditions or redundant components

5 DAMPERS

Dampers are used in ventilation systems to control environment pressures, temperatures, and flow rates. There are four types of dampers that are most commonly used in the nuclear industry, the isolation, control, back draft , and fire damper. Dampers can be constructed with parallel or opposed blades, which can be “flat” or “airfoil”-shaped. Parallel blade dampers are better suited for isolation applications due to the undesirable flow pattern through the blades at partially open positions. Either type of damper will benefit from an airfoil blade design, which will improve performance of the system by reducing pressure loss associated with an open damper blade obstructing the air-stream.

5.1 Types of Dampers

5.1.1 Isolation Dampers

Isolation dampers are used to prevent the flow of air from one area to another and contain metallic, silicone, or other types of seals, such as rubber and plastic. The seals are provided to ensure that a leak-tight seal exists when the damper is in the closed position. Frequently two isolation dampers are provided in series to ensure adequate protection for the area served. These dampers can be designed in both parallel and opposed blade configurations. Parallel blade isolation damper design should be carefully constructed and installed with an appropriate actuator to ensure that the blades are positioned exactly parallel to the air-stream when in the open position. This will minimize the obstruction in the air-stream and result in an optimized (low) pressure drop associated with the open damper under full flow conditions.

Control dampers include two-position and modulating dampers. Specialty isolation dampers used in the nuclear industry vary in design, while most control dampers are either parallel blade or opposed blade. Parallel blade dampers are generally more rugged, less expensive, and simpler in design than opposed blade dampers. Parallel blade dampers should not be used in modulating applications because of their non-linear flow characteristics (differences are described in detail in ASHRAE Applications Manual, chapter 41.6).

Louvers are bladed assemblies designed to be installed at interfaces between HVAC systems and the outdoors. Louvers prevent weather (precipitation) and large airborne objects (birds and leaves) from entering the system. Adjustable louvers operate like parallel blade dampers with the difference being that they do not travel 90 degrees to full-open, rather travel is limited to ensure a downward-sloped surface is presented to the outside of the building. Depending on climate, louvers might be required to isolate freeze-sensitive components (that is, steam coils or chilled water coils) from freezing temperatures when the ventilation system is not operating.

A further specialized type of isolation damper is the “bubble-tight” damper. The “bubble-tight” damper will provide the optimum effectiveness in airflow isolation between spaces. Whereas most isolation dampers are rated for various amounts of leakage (based on the area of the damper), bubble-tight dampers can provide zero leakage at reasonable differential pressures. These dampers often resemble valves in appearance and bulk, with a single blade providing a positive seal. A heavy-duty actuator that will produce sufficient closing torque to the sealing surfaces is also required. The cost of these dampers is high and enhanced structural support is often required. Also, the flow characteristics of an opposed blade damper are more linear than on parallel blade dampers.

5.1.2 Control Dampers

Control dampers are used to balance ventilation system flow rates and pressures. The control damper can be operated automatically (using an actuator) to modulate the damper and to allow an appropriate amount of airflow to achieve the desired operating parameter (flow rate or temperature). As in the isolation damper, the actuator can be driven by pressurized air, an electric motor, or a motor-hydraulic unit (electro-hydraulic). The damper can also be operated manually and secured at the desired position based on similar operating conditions. The control flexibility of a manual damper is limited because it is set very infrequently, usually during a system balance. Opposed blade configurations are normally the preferred option, as these dampers are usually positioned at some point between fully open and fully closed. This eliminates the directionally deflected downstream flow characteristic of the parallel blade damper. Also, the flow characteristics of an opposed blade damper are more linear than of parallel blade dampers.

Most ventilation systems include manual balancing dampers. These dampers are usually only manipulated during the initial terminal air balance (TAB) or subsequent balance verification efforts. There are four primary types of manual balancing dampers. They include:

Terminal opposed blade dampers (TOBs) are part of the supply, return, or exhaust termination device. These termination devices are commonly called diffusers, grilles, outlets, or registers, however, each has a specific function-related definition.

Duct restricting volume dampers, usually referred to simply as volume dampers, can be single or multiple blade, and parallel or opposed blade. These dampers are designed to restrict the flow through the duct by reducing the free area (see Figure 5-1).

Splitter dampers are installed at duct branch fittings or “Y” fittings. These dampers are usually made from a single sheet of metal hinged at the neck of the fitting with one or more adjusting rods at the movable end. The dampers control the flow through the branch duct by controlling the effective cross-section of the branch and main duct. Splitter dampers are preferred for TAB because they generally create less static pressure than typical volume dampers.

Scoop dampers are similar to splitter dampers but are only used with supply air outlets that are installed on the main supply or trunk ducts. These dampers can be constructed from a single sheet or multiple curved blades attached to rails. The damper movable end is extended into the airstream to direct the required airflow out of the outlet.

5.1.3 Inlet Vane Dampers

In some applications, dampers are added at the inlet of a fan. In many cases, this is done to control the fan’s output characteristics or inlet swirl of the flow. In other cases, this is done to control other system characteristics such as system resistance. These inlet vane dampers often have radially mounted blades. The movement of the blades can be used to induce variable direction swirl or to reduce flow to a fan, which will affect the operating point on the fan curve.

Inlet vane dampers with fixed vanes are called inlet guide vanes or IGVs. IGVs are used to enhance the performance characteristics of a fan. The need for IGVs is determined during the design of a particular system. IGVs are often used with axial flow fans and compressors. They provide flow conditioning prior to the rotating blades.

Inlet vane dampers and IGVs should be cared for in a manner similar to the other dampers and turning vanes. For variable vane dampers, the seals should be inspected to ensure no damage has occurred and that the seal is sufficiently leak-tight. The dampers should be inspected to ensure that no debris is or could be caught in the dampers. Debris in the dampers or ductwork could get caught in the fan and damage it. The dampers should be operated at a reasonable frequency, both manually and with any associated actuators. This operation will allow for the identification of any inappropriate wear or mechanism damage. Finally, the components of the damper and the actuator should be visually inspected for signs of wear and/or damage.

In dual inlet systems with inlet vane damper control, there are potential implications for bearing damage if one of the inlet dampers fails to open or close. In this case, with one inlet damper open and the other closed, there is an unbalanced force on the impeller of the fan. This will cause excess thrust wear on the impeller bearings. This helps to illustrate why proper inspection of these dampers is very important.

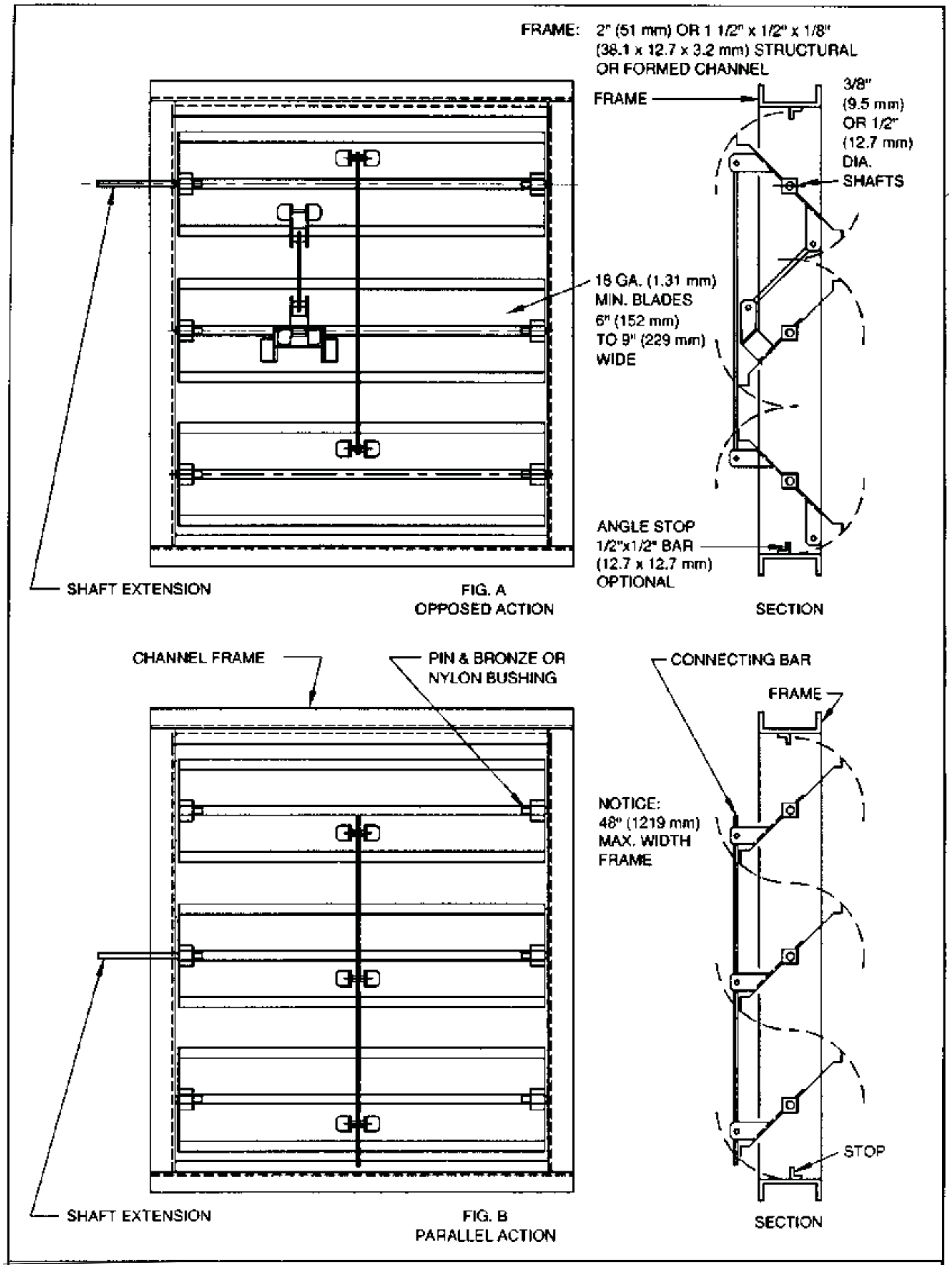


Figure 5-1
Multi-Blade Volume Dampers (Reprinted with courtesy of SMACNA [23])

5.1.4 Backdraft Dampers

Back draft dampers are used to allow the flow of air in one direction only. They also prevent backflow through non-operating fans. This type of damper is useful in preventing the spread of contamination during times of an unwanted reverse airflow (this could occur when a ventilation system is intentionally or unintentionally shut down). The back draft damper is designed so that the damper blades will open when there is a differential pressure across the damper in the correct airflow direction. The damper blade linkage might have counter weights attached so that only a small differential pressure will force open the damper. If the differential pressure across the damper is eliminated, or if a reverse differential pressure is created, the damper will close, thus preventing the flow of air in the reverse direction. There are drawbacks to backdraft dampers. There is an increased head loss associated with forcing the damper open and, due to the relatively small differential pressure that is needed to manipulate the damper, friction losses can alter the damper performance and even prevent its operation.

5.1.5 Fire Dampers

Fire protection dampers are used to mitigate the spread of fire from one location to another by providing a barrier between areas that would otherwise share a pathway through which a fire could spread. Nuclear plants, as well as many large commercial structures, have partitions, floors, and ceilings capable of confining a fire to a given area for some specified time. When an air duct passes through one of these fire barriers, a fire damper is generally required. Some of these dampers are held open by fusible links, whereas others are actuated by smoke detectors or similar devices.

5.1.6 Smoke Dampers

Smoke dampers are used to control the spread of smoke through a ventilation system. These dampers might have actuators or be self-actuated and activated in a manner similar to fire dampers. While fire dampers are rated by hours of fire resistance, smoke dampers are rated by leakage at pressure [24].

5.2 Damper Actuators

Damper actuators are used to control the position of the dampers based on given input signals. These actuators could modulate the damper to any number of positions or they could control the damper to only the open or closed positions. The input signals are typically sent from a controller that monitors specific parameters. When a monitored parameter travels out of a specified range, the controller sends a signal to the actuator, which then adjusts the damper to bring the parameter back into the specified range. The typical monitored parameters are temperature, flow rate, and pressure. Actuators primarily used in the nuclear power industry are the electric, electro-hydraulic, and pneumatic. The electric actuator is essentially a motor, connected to the damper, that utilizes gears to adjust the damper. The electro-hydraulic actuator uses a motor to pressurize a hydraulic system. The input signals are sent to the hydraulic system which controls the position of a piston, connected to the damper linkage. The pneumatic actuator utilizes pressurized air and a manifold to control the damper position. Pneumatic actuators are typically pneumatic piston-type actuators. Control air acts on a flexible diaphragm to position a shaft connected to the damper. These actuators are manufactured for air supplies from 18 psig (124.10563 kPa) to 100 psig (689.4757 kPa).

Pertinent issues related to damper failures caused by actuator malfunctions are addressed in the failure analysis sections of this guide. However, specific and detailed information related to maintenance activities of actuators is not covered in this guide.

5.3 Maintenance Issues and Recommendations

Selection of proper PMs and adequate frequency for dampers in many cases involves input from the operating staff as well as a review of vendor documentation. Proper operation and early indication of degraded performance can be measured through monitoring of system flow, compartment pressure, and the ability of idle fans to stay at rest. See Reference [25], EPRI TR-106857-Volume 20 for guidance.

As with the PM program for other components, the importance of establishing a good baseline condition and maintaining an up-to-date Master Equipment List cannot be overemphasized.

When developing PMs and surveillance activities, a good working knowledge of the total system function and various operating conditions is essential. External control system logic and the various operating modes can initiate problems or degradation but not be obvious in all modes.

Since individual applications and quality of components vary, the PMs established should consider all aspects of the particular application when generating type and frequency of PMs. Newer installations might have visible and accessible linkage external to the ductwork while older models might not. This fact should enforce the need for an established baseline condition supported by a detailed visual inspection.

It is important to maintain current, site-specific vendor documentation to aid in verifying proper installation, application, and recommended inspection minimums. As in other component PM programs, adjustments to routine activities are usually based on performance, significance, operating environment, and age.

Operating mechanisms in many applications contain sub-components that age due to environmental conditions. Vendor-recommended lubricants might vary by application. The PM program should recognize and maintain retrievable documentation for these and other site-specific conditions.

5.3.1 Visual Inspection

Consistent with fan maintenance, visual inspection is a key to maintaining dampers in a power plant environment. The items listed below address primary damper components and attributes to be included as part of a visual inspection program.

5.3.1.1 Blades

Damper blades should be inspected for damage due to foreign material in the ductwork, corrosion, bending, or buckling in the blades. Dirt build up can be a problem with dampers that are exposed to outside air. It is also important to inspect dampers for cracks, brittle seals, frayed seals, pits, and discoloration.

One of the common problems that could cause these types of damage is called racking. Racking refers to a damper that is out of square. This condition can cause blades to rub on the frame and stick in one position. It also causes poor sealing of the blades in the closed position. Visual inspection for this condition should be performed during inspections.

5.3.1.2 Seals

The damper seals in the ventilation system are a key area where system isolation is required. For this reason, their visual inspection is very important. Blade seals should be inspected with dampers in both the open and closed positions. Seals should be verified to be straight, consistent, and free of obvious surface variations. When closed, the blade seals should provide continuous contact along the entire blade length. Damage and degradation can also occur if the fluid or ambient temperatures exceed the allowable range.

5.3.1.3 Bearings and Shaft

The shaft and shaft bearing should be inspected to ensure that the bearings are not damaged and are properly lubricated. The shaft is visually inspected to identify any damage such as obvious bending or wear at any contact points. The damper should be cycled during inspection to observe any evidence of binding or excessive play.

5.3.1.4 Actuators

There are several types of actuators typically used in ventilation systems:

- Diaphragm Air Operated
- Motor Operated
- Manually Operated
- Mechanical Fusible Link
- Electro-Thermal Fusible Link

The proper inspection for each type of actuator should be used based on information from the specific vendor documentation.

5.3.1.5 Couplings and Connections

Couplings and connectors (including all linkages) should be inspected for wear, damage, mechanical strength, application acceptability, and proper alignment.

5.3.1.6 Ductwork

The damper connection to the ductwork should form a tight seal to prevent leakage. Further inspection of the ductwork should be performed to determine if there is any damage to the ductwork from the damper operation. The ductwork should be free of debris that would clog the damper.

5.3.1.7 Position Indication

Indication devices and attributes should be inspected to ensure correctness.

5.3.1.8 Supports

Supports should be inspected on a regular basis. Damage to the supports could be a result of vibration in the ductwork or other impact damage. Support mounting should be inspected for damage.

5.3.1.9 Ease of Operation

Dampers, which are important for safety operations, system isolation, and area pressurization, are typically tested for timed actuation response. Dampers should be tested for ease of operation. If the operation of the dampers is not smooth, further investigation into other potential problems is necessary. When practical, a manual manipulation of the damper is useful in determining chronic wear in the damper.

5.3.2 General Inspection and Maintenance

The following items are suggested as general issues that could be included in a routine maintenance guide for damper maintenance and inspection activities. Suggested routine activities should be considered minimums. The established frequency will be based on the individual application and overall performance of the equipment.

- Establish a baseline condition; correct any installation deficiencies and repair damper internals, seating surfaces, and linkage mechanisms as needed.
- A routine visual inspection internal to the duct should check for loose, damaged, or missing parts, dirt build up, and seating surface condition; where applicable, condition of bearings and internal linkage should be inspected; clean and repair as needed.
- Inspect fire damper tracks for debris or obstruction.

- Inspect the condition of the external linkage, bearings, and all pneumatic actuators.
- Inspect operating mechanisms for medium leakage (air, hydraulic oil).
- Disconnect damper linkage, check damper for free travel, full open to full close, verify tight closure.
- If possible, operate damper using normal control system, verify smoothness and completeness of travel.
- Lubricate bearings and linkage in accordance with a lubrication program (or other process to ensure use of approved lubricants and consistent application).
- Damper seal leakage is visually checked by means of a smoke tube test to determine leak tightness. This testing, as well as the previously described visual inspection of the seals for physical damage and other deterioration, provides a positive visual identification of leakage paths through the damper seal.

5.4 Trending

Parameters for dampers are limited. Trending is primarily needed to verify PM effectiveness and component reliability. The type and frequency of PMs performed should be dictated by overall component reliability.

The number and type of corrective actions needed between PM sets, the level of repair activities prompted by inspection results, and overall system performance are the most useful indicators to be trended.

Maintaining retrievable PM results records will enable a ready review of past history. Coupled with system performance information, evaluation of PM effectiveness, and proper adjustment to type and frequency, should improve overall reliability.

6
EFFECTS ON PERFORMANCE OF FANS AND DAMPERS IN THE SYSTEM

6.1 Controls and Instrumentation

Ventilation systems utilize many different types of instrumentation to measure and monitor system parameters. The performance and reliability of HVAC fans and dampers in nuclear power plant facilities is often impacted by its associated instrumentation and controls. For this reason, brief descriptions of the fundamental parameters required for fan and damper control are provided.

6.1.1 Pressure Measurements

Differential pressure (the pressure drop across a device) is measured across equipment such as fans, filters, and various duct sections in order to determine their operating conditions. For example, an increasing filter differential pressure indicates that the filter is becoming clogged. Differential pressure across a fan can be used to determine the volumetric flow rate through the fan. Differential pressures can be measured using static probes, velocity probes, or pitot tubes. A static probe is a device that is used to measure the static pressure of the area (typically inside of a duct). This probe is constructed of tubing that protrudes into the duct but not into the main flow stream of the air (Figure 6-1). Conversely, a velocity probe is a formed tube in which the opening is faced into the airflow stream and is used to measure the "total" pressure of the system. The "total" pressure is the combination of the static and velocity pressures of the system (Figure 6-2). The pitot tube is a double-walled tube used to determine the velocity pressure of a system. The pitot tube accomplishes this by simultaneously measuring both the total pressure and static pressure. The difference between these two values yields the velocity pressure, which is most useful in determining pressure loss across a section of an HVAC system. The double-walled construction of a pitot tube essentially is a tube within a tube. The outer tube measures the static pressure by using holes on the side of the tube. The inner tube is used to measure the total pressure by facing the open end into the air stream. The difference in these two measurements, as seen by a manometer, is the velocity pressure.

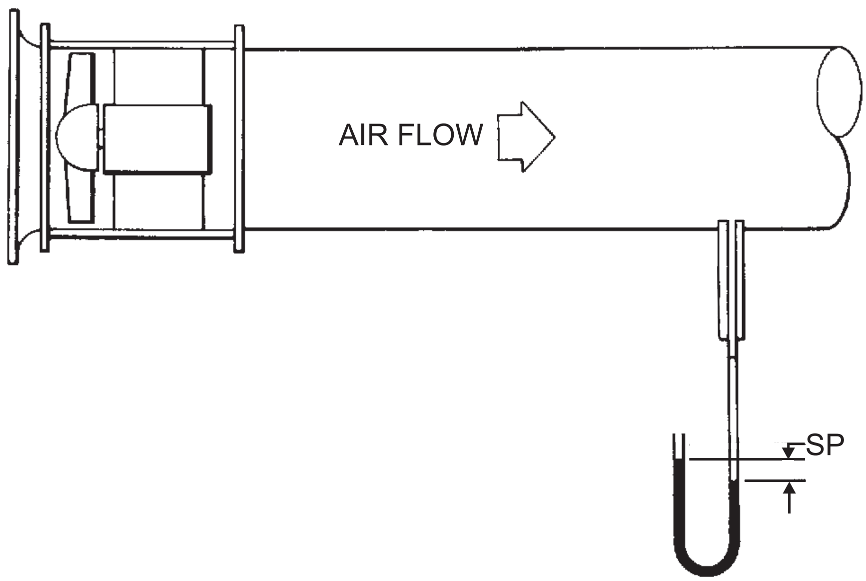


Figure 6-1
Static Pressure Test Position (Courtesy: AMCA Publication 201-90, Adapted from Figure B-4)

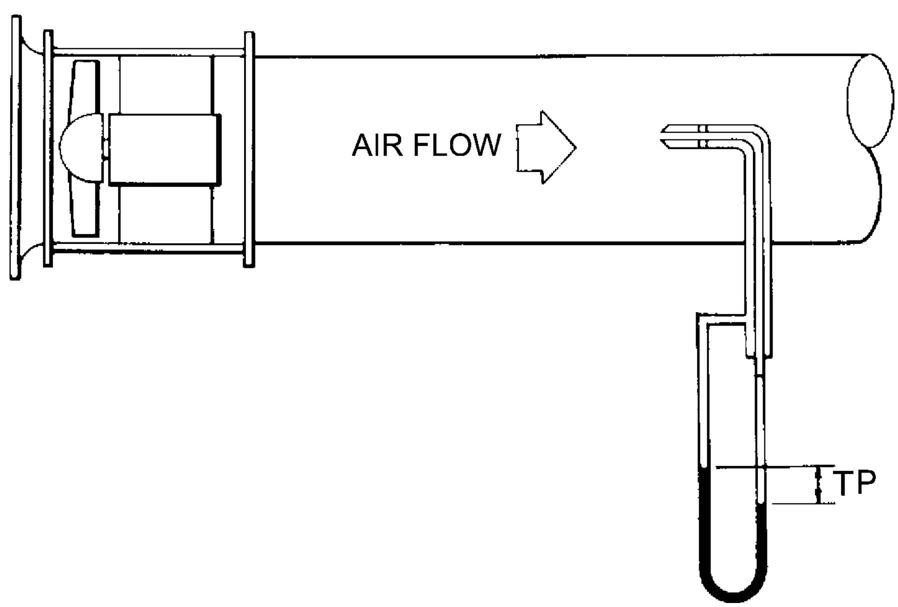


Figure 6-2
Total Pressure Test Position (Courtesy: AMCA Publication 201-90, Figure B-4)

6.1.2 Temperature Measurements

The primary functions of ventilation systems are to control contamination (radiological and/or chemical) and to remove undesired heat from an area or to circulate heat throughout an area. As such, resulting area temperatures are monitored to control HVAC system fans and dampers to maintain desired environmental conditions. Monitoring area temperatures is typically performed by using thermocouples, resistance temperature detectors (RTD), or thermistors.

6.1.2.1 Thermocouples

A thermocouple consists of two dissimilar metal wires that have been joined at one end. As the temperature changes, each metal piece experiences a slightly different electrical effect. A voltage difference is generated at the hot junction due to the difference in energy distribution of thermally energized electrons in each metal. The volume difference produces the requisite, albeit minute, current that enables the measurement of the junction voltage across the cool ends of the two wires. The voltage changes linearly with temperature over a given range, depending on the choice of metals.

6.1.2.2 Resistance Temperature Detectors (RTD)

An RTD relies on the increase in resistance of a metal wire with increasing temperature. As the electrons in the metal gain thermal energy, they move about more rapidly and undergo more frequent collisions with each other and the atomic nuclei. These scattering events reduce the mobility of the electrons, and because resistance is inversely proportional to mobility, the resistance increases. The RTD consists of a coil of fine metal wire in the sensing arm of a wheatstone bridge circuit and an adjustable resistor in the opposing arm. The adjustable resistor is used to balance the bridge, which produces the null output and the equivalent temperature.

6.1.2.3 Thermistor

A thermistor is a resistive element made of semi-conductive material that has a negative coefficient of resistance. The mechanism governing the resistance change of the thermistor is the increase in the number of conducting electrons with an increase in temperature due to thermal generation; that is, the electrons that are tightly bound to the nucleus by coulombic attraction, gain sufficient thermal energy to break away from the nucleus and become influenced by external fields.

6.1.2.4 Direct Reading Temperature Measurement

The previously mentioned devices for temperature measurement can be used for remote temperature readings or a local reading if a readout device is near the measurement device location. If only a local or direct temperature reading is necessary a direct reading thermometer can also be used.

6.2 Effects on Related HVAC Systems

As integral components to most all HVAC systems, the condition of fans and dampers can have a decided effect on the HVAC systems that they support. The following sections describe potential effects to common HVAC systems that could result from under-performing fans or dampers.

6.2.1 Effects on Chiller Systems

Chiller systems are reliant upon the successful operation of associated fans and dampers. Chillers utilize a basic refrigeration cycle with the liquid being cooled (usually water) entering the cooler where it is chilled by liquid refrigerant evaporating at a lower temperature. The refrigerant vaporizes and is drawn into the compressor, which increases the pressure and temperature of the gas so that it can be condensed at the higher temperature in the condenser. The condensed liquid refrigerant then flows to the evaporator through a metering device. A fraction of the liquid refrigerant changes to vapor (flashes) as the pressure drops between the condenser and the evaporator. Air-cooled chiller packages utilize fans to remove heat from the condenser coil. These fans are typically direct-drive axial flow-type designs. An inoperative condenser coil fan will affect the ability of the refrigerant to be adequately cooled and, thus, affect the proper refrigerant feed to the evaporator. Air-cooled chillers also control compressor pressure by cycling the condenser fans during cool ambient temperature conditions.

Except for fans and dampers associated with chiller condensers, fans and dampers have little effect on chiller operation. HVAC systems that utilize chillers typically have at least two temperature control loops. The chilled water control loop is independent of the air temperature control loop that could be affected by changes in airflow. Chilled water and hot water coils are subject to freeze damage caused by malfunctioning fresh air dampers. Typically, when a unit is not operating, the fresh air damper will close. Leakage past this damper during cold weather is a common cause of freeze damage. Because some structures are maintained at a negative pressure, even slight leakage past fresh air dampers can be a problem.

The term flashing is used to describe what normally occurs at the pressure reducing device located at the evaporator (barrel) inlet. Flashing is also used to describe a symptom of undesirable pressure drop in the liquid line and in components located in the liquid line.

Liquid-cooled condenser chillers can also be affected indirectly by fan performance. The chilled water from these chiller units is normally routed to a fan coil package. The fan coil unit utilizes an air-to-water heat exchanger with the chilled water as the cooling medium. An inoperative or malfunctioning fan will cause a reduced heat load on the chilled water system, which will cause a reduced load on the chiller equipment. The reduced load could cause the chiller to cycle more frequently and to go into a hot-gas bypass mode (if supplied on the refrigerant side). In this mode, part of the compressed gas is by-passed to the suction to prevent suction pressure from falling below a pre-set value.

6.2.2 DX Air Conditioning Systems

Direct Expansion (DX) air conditioning systems utilize a cooling coil with refrigerant to cool air flow across the coil. The air conditioning system will normally consist of a fan on the inlet or discharge of the unit with isolation dampers. In addition, the DX system might also have outside air dampers, an exhaust damper, and balancing dampers. The outside air dampers are utilized in systems to bring in fresh air in the space as required per design codes. Since outside air can be at a wide temperature and relative humidity range, a malfunctioning damper can affect DX system performance. Leakage past the damper at cold ambient conditions requires the heaters and humidifiers in the system to operate more frequently. Leakage past the damper during warm air conditions might result in a heat load beyond the capacity of the cooling coil and produce high temperatures in the conditioned space.

DX systems are sensitive to changes in evaporator airflow. Most DX systems require a minimum flow to maintain refrigeration system operation. A reduction in flow is equivalent to a reduction in evaporator load. This can cause compressor oil migration, low pressure trips, evaporator icing, and ultimately compressor damage.

The dampers and fans in DX systems might malfunction causing lower airflow past the cooling coils. This condition might cause a reduced load at the coil, which might result in low refrigerant flows and potential compressor problems associated with insufficient oil transferred by the refrigerant. Also, there are steam heating coils that might freeze if the outside damper leaks.

6.2.3 Exhaust Systems

HVAC exhaust systems at nuclear power plants are used in some applications to ventilate areas that contain equipment that produces a heat load or gas emissions (for example, pump rooms, battery rooms). The exhaust ventilation system removes the heat generated in the space and draws in air from surrounding areas through louvers, doors, or other openings in the space. The malfunction of a damper to fully open in the system would cause inadequate exhaust flow and potentially heat up the area and equipment beyond the temperature limits.

Another exhaust system application is to function in tandem with a supply system to maintain a design airflow in a designated area. The exhaust system will be sized to provide airflow to maintain the area at a positive or negative pressure with respect to its surrounding area. This is usually done such that the more radioactively contaminated area is kept at a higher negative pressure with respect to the lower dose area. The proper operation of fans and dampers in the system is crucial to maintain the area pressures at the designed conditions.

6.2.4 Charcoal Adsorber Units

The Control Room HVAC systems at most plants utilize a charcoal adsorber unit to remove gaseous radioactive elements from the makeup air supply to the Control Room. In addition, all exhaust systems that communicate with the main HVAC, exhaust to the atmosphere from areas that potentially contain airborne radioactivity, by utilizing charcoal adsorber media to remove the gaseous radioactive material from the effluent. Charcoal adsorbers are also used in filtered recirculation and clean up systems to remove radioactive gaseous effluents from the air streams that pass through them. The charcoal adsorber equipment consists of either deep-beds or a series of trays to contain the charcoal. Dampers that bypass the charcoal package unit must be maintained completely closed to ensure that the airflow to be treated is not bypassed allowing radioactive gases to be distributed downstream either to occupied spaces or to the atmosphere. Fans associated with the charcoal adsorber unit need to be maintained to ensure that the airflow through the unit is within design values. If the airflow is too high, the air does not have sufficient residence time in the adsorber bed and the efficiency of the charcoal to remove the radioactive gases is greatly reduced resulting in the release of radioactivity downstream.

6.2.5 Control Room Pressurization

The control room HVAC systems at most plants use a makeup airflow path to provide positive pressurization to the control room envelope during an accident. This is to ensure the health and safety of the operators (and ultimately the health and safety of the public) by not allowing potentially contaminated air to infiltrate into the control room envelope from surrounding areas (including the outside ambient). Because it is unlikely for the whole control room envelope to be completely leak tight, a specified airflow is required to maintain the space at a relatively high positive pressure with respect to the surrounding areas. Therefore, a malfunctioning makeup air fan or damper can cause the control room area to be inadequately pressurized (low airflow) or over-pressurized (high airflow). Low control room pressurization can lead to infiltration of contaminated or toxic gases into the control room and affect the operators. High control room pressures can cause operator discomfort (ears popping) or can cause opening or closing of doors to adjacent spaces to be difficult or impossible by normal means.

6.3 HVAC System Components Inspection Guidelines

Though each component in an HVAC system will have specific requirements for inspection and maintenance, some fundamental guidelines can be used to develop more comprehensive maintenance programs. The following recommendations are provided to suggest attributes that could be included in a plant-specific program for various pieces of HVAC system equipment.

6.3.1 Bearings and Couplings

Both fans and dampers utilize bearings and couplings in similar manners. For dampers, the bearings are typically on the blade shafts. In fan systems, the bearings are on the wheel/rotor axis drive shaft. It is important to maintain proper lubrication for bearings to limit damage. An over-lubricated bearing will tend to overheat. This problem will dissipate with time as grease leaks from the bearing. A normal bearing temperature is 140° F (60° C). Temperatures of 180° F (82.22° C) or higher should be investigated. If the bearing reaches a temperature high enough to boil a drop of water, operation of the equipment related to the bearing should be halted and the bearing replaced. If the bearing is not replaced, the shaft might be damaged or the bearing might seize. Too little lubrication will cause metal-on-metal contact between rollers from the bearing and the shaft supported by the bearing. The contact will damage and potentially ruin the shaft. Sizing can also be an issue with bearings. If the bearing is not able to maintain an applied load, it will be severely damaged and will not supply the proper support to the shaft. Unexpected loads can be produced from high vibration or large unbalanced forces.

In dampers and fans, couplings are used for connection of the actuator to the damper or prime mover to the fan. The main issues with couplings are connection and sizing. The connection between the actuator and the damper or the prime mover and the fan is very important. If the connection is not secure, damage to the actuator/prime mover can occur or the damper/fan can be damaged. Also, if a coupling is sized improperly, damage can be caused at the starting of a fan from shaft inertia. The resulting damage could be a broken coupling, a bent motor, or fan shaft. It is important to monitor the shafts and couplings for stress cracks and damage. The couplings should also be inspected and tested to be sure that they are securely fastened to the shafts.

6.3.2 Ductwork

There is very little maintenance work associated with ducting. The necessary inspection activities associated with ductwork include checking the duct internals for cleanliness and to ensure no foreign material has been permitted into the system that could have an adverse effect on damper or fan performance. Ideally, strategically placed access doors will provide for adequate inspection of duct internals. Ducts with internal insulation should be visually inspected for areas where it has become detached from the duct wall. This results in a decrease in cross-sectional area, which can hinder duct system performance. The insulation in these areas should be replaced or repaired prior to returning the system to service. Turning vanes installed in elbows should also be inspected. Loose vanes should be reattached or removed. If vanes are removed, an appropriate evaluation should be performed to determine the impact to pressure drop through the duct system. Further inspection attention should be given to the support system. Supports should be examined for deterioration or damage. Bent support hangers and deteriorated connections to ductwork and foundations should be the key areas of focus for this examination. The ductwork exterior should also be inspected. Any deterioration or perforation of the ductwork can affect the ability of the ventilation system to satisfactorily function. Any damaged ductwork should be repaired or replaced in accordance with the plant-specific procedure.

6.3.3 Filters

There are many facets of maintenance with regard to filters. The main focus should be on inspecting filters and filter housings for damage, potential leakage paths, cleanliness, and remaining filter capacity. Filters and filter housings should be inspected and tested periodically [22]. Pleated filters should be visually inspected to ensure pleats are oriented in the vertical direction. Filters should be replaced when they reach a specified capacity or after a certain period of time. Detailed information is provided by vendors on filter replacement. Licensing and regulatory commitments will detail the appropriate test methods, test frequency, and satisfactory results. These references should be consulted to ensure that filters are tested adequately.

6.3.4 Door Seals

Door seals are important to ventilation systems in the prevention of leakage. The seals around doors provide isolation for the ventilation system environment envelope. The maintenance of these seals is done by visual inspection of damage and a smoke tube test that will allow for the visualization of leakage locations. Damaged seals are replaced when determined to be unsatisfactory.

6.3.5 Damper Seals

As discussed in the visual inspection section, the condition of damper seals is very important to maintain desired system isolation and control. The maintenance of the damper seals is performed through the periodic visual inspection of the seals and replacement of any seals that are damaged.

6.4 General Practice

Regardless of the specific component being inspected or maintained, certain basic considerations should be made and incorporated into an inspection or maintenance program. The following topics are general considerations for good practice.

6.4.1 Periodic Inspection Requirements

Depending on licensing commitments, the number and type of inspections that are needed will vary. From various vendor information, a general time frame for inspections is between 18 and 24 months. On systems and components that are critical to safety, it is a good practice to inspect the hardware more often. In these cases, a six to twelve month inspection might be more appropriate. The best reference to determine the timeframe for a needed inspection is the plant-specific licensing documentation. If there is hardware for which this guide does not address the need for testing and inspection, the vendor information will provide guidance.

6.4.2 Record Keeping

It is always good practice to maintain records of work done on a system. This could be kept in an electronic file that can be easily updated and accessed. There are specific items for which the NRC requires maintenance and documentation. Such filter items include, but are not limited to, Charcoal filters and High Efficiency Particulate Air (HEPA) filters. Isolation dampers might fall under the periodic testing requirements of the plant valve testing and maintenance program. If ventilation system components fall into this category, a mandatory record system will exist for inspection and maintenance information.

6.4.3 Storage and Handling

Vendor information from damper and fan/blower manufacturers was consulted for information on general storage and handling instructions. In general, there are different levels of storage and handling requirements. For example, equipment supplied by Preferred Metal Technologies includes recommendations for one of four levels of requirements. The most stringent storage requirements specify indoor storage in a humidity and temperature-controlled environment with filtration to provide a dust and harmful vapor-free atmosphere. This storage facility is required to be fire resistant and weather tight. It is required to be protected against vandalism and flood, as well. The floor of the facility must be paved, well drained, and the material stored on pallets. The second level is relaxed in the humidity and filtration requirements, while the third level requires only indoor storage in a flood-protected facility with a well drained, paved floor. The least stringent requirement permits the storage of specified items in an outdoor environment.

In many cases, equipment might have had special balancing or calibration before shipping. Care is needed in these cases to prevent damage to the equipment or the need for expensive analysis, testing, and repair to restore the equipment to proper condition.

Storage of equipment should be indoors, on pallets or skids. Care should be used in placement of equipment to prevent inadvertent damage from moving equipment. Covers and protective coatings should be used to prevent dust and debris from damaging equipment. Dampers are to be stored with the blades in the closed position, flat on the skid or pallet. Dampers should never be stored outside. A fan system can be stored outside if necessary. However, special precautions are to be taken to prevent damage or degradation to the system. Generic precautions for outdoor storage include additional corrosion protection, covering the equipment, tightly sealing bearings, and providing moisture absorbing material. Coverings include tarps, plastic covers, and waterproof paper. For both fans and dampers, additional special instructions for outdoor storage might be provided by the vendor. If there are no outdoor storage instructions, the vendor should be contacted prior to storage of equipment outdoors.

7
SURVEY RESULTS AND ROOT CAUSE ANALYSIS

Surveys were distributed to determine the types of fans and dampers that plants typically use. The results suggest that the types of fans and dampers used in the various plant ventilation systems are independent of their specific application. That is, the required ventilation systems (reactor building ventilation, control room ventilation, auxiliary building ventilation, etc.) could use any of the available fan types, with the obvious exception that propeller fans cannot be used in ducted systems. Selection of a fan for a given application often reflects the preference of the system designer rather than a definitive application guideline. Ventilation system types vary from plant to plant as required by architectural layouts and licensing commitments. Likewise, the system layouts and performance parameters vary from plant to plant. The result of this phenomenon is that existing plant ventilation systems use all combinations of available equipment types to accommodate the wide range of specific layouts for systems with the same functional requirements.

Surveys sent to member plants requested input regarding the following fan attributes for fans used at their facilities:

- Fan types and manufacturers
- Fan blade types
- Drive types
- Capacity ranges
- Bearing styles
- Maintenance activities
- Identification of component replacements

Responses indicated that normal routine maintenance included lubrication of fan and motor bearings, and damper linkages. Inspections were also routinely performed on fan assemblies, damper assemblies, and flexible connections. These maintenance and inspection activities are typically developed from manufacturers' recommendations as well as from plant maintenance input. A summary of the survey results are provided in Appendix A. This table also summarizes failures reported by the responding stations.

7.1 Root Cause Analysis of Principal Failure Modes

In addition to reporting on the type of equipment in use throughout the plant ventilation systems, some stations offered general information on various fan failures. The results and tabulation of the surveys suggested that failures were caused by normal wear, corrosion (weather conditions), improper installation, and motor failures. However, the primary direct cause of fan failures that could potentially be prevented is vibration. Section 4.3 of this report discusses in detail, a number of equipment conditions that could result in vibration that can be attributed to equipment failure. Guidelines to follow when monitoring equipment for vibration failure are as follows:

- Safety first.
- Watch out for high temperatures, wetness, other detrimental environmental conditions.
- Use an accelerometer for all bearing cap measurements.
- Use low frequency accelerometers on slow turning machines.
- Preferred accelerometer mounting is: stud, glue, supermagnet, magnet, hand-held with wax or coupling, hand-held, hand-held with probe extension, in that order.
- Bearing cap measurements must be made in the same location every time.
- Trend velocity (acceleration integrated once) data for bearing cap overall vibration on all machines.
- Take data with great enough resolution to distinguish the frequencies you need to see (for instance, to distinguish 1X rpm and 2X rpm from 1X line frequency – 60.00 Hz - and 2X line frequency – 120.00 Hz - on a 2-pole, nominally 3600 rpm, motor).
- Trend high frequency data such as bearing, gear, rotor bar, or stator slot frequencies in acceleration with a range sufficient to capture three times the fundamental frequency of interest.
- If possible, always take data at the same loads and flows, and track non-vibration parameters for correlation with vibration trends.
- If possible, make phase measurements with variable speed machines.
- If possible, do natural frequency surveys of the machines and attached structures at the start of the vibration program, and store the results.
- Use calibrated instruments that have also been checked for operation and function.
- Make sure you understand calibration and know how and if installed probes function correctly.
- Use a strobe light in the field.
- Use tape recorders, photographs, and videotape as needed to record what you see, hear and think.

Plain or journal bearing machines:

- Make measurements with non-contact displacement probes when possible.
- Make phase measurements when possible.
- Take displacement probe measurements in at least two orthogonal radial directions.
- Take simultaneous data in both directions when possible.
- Evaluate spectra, time waveforms, and orbits when possible.
- Take bearing cap data in velocity at locations that provide a good mount on the bearing.
- Take measurements in three orthogonal directions.
- Trend all measurements.

Rolling element bearing machines:

- Take bearing cap data in acceleration at locations that provide a good solid path to the bearing.
- Use a coupling if necessary.
- Calculate bearing frequencies and take data at a great enough range to capture at least three multiples.
- Take measurements in three orthogonal directions.
- Trend all measurements.

7.1.1 Root Cause Guidelines

Efforts to establish root causes of fan failures should include a collection of data from readily available sources. Useful information in failure determination can be derived from routine surveillance data collected, as well as sub-component design information contained in original procurement documentation. The following items suggest some sources of information useful in collecting baseline data used for failure determination:

- Design data for the system, structure(s), ductwork and components
- Maintenance records
- Vibration test data and trends
- Process data and trends
- Mechanics, operators, and other knowledgeable personnel
- Your own notes from walkdowns, field observations
- Vendor data, manuals, technical bulletins, technical experts
- Data from purchasing and stores on bearings, belts, lubricants, and so on
- Data from any other sources

7.1.2 Possible Failure Causes

Interpretation of the information assembled from selected sources must be processed to determine the eventual root cause of the subject failure. An understanding of possible causes should be developed to help determine the specific cause of vibration responsible for the equipment failure. Some possible causes of vibration are provided as follows:

- Manufacturing flaws
- Improper shipping, storage, handling
- Improper application, unsuitable equipment
- Incorrect component selection, undesirable equipment
- System design flaws
- Structural flaws, foundation failure, shifting
- External loads
- External vibration, improper isolation from ducts, other rotating or reciprocating equipment
- Other induced or built-in component flaws
- Poor maintenance practices, such as bearing installation techniques or belt installation techniques, failure to adhere to tolerances, torque instructions, best practices
- Poor maintenance, cleaning, and lubrication program
- End of useful life of the failed component or part
- Resonance vibration
- Improper or inadequate cleaning or balancing
- Incorrect or inadequate alignment
- Failure to account for thermal growth
- Assembly errors

7.1.3 Probability of Failure Modes

Often, data collected to determine root causes of vibration-induced fan failures is indeterminate in identifying a final attribute. An observed failure might suggest multiple causes. The following general categories are followed in parentheses by a suggested level of probability (low, moderate, or high):

- Residual or accumulated unbalance too high (high)
- Misalignment (high)
- Bad and/or mis-installed belts and/or sheaves (high)
- Bad and/or mis-installed bearings in fan or motor (high)

- Resonances or critical speeds (high to moderate)
- Normal wear, run-to-fail (high to moderate)
- Foundation faults, cracking, voids, movement (moderate)
- Looseness of bearings, bolts (moderate)
- Motor electrical faults (moderate)
- Flow-induced failures, aerodynamic effects (moderate to low)
- Catastrophic failure of a mechanical component (moderate to low)
- Coupling problems (low)
- Gear problems (low)
- Lubricant failure (low)
- Faults induced by ducts or other structural members (low)
- Oil whirl, bad bearing design (low)
- All other faults (low)

7.1.4 Corrective Actions

Upon determination of the cause of the equipment failure, the proper actions should be taken to preclude repeated failure of the same type. The level of action should be weighed against the effort required to implement the subsequent change, as well as the severity and consequence of the subject failure. Some suggested corrective actions are provided as follows:

- Fix problem and do nothing else
- Replace it with improved design
- Improve specifications
- Change or improve feedback and practices of vendors
- Change or improve feedback and practices of shippers
- Change or improve feedback and practices of purchasing, stores
- Redesign the system, component, internal parts, or all of these
- Change or improve feedback and practices of design
- Make field changes
- Change or improve feedback and practices of construction
- Change PdM, PM practices, intervals
- Improve monitoring techniques, frequency, trending techniques
- Change or improve feedback and practices of maintenance

- Change or improve balancing techniques
- Change or improve alignment techniques
- Change or improve belt installation techniques
- Correct blade pitch, damper settings

7.2 Trending Parameters

When trending parameters for fan vibration, attempts should be made to predict faults so they can be corrected in a timely manner avoiding emergent work. The goal in establishing trends is to eliminate unplanned corrective maintenance.

Additionally, trending and failure history information collected can be used to eliminate unnecessary PMs and/or extend intervals between PMs (or shorten the intervals, if appropriate). System engineering should attempt to reduce the task burden for maintenance, operations work control, engineering, stores and others. Control room system monitoring basis is provided in EPRI TR-107668 [26]. This can be used as a guide for other systems. Some criteria that can be applied to fan vibration trending is suggested as follows:

- Trend overall vibration (acceleration, velocity or displacement), from the lowest frequency obtainable up to:
  - At least five times the rpm of plain or journal bearing machines (trend phase at 1X rpm, also)
  - At least ten times the rpm of ball bearing machines
  - Special cases for slow-turning machines, as required
- Trend high frequency vibration for belts, rolling element bearings, gears, motors:
  - Trend belt, bearing, and gear frequencies of interest
  - For rolling element bearings, trend overall vibration from 5,000 to 20,000 Hz
  - Trend gear mesh fundamental and 3X
  - Trend 2X belt frequency
  - Trend acoustic and aerodynamic frequencies of interest, including vanepass, when discovered
  - Trend 1X line and 2X line frequency, rotor bar, and stator slot fundamentals, for AC motors, plus SCR firing frequency (6X) on DC motor vibration
- Trend process parameters, including, but not limited to:
  - Suction pressure
  - Discharge pressure
  - Flow
  - Bearing metal or casing temperatures

– Oil reservoir or outlet temperatures
– Motor current, for each phase if possible
– Motor stator temperature
– Damper position
– Unit load in MW and MVAR
– RPM, especially on variable speed machines and belt drives

8 TRAINING AND PERSONNEL QUALIFICATIONS

8.1 Codes and Standards for Training

There are no federal codes specific to training and qualification programs for HVAC maintenance personnel. Most nuclear power plants have their own mechanical maintenance training and qualification programs. The Institute of Nuclear Power Operations (INPO) develops training standards, evaluates the quality and effectiveness of utility training, and assists member utilities in developing performance-based training programs.

In the course of a comprehensive fan maintenance program, performance guidelines for evaluation will likely be required. The primary source of standards for evaluation of fan performance is the Air Moving and Conditioning Association (AMCA). AMCA Bulletin 210 [27], Test Code for Air Moving Devices, is a standard for determining almost all catalog fan and roof ventilator capacity data.

8.2 Guidelines for Training and Qualifications of Engineering Personnel

INPO Academy Document (ACAD) 98-004 [28] is based primarily on industry-developed job analysis for engineering positions and experience gained from accreditation reviews, INPO plant evaluations, and a review of industry operating experience. These guidelines are not specific to HVAC professionals, but describe a system/component/maintenance program that consists of three components of training and qualification for engineering support:

- Orientation Training
- Position-Specific Training
- Continuance Training

8.3 Guidelines for Training and Qualifications of Maintenance Personnel

INPO Academy Document ACAD 92-008 85–002 [29] provides the framework for maintenance personnel training and qualification programs at nuclear power plants. Three training programs (mechanic, electrician, and instrument and control technician) are addressed by these guidelines. These programs both develop and improve the knowledge and skills of maintenance personnel.

Because maintenance department organizations, disciplines, titles, and responsibilities vary widely among utilities, portions of the program outlined in these guidelines might not be applicable in all cases. Each utility should identify the appropriate subject matter for plant-specific needs.

8.4 Specific Training on HVAC Components

Most utilities provide their own HVAC maintenance training programs. Sometimes it is more economical to train the personnel at the vendor's facility. HVAC maintenance personnel working in a nuclear power plant need to have a foundation in diversified skills. This is in addition to those skills needed for craft or engineering positions.

HVAC related disciplines include:

- Refrigeration and refrigerants
- Electrical
- Controls (electrical and pneumatic) and the calibration of these instruments used on HVAC systems
- Ductwork fabrication and maintenance of ductwork
- Testing and balancing
- Filter testing for nuclear grade filters
- HVAC systems including fan theory
- Ability to read electrical/control schematics, and mechanical drawings

Current day recognition of the impact that releases of chlorine-based compounds have on the environment require very specialized knowledge and training to properly handle refrigerants used in chillers and other refrigeration equipment. Activities related to refrigerant recovery and recycling are monitored to ensure that close tracking of refrigerant inventory is maintained. Improper certification of individuals handling refrigerants, or lapses in refrigerant recordkeeping, can result in substantial fines to users of large refrigeration equipment. The American Refrigeration Institute (ARI) has established standards addressing certifications for organizations and equipment used in refrigerant handling processes, and to ensure that refrigerant management programs meet the required guidelines.

In addition, personnel should possess knowledge of lubrication and the mechanics of rotating equipment specific to HVAC.

There are vocational and technical colleges to train personnel in each skill listed above, as well as in system testing and balancing. Fan manufacturers have training on most HVAC components.

9 REFERENCES

1. American Society for Heating Refrigeration and Air Conditioning Engineers (ASHRAE) Standard 62, “Ventilation for Acceptable Indoor Air Quality.”

2. Code of Federal Regulations, Title 10 Nuclear Regulatory Commission, Part 20, “Standards for Protection Against Radiation.”

3. Code of Federal Regulations, Title 10 Nuclear Regulatory Commission, Part 50, “Domestic Licensing of Production and Utilization Facilities.”

   3a. Code of Federal Regulations, Title 10 Nuclear Regulatory Commission, Part 50.34, “Contents of Applications; Technical Information.”

   3b. Code of Federal Regulations, Title 10 Nuclear Regulatory Commission, Part 50.36, “Technical Specifications.”

   3c. Code of Federal Regulations, Title 10 Nuclear Regulatory Commission, 50.65, “Requirements for Monitoring the Effectiveness of Maintenance at Nuclear Power Plants.”

4. Code of Federal Regulations, Title 10 Nuclear Regulatory Commission, Part 100, “Revocation, Suspension, and Modification of Licenses and Construction Permits for Cause.”

5. Nuclear Regulatory Commission, Regulatory Guide 1.52, Dated 3/1/1978, “Design, Testing, and Maintenance Criteria for Post Accident Engineered Safety Feature Atmosphere Cleanup System Air Filtration and Adsorption Units of Light-Water-Cooled Nuclear Power Plants,” June, 1973, (Revision 1, July, 1976).

6. Nuclear Regulatory Commission, Regulatory Guide 1.78, Dated 6/1/1974, “Assumptions for Evaluating the Habitability of a Nuclear Power Plant Control Room During a Postulated Hazardous Chemical Release,” June, 1974.

7. Nuclear Regulatory Commission, Regulatory Guide 1.95, Dated 1/1/1977, “Protection of Nuclear Power Plant Control Room Operators Against an Accident Chlorine Release,” February, 1975.

8. Nuclear Regulatory Commission, Regulatory Guide 1.140, “Design, Testing, and Maintenance Criteria for Normal Ventilation Exhaust System Air Filtration and Adsorption Units of Light-Water-Cooled Nuclear Power Plants.”

9. NUREG 0800, “Standard Review Plan for the Review of Safety Analysis Reports for Nuclear Power Plants,” 1989.

10. American National Standards Institute/American Society of Mechanical Engineers, ANSI/ASME AG-1, “Code on Nuclear Air and Gas Treatment,” 1997-00-00.

11. American National Standards Institute/American Society of Mechanical Engineers, ANSI/ASME N509, “Nuclear Power Plant Air Cleaning Units and Components (N509-89 R96),” 1989.

12. American National Standards Institute/American Society of Mechanical Engineers, ANSI/ASME N510, “Testing of Nuclear Air-Treatment Systems (N510-89 R95),” 1989.

13. American Nuclear Society, ANS 56.6, “Pressurized Water Reactor Containment Ventilation Systems,” 1986-00-00.

14. American Nuclear Society, ANS 56.7, “Boiling Water Reactor Containment Ventilation Systems R,” 1978-00-00.

15. Institute of Electrical & Electronics Engineers, Inc., IEEE 323, “Standard for Qualifying Class 1E Equipment for Nuclear Power Generating Stations R,” 1990.

16. Standard Review Plan, SRP 6.4, “Control Room Habitability System.”

17. Standard Review Plan, SRP 9.4.1, “Control Room Area Ventilation System.”

18. NUREG/CR-3786, “A Review of Regulatory Requirements Governing Control Room Habitability Systems,” August 1, 1984.

19. Institute of Electrical & Electronics Engineers, Inc., IEEE 484, “Recommended Practice for Installation Design and Installation of Vented Lead-Acid Batteries for Stationary Applications,” 1996.

20. Air Moving and Conditioning Association (AMCA) Bulletin 201, “Fans and Systems,” 1990.

21. *Electric Motor Predictive and Preventive Maintenance Guide*. EPRI (NMAC): July, 1992. Report NP-7502.

22. *PM Basis for HVAC-Air Handling Equipment.* EPRI, Palo Alto, CA: December, 1997. Report TR-106857, Volume 21.

23. Sheet Metal and Air Conditioning Contractors’ National Association, Inc., “HVAC Duct Construction Standards, Metal and Flexible,” copyrighted, used with permission. 2nd edition, 1995.

24. UL-555, “Fire Dampers”, 6th edition, June, 1999.

25. *PM Basis for HVAC Dampers and Ducting*, EPRI, Palo Alto, CA: December, 1997. Report TR-106857, Volume 20.

26. *Guideline for System Monitoring by System Engineers*, EPRI, Palo Alto, CA: March, 1997. Report TR-107668.

27. Air Moving and Conditioning Association (AMCA) Bulletin 210, “Test Code for Air Moving Devices.”

28. Institute of Nuclear Power Operations, Academy Document (ACAD) 98-004, “Guidelines for Training and Qualifications of Engineering Personnel.”

29. Institute of Nuclear Power Operations, Academy Document (ACAD) 92-008 85–002, “Guidelines for Training and Qualifications of Maintenance Personnel.”

10 BIBLIOGRAPHY

Advanced Vibration Measurement and Analysis. Columbus, Ohio: IRD Mechanalysis, Inc., 1980.

Applying Machinery Vibration Monitoring. NP-6340, Palo Alto, CA: EPRI, April 1989.

Baumeister, T., et al. *Marks' Standard Handbook for Mechanical Engineers. 10th edition*, New York: McGraw-Hill, 1996.

Blake, Michael P., and William S. Mitchell. *Vibration and Acoustic Measurement Handbook.* New York: Spartan Books, 1972.

Blevins, Robert D., *Flow-Induced Vibration.* 2nd edition, New York: Van Nostrand Reinhold, 1990.

Blevins, Robert D., *Formulas for Natural Frequency and Mode Shape*. Malabar, Florida: Robert E. Krieger Publishing Company, 1984.

Bloch, Heinz P., and Fred K. Geitner, *Improving Machinery Reliability, Machinery Failure Analysis and Troubleshooting, Machinery Component Maintenance and Repair, Major Process Equipment Maintenance and Repair* (4 vol., various editions). Gulf Publishing Company, 1990-1995.

Bolton, A. N., "Pressure Pulsations and Rotating Stall." Conference on Vibrations and Noise in Pump, Fan and Compressor Installations. Southhampton, England: Institution of Mechanical Engineers, 1975.

Chiu, Chong, *Root Cause Analysis and Corrective Actions for Power Plants.* San Clemente, CA: Failure Prevention, Inc., 1992.

Condition-Monitoring Guidelines for Rolling Element Bearings. TR-100160, Palo Alto, CA: EPRI, November 1991.

Crawford, Arthur R., and Steve Crawford, *The Simplified Handbook of Vibration Analysis, Volumes I and II*. Computational Systems, Inc., 1992.

Darlow, Mark S., *Balancing of High-Speed Machinery*. Springer-Verlag, 1989.

Daugherty, Robert L., and Joseph B. Franzini, *Fluid Mechanics With Engineering Applications.* 7th edition, New York: McGraw-Hill, 1977.

DeLaval Engineering Handbook, 3rd edition. Edited by Hans Gartmann. New York: McGraw-Hill, 1970.

Giles, Ranald V., *Fluid Mechanics and Hydraulics.* 2nd edition, New York: McGraw-Hill, 1962.

Gordon, Colin G., "Fan Noise and Its Prediction." Paper published for the Conference on Fan Technology and Practice, London, England: The Institution of Mechanical Engineers, 1974.

Guy, Kevin R., *Case Histories: Power Industry*. Vibration Institute, 1993.

Jackson, Charles S., *The Practical Vibration Primer.* Gulf Publishing Company, 1979.

Manual of Bearing Failures and Repair in Power Plant Rotating Equipment. GS-7353, Palo Alto, CA: EPRI, July 1991.

McConnell, Kenneth G., *Vibration Testing*. New York: John Wiley & Sons, 1995.

McGraw-Hill Dictionary of Scientific and Technical Terms, 5th edition. Editor in Chief, Sybil P. Parker, New York: McGraw-Hill, 1994.

Mitchell, John S., *Machinery Analysis and Monitoring.* Tulsa, Oklahoma: Pennwell Publishing Company, 1981.

Mobley, R. Keith, *An Introduction to Predictive Maintenance.* Van Nostrand Reinhold, 1990.

NRC GL 99-02, “Laboratory Testing of Nuclear Grade Activated Charcoal”, June 3, 1999.

Nuclear Regulatory Commission, Regulatory Guide 1.160.

NUMARC Guideline 93-01.

Otnes, Robert K., and Loren Enochson, *Applied Time Series Analysis, Volume I: Basic Techniques.* New York: John Wiley and Sons, 1978.

Piotrowski, John, *Shaft Alignment Handbook.* 2nd edition, expanded. New York: Marcel Dekker, Inc., 1995.

Randall, R. B., *Frequency Analysis.* Naerum, Denmark: Bruel & Kjaer, 1977.

Shock & Vibration Handbook, 3rd edition. Edited by Cyril M. Harris, New York: McGraw-Hill, 1988.

Skelly, Thomas W., "Understanding Load Commutated Inverter Drives." *Electrical Consultant*, July/August, 1983.

Taylor, James I., *The Vibration Analysis Handbook*, 1st edition. Vibration Consultants, Inc., 1994.

Thompson, William M., *Theory of Vibration with Applications.* Englewood Cliffs, NJ: Prentice-Hall, Inc., 1972.

Vibration Diagnostic Chart. Charlotte, North Carolina: Technical Associates of Charlotte, Inc., 1992.

Vibration Sensor Mounting Guideline. GS-7406. Palo Alto, CA: EPRI, July 1991.

Wowk, Victor, *Machinery Vibration: Measurement and Analysis.* New York: McGraw-Hill, 1991.

A
SURVEY RESULTS

Review the following chart for survey data.

NMAC HVAC FANS & DAMPERS GUIDE

SURVEY RESULTS

FAN PARAMETER	# SURVEYS	REACTOR BUILDING	# SURVEYS	AUXILIARY BUILDING	# SURVEYS	TURBINE BUILDING
CENTRIFUGAL	11		14		15	
DIRECT DRIVE	8		7		6	
BELT – FIXED SHEAVE	4		9		10	
BELT – ADJ. SHEAVE	2		7		5	
SUPPLY	7		14		13	
EXHAUST	6		13		11	
CIRCULATION	6		7		8	
AIR CLEANING	4		9		7	
HEATING	3		10		6	
COOLING	7		10		11	
VENTILATION	1		4		1	
FAN ROLL. ELEM. BRGS.	7		10		9	
MOTOR ROLL. ELEM. BRGS.	9		11		11	

REACTOR BUILDING

FAILURE CAUSE REPORTED (#)

fan casing (1),
fan bearings (5),
fan shaft (2),
coupling (2),
belts (3),
sheaves (2),
motor failure (2),
motor bearings (5)

FAILURE MODE REPORTED (#)

none reported

AUXILIARY BUILDING

FAILURE CAUSE REPORTED (#)

fan assembly (1),
fan casing (4),
fan impeller (2),
fan bearings (5),
fan shaft (6),
belts (13),
sheaves (12),
motor failure (6),
motor shaft (1),
motor bearings (6),
damper motor (1)

FAILURE MODE REPORTED (#)

catastrophic fan shaft failure due to bearing failure (1),
bearing corrosion (1),
variable sheaves replaced due to vibration (1),
bearing wear (1),
bearing races worn (1),
weather conditions (1),
belt normal wear (1),
motor normal wear (1),
normal wear, unspecified (4)

TURBINE BUILDING

FAILURE CAUSE REPORTED (#)

fan assembly (3),
fan casing (5),
fan impeller (3),
fan bearings (5),
fan shaft (4),
belts (8),
sheaves (7),
motor failure (1),
motor bearings (6)

FAILURE MODE REPORTED (#)

casing broken (1),
casing corrosion (1),
bearing corrosion (1),
shaft corrosion (1),
normal wear, unspecified (3)

AXIAL - VANEAXIAL	17	13	15
VARIABLE PITCH	2	0	0
AXIAL – TUBE	1	0	2
AXIAL - PROPELLER	0	2	6
DIRECT DRIVE	17	12	14
BELT – FIXED SHEAVE	0	5	8
BELT – ADJ. SHEAVE	0	0	0
SUPPLY	5	9	8
EXHAUST	7	11	14
CIRCULATION	17	7	8
AIR CLEANING	2	12	4
HEATING	0	10	2
COOLING	14	10	12
VENTILATION	1	2	3
BOOSTER	1	1	0
FAN ROLL. ELEM. BRGS.	10	10	9
MOTOR ROLL. ELEM. BRGS.	12	13	15

FAILURE CAUSE REPORTED (#) fan assembly (1), fan casing (1), fan impeller (3), fan bearings (6), fan shaft (2), coupling (1), belts (1), sheaves (1), motor failure (4), motor bearings (8)	**FAILURE CAUSE REPORTED (#)** fan assembly (1), fan casing (4), fan impeller (3), fan bearings (5), fan shaft (2), coupling (1), belts (5), sheaves (5), motor failure (9), motor bearings (5)	**FAILURE CAUSE REPORTED (#)** fan assembly (2), fan casing (6), fan impeller (4), fan bearings (8), fan shaft (5), belts (7), sheaves (6), motor bearings (8)
FAILURE MODE REPORTED (#) motor routinely replaced every other outage (1), motor bearings (1), motor seals (1), motor windings (1), normal wear, unspecified (2)	**FAILURE MODE REPORTED (#)** casing corrosion (1), bearing corrosion (1), broken support bracing (1), disch. damper broken (1), unbalanced fan (1), motor windings (5), weather conditions (1), normal wear, unspecified (5)	**FAILURE MODE REPORTED (#)** fan casing normal wear (1), bearing corrosion (1), normal wear, unspecified (3), run-to-fail (3)

Notes:

1. One respondent reported initial limited success identifying bearing failures using vibration monitoring. This was attributed to non-rigid construction, background vibration,and inaccessibility of bearings. Later success in identifying premature and end-of-life bearing failures was attributed to comprehensive training, a questioning attitude,and the high level of cumulative experience of maintenance department personnel.