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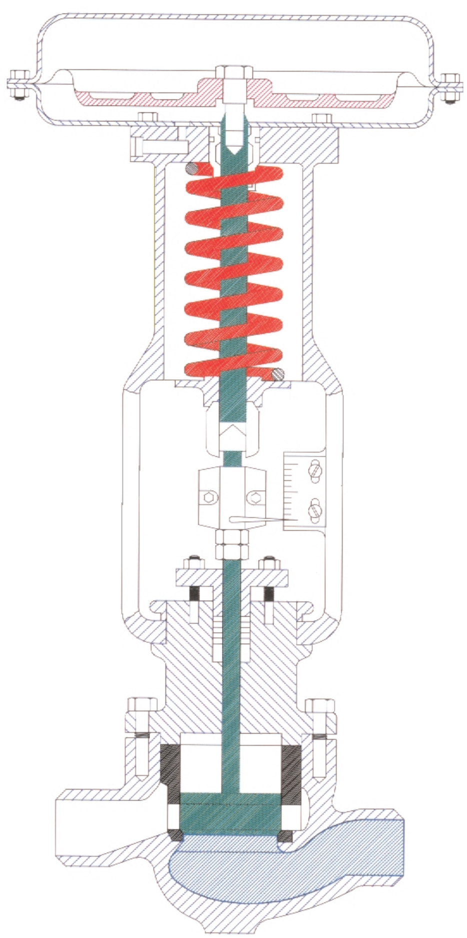
Guide for Evaluating Air-Operated Valve Uncertainties and Actuator Setup Parameters

Technical Report



Guide for Evaluating Air-Operated Valve Uncertainties and Actuator Setup Parameters

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REPORT SUMMARY

This report helps utility engineers evaluate uncertainties and actuator setup parameters for air-operated valves (AOVs).

Background

AOVs in nuclear power plants are designed and set up to ensure proper operation under design basis conditions. To ensure that proper AOV setup is maintained, air pressure and spring preload (for spring return actuators) need to be controlled. The allowable limits should be based on the functional requirements of the AOV. For example, air pressure should be high enough to assure proper operation for the air stroke but not so high that the valve or actuator may be damaged. For spring return actuators, the spring preload should be high enough to assure proper operation for the spring stroke but not so high that the spring is overstressed or margin for the air stroke is insufficient.

This setup guide expands on EPRI's *AOV Evaluation Guide* (TR-107322) by providing methods and equations to

- Determine allowable ranges of setup parameters for an AOV. Setup parameters include minimum and maximum allowable air pressure and minimum and maximum allowable spring preload.
- Determine the margins for successful operation of an AOV, given the actual values of the setup parameters (air pressure and spring preload).
- Determine the effect of uncertainties on allowable setup parameter ranges and margins.

Objective

To provide methods for considering the effects of uncertainties (for example, air pressure and spring preload) and for defining air-operated valve actuator setup parameters.

Approach

The project team developed the methods by applying first principles to create the equations needed to quantitatively account for uncertainties in air-operated valve design performance.

Results

The equations in this guide allow for a comprehensive evaluation of AOV design and setup. The method for calculating allowable setup parameters allows users to determine the entire range of allowable setup parameters, which simplifies AOV static setup testing. The method for combining random uncertainties using square-root-sum-of-the-squares provides justified (but not overly conservative) total combined uncertainties for use in calculating margins and allowable setup parameters.

EPRI Perspective

This guide provides, for the first time, detailed methods for addressing key uncertainties in evaluating air-operated valve design performance and for defining actuator setup parameters to accommodate such uncertainties.

Keywords

Valves
Air-operated valves

EXECUTIVE SUMMARY

AOVs in nuclear power plants are designed and set up to ensure proper operation under design basis conditions. To ensure that proper AOV setup is maintained, air pressure and spring preload (for spring return actuators) need to be controlled. The allowable limits should be based on the functional requirements of the AOV. For example, the air pressure should be high enough to assure proper operation for the air stroke but not so high that the valve or actuator may be damaged. For spring return actuators, the spring preload should be high enough to assure proper operation for the spring stroke but not so high that the spring is overstressed or margin for the air stroke is insufficient.

This Setup Guide expands on the guidance in the EPRI AOV Evaluation Guide (TR-107322) by providing methods and equations to:

- Determine the allowable ranges of setup parameters for an AOV. Setup parameters include minimum and maximum allowable air pressure, and minimum and maximum allowable spring preload.
- Determine the margins for successful operation of an AOV, given the actual values of the setup parameters (i.e., air pressure and spring preload).
- Determine the effect of uncertainties on the allowable setup parameter ranges and margins.

The equations in this guide allow for a comprehensive evaluation of AOV design and setup. The method for calculating allowable setup parameters allows users to determine the *entire* range of allowable setup parameters, which simplifies AOV static setup testing. The method for combining random uncertainties using square-root-sum-of-the-squares provides justified (but not overly conservative) total combined uncertainties for use in calculating margins and allowable setup parameters.

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INTRODUCTION

Background

Reference (1), which is the EPRI AOV Evaluation Guide, provides guidance and equations for evaluating air-operated valves (AOVs). Section 7 of Reference (1) provides equations for evaluating actuator capability for typical linear and rotary air actuators, and Section 8 of Reference (1) provides equations for calculating margins.

This document, which is an AOV Setup Guide, expands on the guidance in Reference (1). Specifically, this guide covers the following areas.

- Calculating allowable AOV setup parameters,
- Calculating AOV margins, and
- Statistically combining uncertainties associated with evaluating an AOV and incorporating the total combined uncertainty into the equations for allowable setup parameters and margin.

Purpose

The purpose of this Setup Guide is to provide the methods and equations for users to:

- Determine the allowable ranges of setup parameters for an AOV. Setup parameters include minimum and maximum allowable air pressure, and minimum and maximum allowable spring preload.
- Determine the margins for successful operation of an AOV, given the actual values of the setup parameters (i.e., air pressure and spring preload).
- Determine the effect of uncertainties on the allowable setup parameter ranges and margins.

Scope

This guide covers the following linear actuator types.

- Double acting air cylinder (single and double ended)
- Double acting air cylinder with spring return (direct and reverse acting)
- Single acting air cylinder with spring return (direct and reverse acting)
- Single acting diaphragm with spring return (direct and reverse acting)

- Single acting diaphragm with spring return and increased mechanical advantage (direct and reverse acting)

This guide covers the following rotary actuator types.

- Double acting scotch yoke air cylinder
- Single acting scotch yoke air cylinder with spring return
- Rotary diaphragm with spring return
- Double acting rack and pinion air cylinder
- Single acting rack and pinion air cylinder with spring return

See Reference (1) for descriptions and figures of these actuator types.

Organization

Section 2 of this report provides a general overview of this Setup Guide. Section 3 provides guidance and equations for calculating allowable setup parameters. Section 4 provides guidance for calculating AOV margins. Section 5 provides guidance for statistically combining and applying uncertainties. Section 6 provides a sample problem. Section 7 lists the references used in this Setup Guide.

Definitions

The following terms are used in this report.

Term	Definition
Air stroke	An AOV stroke in which the valve is driven by air pressure only. For actuators with spring return, air pressure also compresses the actuator spring during the air stroke. See Table 1-1.
Spring stroke	An AOV stroke in which the valve is driven by spring force. For double acting actuators with spring return, the valve is also driven by air pressure during the spring stroke. See Table 1-1.
Extension stroke	An AOV stroke in which the actuator stem moves toward the valve. For a direct acting, rising stem valve, the extension stroke is the closing stroke. For a direct acting actuator on a rising stem valve, the extension stroke is the air stroke. See Table 1-1.
Retraction stroke	An AOV stroke in which the actuator stem moves away from the valve. For a direct acting, rising stem valve, the retraction stroke is the opening stroke. For a direct acting actuator on a rising stem valve, the retraction stroke is the spring stroke. See Table 1-1.

The following variables are used in this report.

User Inputs

Variable	Definition	Ref (1) Equiv.[(1)]
η	Efficiency for quarter turn actuators	η
A_{CAP}	Effective area of the cap side of the diaphragm (in^2 or m^2). A_{CAP} may vary with stroke.	A_{EXT} and A_{RET}
A_{ROD}	Effective area of the stem side of the diaphragm (in^2 or m^2). A_{ROD} may vary with stroke.	A_{EXT} and A_{RET}
b	Length of moment arm for quarter turn diaphragm actuators (in or m)	b
c	Distance from the piston or diaphragm actuator center line to the center line of the lever or gear pivot (in or m)	C
D	Diameter of piston, generally nominal cylinder size or seal diameter (in or m)	D
d	Diameter of actuator stem (in or m)	d
D_{PG}	Pitch diameter of pinion gear in rack and pinion actuator (in or m)	D_{PG}
E	Mechanical advantage multiplier (set to 1 if actuator has no mechanical advantage). The value of E may vary with stroke. The value of E used in any equation in this guide should be the value applicable at the stroke position being evaluated.	ME
F_D	Cylinder or diaphragm friction force (lb or N)	F_D
F_{MAAT}	Maximum allowable actuator thrust (lb or N)	---
T_{MAVT}	Maximum allowable valve thrust or torque (lb or in-lbs, or N or N-m)	---
F_{MSSL}	Maximum safe spring load (lb or N)	---
T_{RAIR}	Required thrust or torque for the air stroke (lb or in-lbs, or N or N-m). T_{RAIR} may vary with stroke. The value of T_{RAIR} used in any equation in this guide should be the value applicable at the stroke position being evaluated.	---
T_{RSPR}	Required thrust or torque for the spring stroke (lb or in-lbs, or N or N-m). T_{RSPR} may vary with stroke. The value of T_{RSPR} used in any equation in this guide should be the value applicable at the stroke position being evaluated.	---
F_s'	Actual spring preload (lb or N)	S_P
K_s	Spring constant (lb/in or N/m)	S_R
L_V	Valve stroke length (in or m)	L
N_{piston}	Number of pistons in rack and pinion actuator	N_{piston}
P_A'	Actual air pressure (psig or Pa)	P_A

Variable	Definition	Ref (1) Equiv.[1]
P_{ATM}	Pressure of the surroundings where cylinder pressure is exhausted during design basis conditions. This parameter will normally be 0 psig or 0 Pa gage; however, if a valve is in an area where the pressure may be elevated when the valve strokes, P_{ATM} may be greater than zero.	---
U_{AAIR}	Random uncertainty for A_{AIR} (%)	---
U_{FD}	Random uncertainty for F_D (%)	---
$U_{FS'}$	Random uncertainty for F_S' (%)	---
$U_{FS'\text{-}bias}$	Bias uncertainty for F_S' (%)	---
U_{KS}	Random uncertainty for K_S (%)	---
U_{η}	Random uncertainty for actuator efficiency, η (%)	---
$U_{PA'}$	Random uncertainty for P_A' (%)	---
$U_{PA'\text{-}bias}$	Bias uncertainty for P_A' (%)	---
U_{LV}	Random uncertainty for L_V (%)	---

Note (1): This column lists the symbol used for this term in Section 7 of Reference (1), if applicable.

Calculated Values

Variable	Definition
F_{SMAX}	Maximum allowable spring preload (lb or N)
F_{SMIN}	Minimum allowable spring preload (lb or N)
M_{OA}	Margin for air stroke operation (%)
M_{OS}	Margin for spring stroke operation (%)
M_{SM}	Structural margin (%)
M_{SO}	Margin for overstressing the spring (%)
P_{AMAX}	Maximum allowable air pressure (psig or Pa)
P_{AMIN}	Minimum allowable air pressure (psig or Pa)
U_{OA}	Total uncertainty for air stroke operation (%)
U_{OS}	Total uncertainty for spring stroke operation (%)
U_{SMA}	Total uncertainty for actuator structural margin (%)
U_{SMV}	Total uncertainty for valve structural margin (%)
U_{SO}	Total uncertainty for overstressing the spring (%)

Other Variables

Variable	Definition
θ	Angular position of yoke (-45° $\leq \theta \leq$ 45°), moment arm (-45° $\leq \theta \leq$ 45°), or pinion gear (0° $\leq \theta \leq$ 90°) (degrees). θ equals -45° (for scotch yoke and rotary) or 0° (for rack and pinion) at the beginning of the air stroke (when the spring is fully extended).
A_{AIR}	Generic term for the area on which the air pressure acts to drive the air stroke (in^2 or m^2). A_{AIR} may vary with stroke position. The value of A_{AIR} used in any equation in this guide should be the value applicable at the stroke position being evaluated.
B	Spring force multiplier (set to 1 if there is a spring in the actuator and 0 if there is no spring)
C	Coefficient for air assistance term (set to 1 if the spring stroke is air-assisted and 0 if it is not)
F_{AIR}:	Maximum actuator thrust (lb or N)
F_s	Generic term for spring preload (lb or N)
G	Spring travel multiplier
M	Generic term for moment arm length multiplied by actuator efficiency (in or m)
P_A	Generic term for available air pressure (psig or Pa)
S_{AIR}	Generic term for spring compression for the air stroke (in or m)
S_{MAX}	Maximum spring compression (in or m)
S_{SPR}	Generic term for spring compression for the spring stroke (in or m)
T_{AIR}	Generic term for actuator air stroke capability (lb or in-lbs, or N or N-m)
T_{SPR}	Generic term for actuator spring stroke capability (lb or in-lbs, or N or N-m)
x_{EXT}	Stroke position for the extension stroke (x_{EXT} = 0 at the beginning of the extension stroke; x_{EXT} = L_v at the end of the extension stroke) (in or m)
x_{RET}	Stroke position for the retraction stroke (x_{RET} = 0 at the beginning of the retraction stroke; x_{RET} = L_v at the end of the retraction stroke) (in or m)

Table 1-1
Actuator Stroke Cross-Reference

Actuator Type	Extension Stroke	Retraction Stroke
Double acting air cylinder (single and double ended)	Air stroke	Air stroke
Double acting air cylinder with spring return (direct acting)	Air stroke	Spring stroke
Double acting air cylinder with spring return (reverse acting)	Spring stroke	Air stroke
Single acting air cylinder with spring return (direct acting)	Air stroke	Spring stroke
Single acting air cylinder with spring return (reverse acting)	Spring stroke	Air stroke
Single acting diaphragm with spring return (direct acting)	Air stroke	Spring stroke
Single acting diaphragm with spring return (reverse acting)	Spring stroke	Air stroke
Single acting diaphragm with spring return and increased mechanical advantage (direct acting)	Air stroke	Spring stroke
Single acting diaphragm with spring return and increased mechanical advantage (reverse acting)	Spring stroke	Air stroke
Double acting scotch yoke air cylinder	Air stroke	Air stroke
Single acting scotch yoke air cylinder with spring return	Air stroke	Spring stroke
Rotary diaphragm with spring return	Air stroke	Spring stroke
Double acting rack and pinion air cylinder	Air stroke	Air stroke
Single acting rack and pinion air cylinder with spring return	Air stroke	Spring stroke

2 OVERVIEW OF AOV SETUP GUIDE

AOVs in nuclear power plants are designed and set up to ensure proper operation under design basis conditions. To ensure that proper AOV setup is maintained, air pressure and spring preload (for spring return actuators) need to be controlled. The allowable limits should be based on the functional requirements of the AOV. For example, the air pressure should be high enough to assure proper operation for the air stroke but not so high that the valve or actuator may be damaged. For spring return actuators, the spring preload should be high enough to assure proper operation for the spring stroke but not so high that the spring is overstressed or margin for the air stroke is insufficient.

This Setup Guide provides equations for calculating the allowable setup parameters for AOVs. In addition, equations for calculating margin and methods for combining uncertainties are provided. The sections below provide an overview of the Setup Guide.

Allowable Setup Parameters

Four allowable setup parameters are calculated -- minimum and maximum allowable air pressure (applicable to all AOVs) and minimum and maximum allowable spring preload (applicable to spring return actuators).

The following generic equations for actuator capability are derived (see Section 1 for variable definitions). These equations can be applied to any of the actuator types covered by this guide using the cross-reference information in Table 3-1 and Table 3-2. Key terms in the equations are numbered and described below the equation.

(Air stroke)

$$T_{AIR} = \Big[\underbrace{A_{AIR} \cdot (P_A - P_{ATM})}_{①} - \underbrace{B \cdot (F_S + S_{AIR} K_S)}_{②} - \underbrace{F_D}_{③}\Big] \cdot \underbrace{M}_{④} \cdot \underbrace{E}_{⑤}$$

Equation 2-1

Key terms

1. Air pressure force (driving force for stroke)

2. Spring force (resistive force; B is set to zero for actuators with no spring)

3. Actuator friction force (resistive force)

4. Moment arm term (for quarter turn actuators; set to 1 for rising stem actuators)

5. Mechanical advantage (set to 1 if actuator has no mechanical advantage)

(Spring stroke)
$$T_{SPR} = \Big[\underbrace{C \cdot A_{AIR} \cdot \left(P_A - P_{ATM}\right)}_{①} + \underbrace{B \cdot \left[F_S + S_{SPR} K_S\right]}_{②} - \underbrace{F_D}_{③}\Big] \cdot \underbrace{M}_{④} \cdot \underbrace{E}_{⑤}$$
Equation 2-2

Key terms

1. Air pressure force (C=0 if spring stroke is not air-assisted)

2. Spring force (driving force for stroke)

3. Actuator friction force (resistive force)

4. Moment arm term (for quarter turn actuators; set to 1 for rising stem actuators)

5. Mechanical advantage (set to 1 if actuator has no mechanical advantage)

The allowable setup parameters are determined as follows.

- *Minimum allowable air pressure* -- Assures margin for operation for the air stroke. Calculated by setting the actuator capability for the air stroke equal to the required thrust or torque for the air stroke and solving for P_A. For double acting actuators with spring return, a second air pressure limit is calculated by setting the actuator capability for the spring stroke equal to the required thrust or torque for the spring stroke and solving for P_A. This limit assures margin for operation for the spring stroke.

- *Maximum allowable air pressure* -- Assures structural limits for the valve and actuator are not exceeded. Calculated as the lesser of the limit based on maximum allowable valve thrust or torque (T_{MAVT}) and the limit based on maximum allowable actuator thrust (F_{MAAT}). The limit based on T_{MAVT} is calculated by setting the actuator capability for the air stroke (T_{AIR}) equal to T_{MAVT} and solving for P_A. The limit based on F_{MAAT} is calculated by setting T_{AIR} to F_{MAAT} while setting the spring load and atmospheric pressure to zero and solving for P_A. For double acting actuators with spring return, a second air pressure limit based on T_{MAVT} is calculated by setting the actuator capability for the spring stroke equal to T_{MAVT} and solving for P_A.

- *Minimum allowable spring preload* -- Assures margin for operation for the spring stroke and prevents the valve from being overloaded. The limit based on spring stroke operation is calculated by setting the actuator capability for the spring stroke equal to the required thrust or torque for the spring stroke and solving for F_S. The limit based on the valve structural limit is calculated by setting the actuator capability for the air stroke equal to the maximum allowable valve thrust and solving for F_S.

- *Maximum allowable spring preload* -- Assures margin for operation for the air stroke and prevents the spring from being overstressed. Calculated as the lesser of the limit based on the required thrust or torque for the air stroke (T_{RAIR}) and the limit based on the maximum safe spring load (F_{MSSL}). The limit based on T_{RAIR} is calculated by setting the actuator capability for the air stroke equal to T_{RAIR} and solving for F_S. The limit based on F_{MSSL} is calculated by setting the maximum spring load equal to F_{MSSL} and solving for F_S.

Margins

Margins are calculated by comparing thrust or torque limits to actual values. Four margins are calculated, as described below.

- The *margin for operation for the air stroke* compares the actuator capability with the required thrust or torque for the air stroke.
- The *margin for operation for the spring stroke* compares the actuator capability with the required thrust or torque for the spring stroke.
- The *margin for overstressing the spring* compares the maximum safe spring load with the maximum spring load.
- The *structural margin* is the lesser of the margin for overstressing the valve and the margin for overstressing the actuator. The margin for overstressing the valve compares the maximum allowable valve thrust or torque with the maximum thrust or torque for the air stroke (the spring stroke is used for double acting air cylinders with spring return). The margin for overstressing the actuator compares the maximum allowable actuator thrust with the maximum thrust for the air stroke.

Incorporating Uncertainties

In the implementation of the margin and setup equations in this guide, there may be uncertainties related to the values used for some of the inputs. To assure conservative values are obtained, the calculated margins and setup parameters must be adjusted for these uncertainties. The margin and setup equations in this guide include five different total uncertainty terms, as follows.

- U_{OA}: Uncertainty for air stroke operation (%), equal to the uncertainty on the actuator capability for the air stroke
- U_{OS}: Uncertainty for spring stroke operation (%), equal to the uncertainty on the actuator capability for the spring stroke
- U_{SMA}: Uncertainty for actuator structural margin (%), equal to the uncertainty on the maximum actuator thrust
- U_{SMV}: Uncertainty for valve structural margin (%), equal to the uncertainty on the maximum thrust or torque applied to the valve
- U_{SO}: Uncertainty for overstressing the spring (%), equal to the uncertainty on the maximum spring load

These terms represent total *combined* uncertainties and include uncertainties from specific parameters used in the calculations. For example, U_{OA} includes uncertainties related to the pressure area, A_{AIR}, and the actual available air pressure, P_A', since these parameters are used to calculate the actuator capability for the air stroke.

In this guide, nine input parameter uncertainties are considered, as listed below. These uncertainties may cover potential inaccuracies in design values for these parameters (e.g., values obtained from the vendor) or in measured values (e.g., based on the accuracy of the diagnostic equipment used). The bias uncertainties may cover potential degradation.

- U_{AAIR}: Random uncertainty for actuator effective area (A_{AIR})%
- U_{FD}: Random uncertainty for actuator friction force (F_D)%
- $U_{FS'}$: Random uncertainty for actual spring preload (F_S')%
- U_{KS}: Random uncertainty for spring constant (K_S)%
- U_η: Random uncertainty for actuator efficiency (η)%
- $U_{PA'}$: Random uncertainty for actual air pressure (P_A')%
- U_{LV}: Random uncertainty for valve stroke length (L_V)%
- $U_{FS'\text{-bias}}$: Bias uncertainty for actual spring preload (F_S')%
- $U_{PA'\text{-bias}}$: Bias uncertainty for actual air pressure (P_A')%

Since these parameter uncertainties are expressed as a percentage of the parameter, and the units for each parameter are different, they cannot be combined directly to calculate the total combined uncertainty. Each parameter uncertainty (in %) must be converted to an uncertainty in pounds or inch-pounds. The parameter uncertainties are then combined using square-root-sum-of-the-squares to obtain total combined uncertainties in lbs or in-lbs (or N or N-m), which are converted to total combined uncertainties that can be used in the margin and setup parameter equations.

Use of this Guide to Evaluate AOVs

The actuator types covered by this guide can be separated into three groups, as described below.

Double Acting Actuators (without Spring Return)

The following actuator types are in this group.

- Double acting air cylinder (single and double ended)
- Double acting scotch yoke air cylinder
- Double acting rack and pinion air cylinder

For these actuators, both the extension and retraction strokes are air strokes. The following setup parameters and margins should be calculated for these actuators.

- Minimum allowable air pressure, per Equation 3-1 (should be implemented twice -- once for the extension stroke and once for the retraction stroke).
- Maximum allowable air pressure, per Equation 3-2 and Equation 3-3 (should be implemented twice -- once for the extension stroke and once for the retraction stroke).
- Margin for operation for the air stroke, per Equation 4-1 (should be implemented twice -- once for the extension stroke and once for the retraction stroke).
- Structural margin, per Equation 4-4 and Equation 4-6 (should be implemented twice -- once for the extension stroke and once for the retraction stroke).

Single Acting Actuators with Spring Return

The following actuator types are in this group.

- Single acting air cylinder with spring return (direct and reverse acting)
- Single acting diaphragm with spring return (direct and reverse acting)
- Single acting diaphragm with spring return and increased mechanical advantage (direct and reverse acting)
- Single acting scotch yoke air cylinder with spring return
- Rotary diaphragm with spring return
- Single acting rack and pinion air cylinder with spring return

The following setup parameters and margins should be calculated for these actuators.

- Minimum allowable air pressure, per Equation 3-1.
- Maximum allowable air pressure, per Equation 3-3 and Equation 3-3.
- Minimum allowable spring preload, per Equation 3-4 and Equation 3-5.
- Maximum allowable spring preload, per Equation 3-6 and Equation 3-7.
- Margin for operation for the air stroke, per Equation 4-1.
- Margin for operation for the spring stroke, per Equation 4-2.
- Margin for overstressing the spring, per Equation 4-3.
- Structural margin, per Equation 4-4 and Equation 4-6.

Double Acting Actuators with Spring Return

The double acting air cylinder with spring return (direct and reverse acting) is in this group. The following setup parameters and margins should be calculated for these actuators.

- Minimum allowable air pressure, per Equation 3-1 and Equation 3-8.
- Maximum allowable air pressure, per Equation 3-3 and Equation 3-9.

- Minimum allowable spring preload, per Equation 3-4 and Equation 3-5.
- Maximum allowable spring preload, per Equation 3-6 and Equation 3-7.
- Margin for operation for the air stroke, per Equation 4-1.
- Margin for operation for the spring stroke, per Equation 4-2.
- Margin for overstressing the spring, per Equation 4-3.
- Structural margin, per Equation 4-5 and Equation 4-6.

3

DETERMINING ALLOWABLE SETUP PARAMETERS

This section provides equations for calculating allowable setup parameters for AOVs. As with Equations 2-1 and 2-2, the equations in this section are generic and can be applied to any actuator covered by this guide, using the cross-reference information in Table 3-1 and Table 3-2.

Minimum and maximum allowable air pressure should be calculated for all AOVs. Minimum and maximum allowable spring preload should be calculated for AOVs with spring return actuators. For double acting, rising stem actuators with spring return, additional equations are required for minimum and maximum allowable air pressure because both the extension and retraction strokes use air to stroke the valve.

Minimum Allowable Air Pressure

The minimum allowable air pressure assures margin for operation for the air stroke. P_{AMIN} is calculated using the equation below.

$$P_{AMIN} = P_{ATM} + \frac{\frac{T_{RAIR}}{M \cdot E}(1 + U_{OA}) + F_D + B \cdot \left(F_S + S_{AIR} K_S\right)}{A_{AIR}}$$

Equation 3-1

P_{AMIN} should be evaluated at the stroke position with minimum margin for operation for the air stroke. Equation 4-1 and Equation 5-1 can be used to determine this stroke position. For rising stem actuators, the minimum margin typically occurs at the beginning of the stroke ($S_{AIR} = 0$) or the end of the stroke ($S_{AIR} = L_V$). For these actuators, the user should implement Equation 4-1 and Equation 5-1 at the beginning and end of the air stroke to determine the stroke position with minimum margin. For rotary actuators, the minimum margin may occur at a mid-stroke position. For these actuators, the user should implement Equation 4-1 and Equation 5-1 for the entire valve stroke (e.g., in 1° or 2° disk angle increments) to determine the stroke position with minimum margin.

For double acting actuators with no spring, Equation 3-1 should be implemented twice -- once for each stroke direction since both strokes are "air" strokes.

Maximum Allowable Air Pressure

The maximum allowable air pressure assures structural limits for the valve and actuator are not exceeded. P_{AMAX} is the lesser of the values calculated using the equations below.

$$P_{AMAX} = P_{ATM} + \frac{\frac{T_{MAVT}}{M \cdot E}(1 - U_{SMV}) + F_D + B \cdot \left(F_S + S_{AIR} K_S\right)}{A_{AIR}}$$ **Equation 3-2**

$$P_{AMAX} = \frac{F_{MAAT}(1 - U_{SMA})}{A_{AIR}}$$ **Equation 3-3**

These equations should be evaluated at the end of the air stroke only ($S_{AIR} = L_V$).

Minimum Allowable Spring Preload (Spring Return Actuators Only)

The minimum allowable spring preload assures margin for operation for the spring stroke and prevents the valve from being overloaded during the air stroke. F_{SMIN} is the greater of the values calculated using the equations below.

$$F_{SMIN} = \frac{T_{RSPR}}{M \cdot E}(1 + U_{OS}) - S_{SPR} K_S + F_D - C \cdot A_{AIR} \cdot \left(P_A - P_{ATM}\right)$$ **Equation 3-4**

$$F_{SMIN} = A_{AIR}\left(P_A - P_{ATM}\right) - F_D - \frac{T_{MAVT}}{M \cdot E}(1 - U_{SMV}) - S_{AIR} K_S$$ **Equation 3-5**

Equation 3-4 should be evaluated at the stroke position with minimum margin for operation for the spring stroke. Equation 4-2 and Equation 5-3 can be used to determine this stroke position. For rising stem actuators, the minimum margin typically occurs at the beginning of the spring stroke ($S_{SPR} = L_V$) or the end of the spring stroke ($S_{SPR} = 0$). For these actuators, the user should implement Equation 4-2 and Equation 5-3 at the beginning and end of the spring stroke to determine the stroke position with minimum margin. For rotary actuators, the minimum margin may occur at a mid-stroke position. For these actuators, the user should implement Equation 4-2 and Equation 5-3 for the entire valve stroke (e.g., in 1° or 2° disk angle increments) to determine the stroke position with minimum margin.

Equation 3-5 should only be evaluated at the end of the air stroke ($S_{AIR}=L_V$). F_{SMIN} is not applicable for actuators without springs.

Maximum Allowable Spring Preload (Spring Return Actuators Only)

The maximum allowable spring preload assures margin for operation for the air stroke and prevents the spring from being overstressed. F_{SMAX} is the lesser of the values calculated using the equations below.

$$F_{SMAX} = A_{AIR}\left(P_A - P_{ATM}\right) - F_D - \frac{T_{RAIR}}{M \cdot E}(1 + U_{OA}) - S_{AIR}K_S$$ **Equation 3-6**

$$F_{SMAX} = F_{MSSL}(1 - U_{SO}) - S_{max}K_S$$ **Equation 3-7**

Equation 3-6 should be evaluated at the stroke position with minimum margin for operation for the air stroke. See the section titled Minimum Allowable Air Pressure for a discussion of how to determine this stroke position. F_{SMAX} is not applicable for actuators without springs.

Additional Equations for Double Acting Cylinders with Spring Return

For double acting cylinders with spring return (rising stem only), two additional equations are needed. The equations are needed because air pressure is used to stroke the valve in both directions (i.e., the air stroke and the spring stroke). Therefore, both stroke directions need to be considered when calculating air pressure limits.

The following equation should be included in the evaluation of the minimum allowable air pressure for the spring stroke.

$$P_{AMIN} = P_{ATM} + \frac{\frac{T_{RSPR}}{M \cdot E}\left(1 + U_{OS}\right) + F_D - B \cdot \left(F_S + S_{SPR}K_S\right)}{A_{AIR}}$$ **Equation 3-8**

P_{AMIN} is the lesser of the value calculated above and the value calculated from Equation 3-1. Equation 3-8 should be evaluated at the stroke position with minimum margin for operation for the spring stroke. See the section titled Minimum Allowable Spring Preload (Spring Return Actuators Only) for a discussion of how to determine this stroke position.

The following equation should be included in the evaluation of the maximum allowable air pressure for the spring stroke based on maximum allowable valve thrust.

$$P_{AMAX} = P_{ATM} + \frac{\frac{T_{MAVT}}{M \cdot E}\left(1 - U_{SMV}\right) + F_D - B \cdot \left(F_S + S_{SPR}K_S\right)}{A_{AIR}}$$ **Equation 3-9**

Equation 3-9 replaces Equation 3-2 and should be evaluated at the end of the spring stroke only ($S_{SPR} = 0$).

Table 3-1
Cross Reference for Rising Stem Actuators

Actuator	A_{AIR}	B	C	E	S_{AIR}	S_{SPR}
Double acting air cylinder - single ended[3] (air/extension stroke)	$\frac{\pi}{4}D^2$	0	--	1	--	--
Double acting air cylinder - single ended[3] (air/retraction stroke)	$\frac{\pi}{4}(D^2-d^2)$	0	--	1	--	--
Double acting air cylinder - double ended[3] (air/extension stroke)	$\frac{\pi}{4}(D^2-d^2)$	0	--	1	--	--
Double acting air cylinder - double ended[3] (air/retraction stroke)	$\frac{\pi}{4}(D^2-d^2)$	0	--	1	--	--
Double acting air cylinder w/ spring return (direct acting, air/extension stroke)	$\frac{\pi}{4}D^2$	1	--	1	x_{EXT}	--
Double acting air cylinder w/ spring return (direct acting, spring retraction stroke)	$\frac{\pi}{4}(D^2-d^2)$	1	1	1	--	L_V - x_{RET}
Double acting air cylinder w/ spring return (reverse acting, spring extension stroke)	$\frac{\pi}{4}D^2$	1	1	1	--	$L_V - x_{EXT}$
Double acting air cylinder w/ spring return (reverse acting, air/retraction stroke)	$\frac{\pi}{4}(D^2-d^2)$	1	--	1	x_{RET}	--
Single acting air cylinder w/spring return (direct acting)	$\frac{\pi}{4}D^2$	1	0	1	x_{EXT}	L_V - x_{RET}
Single acting air cylinder w/spring return (reverse acting)	$\frac{\pi}{4}(D^2-d^2)$	1	0	1	x_{RET}	L_V - x_{EXT}
Single acting diaphragm w/ spring return (direct acting)	A_{CAP}	1	0	1	x_{EXT}	L_V - x_{RET}
Single acting diaphragm w/ spring return (reverse acting)	A_{ROD}	1	0	1	x_{RET}	L_V - x_{EXT}
Single acting diaphragm w/ spring return and increased mechanical advantage (direct acting)	A_{CAP}	1	0	Note (1)	x_{EXT}	L_V - x_{RET}
Single acting diaphragm w/ spring return and increased mechanical advantage (reverse acting)	A_{ROD}	1	0	Note (1)	x_{RET}	L_V - x_{EXT}

Note (1): Mechanical advantage coefficient from vendor.
Note (2): For rising stem valves M is equal to 1.
Note (3): For double acting actuators without springs, both extension and retraction strokes are considered air strokes.
Note (4): For all rising stem valves S_{max} equals L_V.

Table 3-2
Cross Reference for Quarter Turn Actuators

Actuator	A_{AIR}	B	C	S_{AIR} and S_{SPR} (2)	M(2)	S_{max}
Double acting scotch yoke air cylinder (extension stroke)	$\frac{\pi}{4}D^2$	0	--	--	$\eta \cdot \frac{c}{\cos^2\theta}$	--
Double acting scotch yoke air cylinder (retraction stroke)	$\frac{\pi}{4}(D^2 - d^2)$	0	--	--	$\eta \cdot \frac{c}{\cos^2\theta}$	--
Single acting scotch yoke air cylinder w/spring return (direct acting)	$\frac{\pi}{4}D^2$	1	0	c (1+tanθ)	$\eta \cdot \frac{c}{\cos^2\theta}$	2c
Rotary diaphragm w/ spring return (direct acting)	A_{CAP}	1	0	$\frac{\sqrt{2}}{2}$ b (1+tanθ)	$\eta \times b \cos\theta$	$\sqrt{2}$ b
Rotary diaphragm w/ spring return (reverse acting)	A_{ROD}	1	0	$\frac{\sqrt{2}}{2}$ b (1+tanθ)	$\eta \times b \cos\theta$	$\sqrt{2}$ b
Double acting rack and pinion air cylinder (extension stroke)	$\frac{\pi}{4}D^2$	0	--	--	$\eta \times N_{piston} \times \frac{D_{PG}}{2}$	--
Double acting rack and pinion air cylinder (retraction stroke)	$\frac{\pi}{4}D^2$	0	--	--	$\eta \times N_{piston} \times \frac{D_{PG}}{2}$	--
Single acting rack and pinion air cylinder w/ spring return	$\frac{\pi}{4}D^2$	1	0	$\frac{\theta}{90} \times \frac{\pi}{4} D_{PG}$	$\eta \times N_{piston} \times \frac{D_{PG}}{2}$	$\frac{\pi}{4}D_{PG}$

Note (1): Set E to 1 for all quarter turn actuators.

Note (2): For scotch yoke and rotary diaphragm, -45° ≤ θ ≤ 45°. For rack and pinion actuators, 0° ≤ θ ≤ 90°.

4
CALCULATING MARGINS

This section provides equations for calculating AOV margins. Four margins are calculated.

Margin for Operation for Air Stroke

The margin for operation for the air stroke compares the actuator capability and the required thrust or torque for the air stroke. The equation is shown below.

$$M_{OA} = \frac{T_{AIR} - T_{RAIR}(1 + U_{OA})}{T_{RAIR}(1 + U_{OA})} \times 100$$ **Equation 4-1**

T_{AIR} should be calculated using the actual spring preload and air pressure (i.e., F_S' as F_S and P_A' as P_A) in Equation 2-1. M_{OA} can be calculated at any stroke position of the air stroke. For rising stem actuators, the minimum margin typically occurs at the beginning of the air stroke ($S_{AIR} = 0$) or the end of the air stroke ($S_{AIR} = L_V$). The user should evaluate both of these stroke positions to determine the stroke position with minimum margin. For rotary actuators, the minimum margin may occur at a mid-stroke position. For these actuators, the user should evaluate the entire valve stroke (e.g., in 1° or 2° disk angle increments) to determine the stroke position with minimum margin.

For double acting actuators with no spring, Equation 4-1 should be implemented twice -- once for each stroke direction since both strokes are "air" strokes.

Margin for Operation for Spring Stroke (Spring Return Actuators Only)

The margin for operation for the spring stroke compares the actuator capability and the required thrust or torque for the spring stroke. The equation is shown below.

$$M_{OS} = \frac{T_{SPR} - T_{RSPR}(1 + U_{OS})}{T_{RSPR}(1 + U_{OS})} \times 100$$ **Equation 4-2**

T_{SPR} should be calculated using the actual spring preload and air pressure (i.e., F_S' as F_S and P_A' as P_A) in Equation 2-2. M_{OS} can be calculated at any stroke position of the spring stroke. For rising stem actuators, the minimum margin typically occurs at the beginning of the spring stroke ($S_{SPR} = L_V$) or the end of the spring stroke ($S_{SPR} = 0$). The user should evaluate both of these stroke positions to determine the stroke position with minimum margin. For rotary actuators, the minimum margin may occur at a mid-stroke position. For these actuators, the user should evaluate the entire valve stroke (e.g., in 1° or 2° disk angle increments) to determine the stroke position with minimum margin.

Margin for Overstressing the Spring (Spring Return Actuators Only)

The margin for overstressing the spring compares the maximum safe spring load (F_{MSSL}) and the maximum spring load. The equation is shown below. This equation is not stroke position-dependent.

$$M_{SO} = \frac{F_{MSSL}(1 - U_{SO}) - F_S' - S_{max} K_S}{F_{MSSL}(1 - U_{SO})} \times 100 \qquad \textbf{Equation 4-3}$$

Structural Margin

The structural margin is the lesser of the margin for overstressing the valve and the margin for overstressing the actuator.

Margin for overstressing the valve

The margin for overstressing the valve compares the maximum allowable valve thrust or torque (T_{MAVT}) and the maximum thrust or torque for the air stroke. The equation is shown below.

$$M_{SM} = \frac{T_{MAVT}(1 - U_{SMV}) - T_{AIR}}{T_{MAVT}(1 - U_{SMV})} \times 100 \qquad \textbf{Equation 4-4}$$

T_{AIR} should be calculated using the actual spring preload and air pressure (i.e., F_S' as F_S and P_A' as P_A) in Equation 2-1. Equation 4-4 should be evaluated at the end of the air stroke ($S_{AIR} = L_V$).

For double acting actuators with spring return, margin for overstressing the valve is calculated using the following equation.

$$M_{SM} = \frac{T_{MAVT}(1 - U_{SMV}) - T_{SPR}}{T_{MAVT}(1 - U_{SMV})} \times 100 \qquad \textbf{Equation 4-5}$$

T_{AIR} should be calculated using the actual spring preload and air pressure (i.e., F_S' as F_S and P_A' as P_A) in Equation 2-2. Equation 4-5 should be evaluated at the end of the spring stroke only ($S_{SPR} = 0$).

Margin for overstressing the actuator

The margin for overstressing the actuator compares the maximum allowable actuator thrust (F_{MAAT}) and the maximum thrust or torque for the air stroke. The equation is shown below.

$$M_{SM} = \frac{F_{MAAT}(1 - U_{SMA}) - A_{AIR}P_A'}{F_{MAAT}(1 - U_{SMA})} \times 100$$ **Equation 4-6**

Equation 4-6 should be evaluated at the end of the air stroke only ($S_{AIR} = L_V$).

For double acting actuators with no spring, these equations should be implemented twice -- once for each stroke direction since both strokes are "air" strokes.

5

INCORPORATING UNCERTAINTIES

This section provides equations for combining uncertainties related to AOV setup and applying the combined uncertainties in the equations for allowable setup parameters and margins.

The equations for setup parameters in Section 3 and margins in Section 4 include the following five terms for total combined uncertainty.

- U_{OA}: Uncertainty for air stroke operation (%)
- U_{OS}: Uncertainty for spring stroke operation (%)
- U_{SMA}: Uncertainty for actuator structural margin (%)
- U_{SMV}: Uncertainty for valve structural margin (%)
- U_{SO}: Uncertainty for overstressing the spring (%)

When using these equations to calculate uncertainties for use in an allowable setup parameter or margin equation, the uncertainty equation must be evaluated at the same stroke position at which the allowable setup parameter or margin equation is evaluated.

Uncertainty for Air Stroke Operation (U_{OA})

U_{OA} is calculated using the equations below. T_{AIR} should be calculated using the actual spring preload and air pressure (i.e., F_S' as F_S and P_A' as P_A) in Equation 2-1.

$$U_{OA} = \frac{U_{TOT\_OA}}{T_{AIR} - U_{TOT\_OA}}$$ **Equation 5-1**

$$U_{TOT\_OA} = (U_{PA'\text{-}bias} \cdot A_{AIR} \cdot P_A' \cdot M \cdot E) + \sqrt{\begin{aligned}&(U_{AAIR} \cdot (P_A' - P_{ATM}) \cdot A_{AIR} \cdot M \cdot E)^2 \\ &+ (U_{PA'} \cdot A_{AIR} \cdot P_A' \cdot M \cdot E)^2 \\ &+ (U_{FS'} \cdot (-B) \cdot F_S' \cdot M \cdot E)^2 \\ &+ (U_{FD} \cdot (-F_D) \cdot M \cdot E)^2 \\ &+ (U_{LV} \cdot (-B) \cdot K_S \cdot S_{AIR} \cdot M \cdot E)^2 \\ &+ (U_{KS} \cdot (-B) \cdot S_{AIR} \cdot K_S \cdot M \cdot E)^2 \\ &+ (U_\eta \cdot [A_{AIR} \cdot (P_A' - P_{ATM}) - B \cdot (F_S' + S_{AIR} \cdot K_S) - F_D] \cdot M \cdot E)^2\end{aligned}}$$ **Equation 5-2**

Note that potential degradation in the spring preload would decrease U_{TOT_OA}; therefore, $U_{FS'\text{-}bias}$ is not included in Equation 5-2. U_{OA} is used in calculating margin for air stroke operation

(Equation 4-1), minimum allowable air pressure (Equation 3-1) and maximum allowable spring preload (Equation 3-6).

Uncertainty for Spring Stroke Operation (U_{OS})

U_{OS} is calculated using the equations below. T_{SPR} should be calculated using the actual spring preload and air pressure (i.e., F_S' as F_S and P_A' as P_A) in Equation 2-2.

$$U_{OS} = \frac{U_{TOT\_OS}}{T_{SPR} - U_{TOT\_OS}} \quad \textbf{Equation 5-3}$$

$$U_{TOT\_OS} = \begin{bmatrix} (U_{PA'\text{-bias}} \cdot C \cdot A_{AIR} \cdot P_A' \cdot M \cdot E) \\ + (U_{FS'\text{-bias}} \cdot B \cdot F_S' \cdot M \cdot E) \end{bmatrix} + \sqrt{\begin{matrix} (U_{AAIR} \cdot C \cdot (P_A' - P_{ATM}) \cdot A_{AIR} \cdot M \cdot E)^2 \\ + (U_{PA'} \cdot C \cdot A_{AIR} \cdot P_A' \cdot M \cdot E)^2 \\ + (U_{FS'} \cdot B \cdot F_S' \cdot M \cdot E)^2 \\ + (U_{FD} \cdot (-F_D) \cdot M \cdot E)^2 \\ + (U_{LV} \cdot B \cdot K_S \cdot S_{SPR} \cdot M \cdot E)^2 \\ + (U_{KS} \cdot B \cdot S_{SPR} \cdot K_S \cdot M \cdot E)^2 \\ + (U_{\eta} \cdot [C \cdot A_{AIR} \cdot (P_A' - P_{ATM}) + B \cdot (F_S' + S_{SPR} \cdot K_S) - F_D] \cdot M \cdot E)^2 \end{matrix}} \quad \textbf{Equation 5-4}$$

U_{OS} is used in calculating margin for spring stroke operation (Equation 4-2) and minimum allowable spring preload (Equation 3-4). For double acting actuators with spring return, U_{OS} is also used in calculating minimum allowable air pressure for the spring stroke (Equation 3-8).

Uncertainty for Overstressing the Spring (U_{SO})

U_{SO} is calculated using the equations below.

$$U_{SO} = \frac{U_{TOT\_SO}}{U_{TOT\_SO} + (F_S' + S_{max} K_S)} \quad \textbf{Equation 5-5}$$

$$U_{TOT\_SO} = (U_{FS'-bias} \cdot F_S') + \sqrt{\begin{matrix} (U_{FS'} \cdot F_S')^2 \\ + (U_{LV} \cdot K_S \cdot S_{MAX})^2 \\ + (U_{KS} \cdot S_{MAX} \cdot K_S)^2 \end{matrix}} \quad \textbf{Equation 5-6}$$

U_{SO} is used in calculating margin for overstressing the spring (Equation 4-3) and maximum allowable spring preload (Equation 3-7).

Uncertainty for Valve Structural Margin (U_{SMV})

U_{SMV} is calculated using the equations below.

$$U_{SMV} = \frac{U_{TOT\_SMV}}{U_{TOT\_SMV} + T_{AIR}}$$ **Equation 5-7**

$$U_{TOT\_SMV} = \left(U_{PA'\text{-bias}} \cdot A_{AIR} \cdot P_A' \cdot M \cdot E\right) + \sqrt{\begin{array}{l} \left(U_{AAIR} \cdot (P_A' - P_{ATM}) \cdot A_{AIR} \cdot M \cdot E\right)^2 \\ + \left(U_{PA'} \cdot A_{AIR} \cdot P_A' \cdot M \cdot E\right)^2 \\ + \left(U_{FS'} \cdot (-B) \cdot F_S' \cdot M \cdot E\right)^2 \\ + \left(U_{FD} \cdot (-F_D) \cdot M \cdot E\right)^2 \\ + \left(U_{LV} \cdot (-B) \cdot K_S \cdot S_{AIR} \cdot M \cdot E\right)^2 \\ + \left(U_{KS} \cdot (-B) \cdot S_{AIR} \cdot K_S \cdot M \cdot E\right)^2 \\ + \left(U_{\eta} \cdot [A_{AIR} \cdot (P_A' - P_{ATM}) - B \cdot (F_S' + S_{AIR} \cdot K_S) - F_D] \cdot M \cdot E\right)^2 \end{array}}$$ **Equation 5-8**

Note that potential degradation in the spring preload would decrease U_{TOT_SMV}; therefore, $U_{FS'\text{-bias}}$ is not included in Equation 5-8. U_{SMV} is used in calculating margin for overstressing the valve (Equation 4-4), maximum allowable air pressure (Equation 3-2) and minimum allowable spring preload (Equation 3-5).

U_{SMV} is also used for double acting actuators with spring return in calculating margin for overstressing the valve for the spring stroke (Equation 4-5) and maximum allowable air pressure for the spring stroke (Equation 3-9). For these actuators, U_{SMV} should be calculated using Equation 5-8 (with S_{SPR} substituted for S_{AIR}) and the equation below.

$$U_{SMV} = \frac{U_{TOT\_SMV}}{U_{TOT\_SMV} + T_{SPR}}$$ **Equation 5-9**

Note that Equation 5-8 (for U_{TOT_SMV}) is identical to Equation 5-2 (for U_{TOT_OA}). The difference is the stroke positions at which these equations are evaluated.

Uncertainty for Actuator Structural Margin (U_{SMA})

U_{SMA} is calculated using the equations below.

$$U_{SMA} = \frac{U_{TOT\_SMA}}{U_{TOT\_SMA} + A_{AIR} \cdot P_A'}$$ **Equation 5-10**

$$U_{TOT\_SMA} = \left(U_{PA'\text{-bias}} \cdot A_{AIR} \cdot P_A'\right) + \sqrt{\begin{array}{l} \left(U_{AAIR} \cdot P_A' \cdot A_{AIR}\right)^2 \\ + \left(U_{PA'} \cdot A_{AIR} \cdot P_A'\right)^2 \end{array}}$$ **Equation 5-11**

U_{SMA} is used in calculating margin for overstressing the actuator (Equation 4-6) and maximum allowable air pressure (Equation 3-3).

Considerations in Calculating Total Combined Uncertainties

The following should be considered when implementing the uncertainty equations above.

- In calculating total combined uncertainties for use in the allowable setup parameter equations, values of P_A' and F_S' are not known since the AOV settings may be adjusted as part of static setup testing. Therefore, it is recommended that conservative values be selected. For example, P_A' could be set to the maximum air supply pressure (e.g., the maximum instrument air system pressure) or P_{AMAX} calculated from Equation 3-3. F_S' could be set to F_{SMAX} calculated from Equation 3-7. Use of these conservative values ensures the valve will be set up properly during the static test. Once the static test is completed (and P_A' and F_S' measured), actual values of P_A' and F_S' can be used in calculating total combined uncertainties for the margin equations.
- For rising stem actuators, M in the uncertainty equations should be set to one, and U_η should be set to zero.
- The uncertainty on valve stroke length, L_V, can be neglected in any of the uncertainty equations if the equation is being evaluated at the beginning of the air stroke (S_{AIR}=0) or at the end of the spring stroke (S_{SPR}=0). The reason is that L_V is not included in the actuator capability equations when the spring is not compressed (beyond its preload).

6
SAMPLE PROBLEM

This section contains a sample problem for a direct acting, rising stem valve with a reverse acting, diaphragm actuator with spring return.

Inputs

Parameter	Value
η, b, c, D_{PG}, N_{piston}, U_η	Not applicable for rising stem AOVs
A_{CAP}	Not applicable for reverse acting actuators
A_{ROD}	150.5 in^2 at beginning of stroke; 158.2 in^2 at end of stroke
D, d	Not applicable for diaphragm actuators
F_D	0 pounds
F_{MAAT}	18,000 pounds
T_{MAVT}	11,000 pounds
F_{MSSL}	13,000 pounds
T_{RAIR}	1000 pounds at beginning of stroke; 1011 pounds at end of stroke
T_{RSPR}	2366 pounds at beginning of stroke; 2789 pounds at end of stroke
F_s'	4063.5 pounds
K_s	1560 lbs/inch
L_V	2 inches
P_A'	70 psig
P_{ATM}	0 psig
U_{AAIR}:	5%
U_{FD}:	5%
$U_{FS'}$:	5%
$U_{FS'\text{-bias}}$:	5%
U_{KS}:	5%
$U_{PA'}$:	5%
$U_{PA'\text{-bias}}$:	5%
U_{LV}:	5%

Per Table 3-1, the following other variables are set, based on the actuator type.

Parameter	Value
A_{AIR}	Equal to A_{ROD} -- 150.5 in^2 at beginning of stroke; 158.2 in^2 at end of stroke
B	1
C	0
E	1
S_{AIR}	Equal to x_{RET} -- 0 at beginning of stroke; L_V at end of stroke
S_{SPR}	Equal to $(L_V - x_{EXT})$ -- L_V at beginning of stroke; 0 at end of stroke
M	Equal to 1 for rising stem actuators
S_{MAX}	Equal to L_V -- 2 inches

Calculating Actuator Capabilities

The first step is to calculate the actuator capabilities. Equation 2-1 and Equation 2-2 are shown below with B set to 1, C set to 0, E set to 1, M set to 1, F_S set to F_S' and P_A set to P_A'.

(Air stroke) $$T_{AIR} = A_{AIR} \cdot (P_A' - P_{ATM}) - (F_S' + S_{AIR} K_S) - F_D$$ **Equation 6-1**

(Spring stroke) $$T_{SPR} = (F_S' + S_{SPR} K_S) - F_D$$ **Equation 6-2**

Using these equations, the following actuator capabilities are calculated.

(Beginning of air stroke) $$T_{AIR} = 150.5 \cdot (70 - 0) - (4063.5 + 0 \cdot 1560) - 0 = 6471.5$$ **Equation 6-3**

(End of air stroke) $$T_{AIR} = 158.2 \cdot (70 - 0) - (4063.5 + 2 \cdot 1560) - 0 = 3890.5$$ **Equation 6-4**

(Beginning of spring stroke) $$T_{SPR} = (4063.5 + 2 \cdot 1560) - 0 = 7183.5$$ **Equation 6-5**

(End of spring stroke) $$T_{SPR} = (4063.5 + 0 \cdot 1560) - 0 = 4063.5$$ **Equation 6-6**

Calculating Uncertainties

The next step is to calculate the various total combined uncertainties. The equations in Section 5 are shown below with B set to 1, C set to 0, E set to 1 and M set to 1.

$$U_{OA} = \frac{U_{TOT\_OA}}{T_{AIR} - U_{TOT\_OA}}$$ **Equation 6-7**

$$U_{TOT\_OA} = \left(U_{PA'\text{-bias}} \cdot A_{AIR} \cdot P_A'\right) + \sqrt{\begin{aligned}&\left(U_{AAIR} \cdot (P_A' - P_{ATM}) \cdot A_{AIR}\right)^2 \\ &+ \left(U_{PA'} \cdot A_{AIR} \cdot P_A'\right)^2 \\ &+ \left(U_{FS'} \cdot F_S'\right)^2 \\ &+ \left(U_{FD} \cdot (-F_D)\right)^2 \\ &+ \left(U_{LV} \cdot K_S \cdot S_{AIR}\right)^2 \\ &+ \left(U_{KS} \cdot S_{AIR} \cdot K_S\right)^2\end{aligned}}$$

Equation 6-8

$$U_{OS} = \frac{U_{TOT\_OS}}{T_{SPR} - U_{TOT\_OS}}$$

Equation 6-9

$$U_{TOT\_OS} = \left(U_{FS'\text{-bias}} \cdot F_S'\right) + \sqrt{\begin{aligned}&+ \left(U_{FS'} \cdot F_S'\right)^2 \\ &+ \left(U_{FD} \cdot (-F_D)\right)^2 \\ &+ \left(U_{LV} \cdot K_S \cdot S_{SPR}\right)^2 \\ &+ \left(U_{KS} \cdot S_{SPR} \cdot K_S\right)^2\end{aligned}}$$

Equation 6-10

$$U_{SO} = \frac{U_{TOT\_SO}}{U_{TOT\_SO} + \left(F_S' + S_{max} K_S\right)}$$

Equation 6-11

$$U_{TOT\_SO} = \left(U_{FS'-bias} \cdot F_S'\right) + \sqrt{\begin{aligned}&\left(U_{FS'} \cdot F_S'\right)^2 \\ &+ \left(U_{LV} \cdot K_S \cdot S_{MAX}\right)^2 \\ &+ \left(U_{KS} \cdot S_{MAX} \cdot K_S\right)^2\end{aligned}}$$

Equation 6-12

$$U_{SMV} = \frac{U_{TOT\_SMV}}{U_{TOT\_SMV} + T_{AIR}}$$

Equation 6-13

$$U_{TOT\_SMV} = \left(U_{PA'\text{-bias}} \cdot A_{AIR} \cdot P_A'\right) + \sqrt{\begin{aligned}&\left(U_{AAIR} \cdot (P_A' - P_{ATM}) \cdot A_{AIR}\right)^2 \\ &+ \left(U_{PA'} \cdot A_{AIR} \cdot P_A'\right)^2 \\ &+ \left(U_{FS'} \cdot F_S'\right)^2 \\ &+ \left(U_{FD} \cdot (-F_D)\right)^2 \\ &+ \left(U_{LV} \cdot K_S \cdot S_{AIR}\right)^2 \\ &+ \left(U_{KS} \cdot S_{AIR} \cdot K_S\right)^2\end{aligned}}$$

Equation 6-14

$$U_{SMA} = \frac{U_{TOT\_SMA}}{U_{TOT\_SMA} + A_{AIR} \cdot P_A'}$$

Equation 6-15

$$U_{TOT\_SMA} = \left(U_{PA'\text{-bias}} \cdot A_{AIR} \cdot P_A'\right) + \sqrt{\begin{array}{l}\left(U_{AAIR} \cdot P_A' \cdot A_{AIR}\right)^2 \\ + \left(U_{PA'} \cdot A_{AIR} \cdot P_A'\right)^2\end{array}} \quad \textbf{Equation 6-16}$$

Using these equations, the following uncertainties are calculated.

(Beginning of stroke)

$$U_{TOT\_OA} = \left(5\% \cdot 150.5 \cdot 70\right) + \sqrt{\begin{array}{l}\left(5\% \cdot (70-0) \cdot 150.5\right)^2 \\ + \left(5\% \cdot 150.5 \cdot 70\right)^2 \\ + \left(5\% \cdot 4063.5\right)^2 \\ + \left(5\% \cdot 0\right)^2 \\ + \left(5\% \cdot 1560 \cdot 0\right)^2 \\ + \left(5\% \cdot 0 \cdot 1560\right)^2\end{array}} = 1298.9 \quad \textbf{Equation 6-17}$$

(Beginning of stroke)

$$U_{OA} = \frac{1298.9}{6471.5 - 1298.9} = 25.1\% \quad \textbf{Equation 6-18}$$

(End of stroke)

$$U_{TOT\_OA} = \left(5\% \cdot 158.2 \cdot 70\right) + \sqrt{\begin{array}{l}\left(5\% \cdot (70-0) \cdot 158.2\right)^2 \\ + \left(5\% \cdot 158.2 \cdot 70\right)^2 \\ + \left(5\% \cdot 4063.5\right)^2 \\ + \left(5\% \cdot 0\right)^2 \\ + \left(5\% \cdot 1560 \cdot 2\right)^2 \\ + \left(5\% \cdot 2 \cdot 1560\right)^2\end{array}} = 1392.2 \quad \textbf{Equation 6-19}$$

(End of stroke)

$$U_{OA} = \frac{1392.2}{3890.5 - 1392.2} = 55.7\% \quad \textbf{Equation 6-20}$$

(Beginning of stroke)

$$U_{TOT\_OS} = \left(5\% \cdot 4063.5\right) + \sqrt{\begin{array}{l} + \left(5\% \cdot 4063.5\right)^2 \\ + \left(5\% \cdot 0\right)^2 \\ + \left(5\% \cdot 1560 \cdot 2\right)^2 \\ + \left(5\% \cdot 2 \cdot 1560\right)^2\end{array}} = 503.1 \quad \textbf{Equation 6-21}$$

(Beginning of stroke)

$$U_{OS} = \frac{503.1}{7183.5 - 503.1} = 7.5\% \quad \textbf{Equation 6-22}$$

(End of stroke) $$U_{TOT\_OS} = (5\% \cdot 4063.5) + \sqrt{\begin{array}{l} +(5\% \cdot 4063.5)^2 \\ +(5\% \cdot 0)^2 \\ +(5\% \cdot 1560 \cdot 0)^2 \\ +(5\% \cdot 0 \cdot 1560)^2 \end{array}} = 406.4$$ **Equation 6-23**

(End of stroke) $$U_{OS} = \frac{406.4}{4063.5 - 406.4} = 11.1\%$$ **Equation 6-24**

$$U_{TOT\_SO} = (5\% \cdot 4063.5) + \sqrt{\begin{array}{l} (5\% \cdot 4063.5)^2 \\ +(5\% \cdot 1560 \cdot 2)^2 \\ +(5\% \cdot 2 \cdot 1560)^2 \end{array}} = 503.1$$ **Equation 6-25**

$$U_{SO} = \frac{503.1}{503.1 + (4063.5 + 2 \cdot 1560)} = 6.6\%$$ **Equation 6-26**

(End of stroke) $$U_{TOT\_SMV} = (5\% \cdot 158.2 \cdot 70) + \sqrt{\begin{array}{l} (5\% \cdot (70-0) \cdot 158.2)^2 \\ +(5\% \cdot 158.2 \cdot 70)^2 \\ +(5\% \cdot 4063.5)^2 \\ +(5\% \cdot 0)^2 \\ +(5\% \cdot 1560 \cdot 2)^2 \\ +(5\% \cdot 2 \cdot 1560)^2 \end{array}} = 1392.2$$ **Equation 6-27**

(End of stroke) $$U_{SMV} = \frac{1183.4}{1183.4 + 3890.5} = 23.3\%$$ **Equation 6-28**

(End of stroke) $$U_{TOT\_SMA} = (5\% \cdot 158.2 \cdot 70) + \sqrt{\begin{array}{l} (5\% \cdot 70 \cdot 158.2)^2 \\ +(5\% \cdot 158.2 \cdot 70)^2 \end{array}} = 1336.8$$ **Equation 6-29**

(End of stroke) $$U_{SMA} = \frac{1336.8}{1336.8 + 158.2 \cdot 70} = 10.8\%$$ **Equation 6-30**

Calculating Allowable Setup Parameters

The next step is to calculate the allowable setup parameters. These calculations are shown below using the equations in Section 3.

(Beginning of stroke) $$P_{AMIN} = 0 + \frac{1000 \cdot (1 + 25.1\%) + 0 + (F_S + 0 \cdot 1560)}{150.5}$$ **Equation 6-31**

For F_S equal to F_S' (4063.5), P_{AMIN} equals 35.3 psig.

(End of stroke) $$P_{AMIN} = 0 + \frac{1011 \cdot (1 + 55.7\%) + 0 + (F_S + 2 \cdot 1560)}{158.2}$$ **Equation 6-32**

For F_S equal to F_S' (4063.5 lbs), P_{AMIN} equals 55.4 psig.

P_{AMIN} is the higher of these two values, or 55.4 psig.

(End of stroke) $$P_{AMAX} = 0 + \frac{11000 \cdot (1 - 23.3\%) + 0 + (F_S + 2 \cdot 1560)}{158.2}$$ **Equation 6-33**

For F_S equal to F_S' (4063.5 lbs), P_{AMAX} equals 98.7 psig.

(End of stroke) $$P_{AMAX} = \frac{18000 \cdot (1 - 10.8\%)}{158.2} = 126 \text{ psig}$$ **Equation 6-34**

P_{AMAX} is the lesser of these two values, or 98.7 psig.

(Beginning of stroke) $$F_{SMIN} = 2366 \cdot (1 + 7.5\%) - 2 \cdot 1560 + 0 = -577 \text{ lbs}$$ **Equation 6-35**

(End of stroke) $$F_{SMIN} = 2789 \cdot (1 + 11.1\%) - 0 \cdot 1560 + 0 = 3099 \text{ lbs}$$ **Equation 6-36**

(End of stroke) $$F_{SMIN} = 158.2(P_A - 0) - 0 - 11000 \cdot (1 - 23.3\%) - 2 \cdot 1560$$ **Equation 6-37**

For P_A equal to P_A' (70 psig), F_{SMIN} equals -483 lbs.

F_{SMIN} is the higher of these three values, or 3099 lbs.

(Beginning of stroke) $$F_{SMAX} = 150.5(P_A - 0) - 0 - 1000(1 + 25.1\%) - 0 \cdot 1560$$ **Equation 6-38**

For P_A equal to P_A' (70 psig), F_{SMIN} equals 9284 lbs.

(End of stroke) $$F_{SMAX} = 158.2(P_A - 0) - 0 - 1011(1 + 55.7\%) - 2 \cdot 1560$$ **Equation 6-39**

For P_A equal to P_A' (70 psig), F_{SMIN} equals 6380 lbs.

$$F_{SMAX} = 13000 \cdot (1 - 6.6\%) - 2 \cdot 1560 = 9022 \text{ lbs}$$ **Equation 6-40**

F_{SMAX} is the lesser of these three values, or 6380 lbs.

Calculating Margins

The final step is to calculate margins. These calculations are shown below using the equations in Section 4.

(Beginning of stroke) $$M_{OA} = \frac{6471.5 - 1000 \cdot (1 + 25.1\%)}{1000 \cdot (1 + 25.1\%)} \times 100 = 417.3\%$$ **Equation 6-41**

(End of stroke) $$M_{OA} = \frac{3890.5 - 1011 \cdot (1 + 55.7\%)}{1011 \cdot (1 + 55.7\%)} \times 100 = 147.2\%$$ **Equation 6-42**

M_{OA} is the lesser of these two values, or 147.2%.

(Beginning of stroke) $$M_{OS} = \frac{7183.5 - 2366 \cdot (1 + 7.5\%)}{2366 \cdot (1 + 7.5\%)} \times 100 = 182.4\%$$ **Equation 6-43**

(End of stroke) $$M_{OS} = \frac{4063.5 - 2789 \cdot (1 + 11.1\%)}{2789 \cdot (1 + 11.1\%)} \times 100 = 31.1\%$$ **Equation 6-44**

M_{OS} is the lesser of these two values, or 31.1%.

$$M_{SO} = \frac{13000 \cdot (1 - 6.6\%) - 4063.5 - 2 \cdot 1560}{13000 \cdot (1 - 6.6\%)} \times 100 = 40.8\%$$ **Equation 6-45**

(End of stroke) $$M_{SM} = \frac{11000 \cdot (1 - 23.3\%) - 3890.5}{11000 \cdot (1 - 23.3\%)} \times 100 = 53.9\%$$ **Equation 6-46**

(End of stroke) $$M_{SM} = \frac{18000 \cdot (1 - 10.8\%) - 158.2 \cdot 70}{18000 \cdot (1 - 10.8\%)} \times 100 = 31.0\%$$ **Equation 6-47**

M_{SM} is the lesser of these two values, or 31.0%.

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