Visible & Infrared Survey Telescope for Astronomy

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Document Title: **Design Report: Axial Support**

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Change Record

Issue	Date	ECN Number	Section(s) Affected	Description of Change/Change Request Reference/Remarks
1.0	7/15/03	03-0527	All	Preliminary Release
A	7/31/03	03-0583	All	Original Release
B	11/12/03	03-0921	4.3, 4.4, 4.5, 4.6	Updated for design changes
C	6/8/04	04-0583	4.4.3.3, 4.4.3.8, 4.5, 4.6	Update for FDR
D	9/22/04	04-0839	3.2, 3.41	Updated for RI 124

Table of Contents

1 Introduction

The Axial Support is a pneumatic linear actuator intended for support of the VISTA M1 mirror. The device utilizes a rolling element diaphragm in a piston/cylinder arrangement to generate a force output from a controlled pressure source. A force load cell is integral to the unit to provide feedback to the control system.

This purpose of this report is to document the design of the Axial Support and verify conformity to the design requirements set forth by VISTA.

2 Acronyms and Abbreviations

VER	VertexRSI
VIS	VISTA
TRE	Technical Report
XXXX	The next sequential number in the series of documents

3 Applicable and Referenced Documents

AD	Title	Number & Issue
AD01	Technical Specification for the Telescope Structure Work Package	VIS-SPE-ATC-01000-0006
AD02	Interface Control Document between M1 Mirror and M1 Cell	VIS-ICD-ATC-02000-03000
AD03	Primary Mirror Interface to Mirror Cell	VIS-DWG-ATC-02000-03000
AD04	VLT Environmental Specification	VLT-SPE-ESO-10000-0004
AD05	M1 Mirror Axial Support	VIS-DWG-ATC-03020-0001
AD06	Wedge – Inner Ring	VIS-DWG-ATC-02000-0003
AD07	Wedge – 2nd Ring	VIS-DWG-ATC-02000-0004
AD08	Wedge – 3rd Ring	VIS-DWG-ATC-02000-0005
AD09	Wedge – Outer Ring	VIS-DWG-ATC-02000-0006
AD10	Axial Actuator Assembly	VIS-DWG-VER-01001-4530
AD11	Verification Plan For: Axial Support	VIS-PLA-VER-03001-0104

Refer to current revision of all documents.

Design Report

3.1 *Scope of the Design*

This report describes in component level detail the design of the Axial Support as related to the various VISTA requirements. The design, material selection and performance of each component as well as the assembly are correlated to the specific requirements, and, where applicable, calculations are included. The Axial Support is defined as the pneumatic assembly and the load cell. The control system is not included in the scope of this report.

3.2 *Assumptions*

- The mounting structure is held to sufficient dimensional tolerances to meet position requirements.
- M1 mirror is assumed to be a rigid body
- Air supply is filtered and dry at 7.24 bar
- One design for all 81 axial actuator locations
- The testing of the design at a local atmospheric pressure of 1.0 bar is representative of site conditions of 750 mb.

3.3 *Materials*

The following materials are used in the construction of the Axial Support. Refer to the Axial Actuator Assembly drawing for detailed component drawings.

3.3.1 Aluminum Alloy per ISO 209 AlMg1SiCu

Used for:

S780-4530-11	Actuator Body
S780-4530-15	Housing

Components made with this material have a black anodised finish (ISO 7599) for corrosion protection.

Physical Properties:
Density: 2.7 g/cm^3

Mechanical Properties:
Tensile Strength: 275 MPa
Ultimate Strength: 300 MPa
Modulus of Elasticity: 69GPa

3.3.2 Stainless Steel per ISO 683/13 4

Used for:
S780-4530-14 Shaft

High strength heat treatable alloy selected for a sliding shaft. Component is case hardened to Rc 50 for wear resistance and precision ground for reduced sliding friction.

Physical Properties:
Density: 7.8 g/cm^3

Mechanical Properties:
Tensile Strength: 345 MPa
Ultimate Strength: 655 MPa
Modulus of Elasticity: 200 GPa

3.3.3 Stainless Steel per ISO 683/13 7

Used for:
S780-4530-20 Thrust Bearing Base

Physical Properties:
Density: 7.8 g/cm^3

Mechanical Properties:
Tensile Strength: 275 MPa
Ultimate Strength: 515 MPa
Modulus of Elasticity: 200 GPa

3.3.4 Stainless Steel per ISO 683/13 11

Used for:
S780-4530-12 Piston
S780-4530-18 Retainer
S780-4530-21 Contact Pad

Physical Properties:
Density: 8.0 g/cm^3

Mechanical Properties:
Tensile Strength: 215 MPa
Ultimate Strength: 505 MPa
Modulus of Elasticity: 200 GPa

3.3.5 Nylon 6/6

Used for:
S780-4530-22 Flexure

Physical Properties:
Density: 1.1 g/cm^3

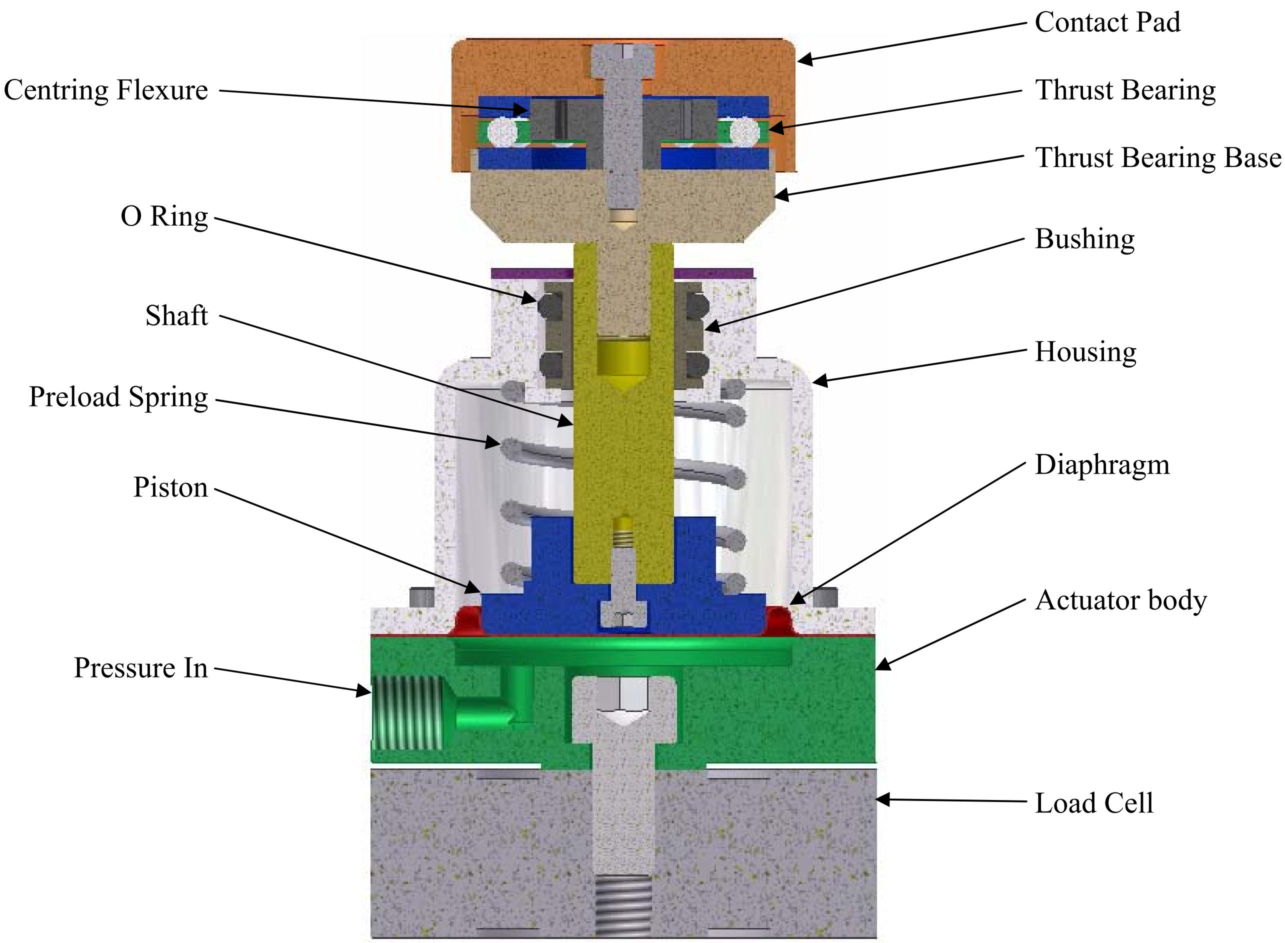
Mechanical Properties:
Tensile Strength: 63 MPa
Ultimate Strength: 73 MPa
Modulus of Elasticity: 2.4 GPa

3.4 Design Description

3.4.1 Theory of Operation

The Axial Support is a pneumatic linear actuator that applies a force to the M1 mirror by application of air pressure on a piston face. A force measurement load cell is integral to the assembly to provide force feedback to the pressure control system. The following figure is a section view of the assembly with the major components identified.

Figure 1: Axial Support Section View



In the non-operating condition (no supply pressure), the contact pad is held in a retracted position by spring force acting on the piston. When a force output is desired, the control system supplies an air pressure that is proportional to the commanded force. The pressure in the volume below the diaphragm moves the piston against the spring force until contact with the mirror pad is made. Increasing pressure from this point on increases the force application.

The spring is present to increase the response time of the support at low operating pressures. When a decrease in force is commanded, the pressure in the cylinder volume (V_c) is discharge to the atmosphere. At high operating pressures, the pressure differential between V_c and the atmosphere is large and the response is rapid. At low operating pressures, the pressure differential is small and response is slower. Addition of a spring preload provides a positive offset to the entire operating pressure range. The optimum amount of preload and spring rate was determined by testing the actuator with the control valve and control system.
The principal of a pneumatic cylinder is that of differential pressure between the cylinder volume and the ambient atmosphere. There is no reason to expect that a gauge pressure at the local altitude (≈1 bar) would result in a different force output than at the site altitude (≈750 mbar).
The support system for the piston, shaft, and contact pad assembly is a plain bearing fabricated from Delrin® Acetal that is supported by two o-rings to allow the bearing to be self-aligning. Based on the coefficient of friction of Delrin (0.25) and the maximum allowable lateral force of 4.5N, the estimated linear friction for the shaft and bearing is 1.3N. It should be noted that the pneumatic section of the axial support is in series with the load cell. As such, internal friction forces do not affect the accuracy of the force measurement, so regardless of the internal friction the force measured by the load cell is the force being applied to the mirror pad.
Lateral displacement between the axial support and the mirror pad is accommodated by the thrust bearing under the contact pad. A centring flexure re-aligns the thrust bearing and the contact pad when contact with the mirror pad is broken. The anticipated operating lateral displacement due to M1 cell flex and thermal expansion is 0.15 mm. The assembly is designed to accommodate 1 mm of travel in any direction.

3.4.2 Requirements

Table 1 indicates the VISTA requirements that are addressed in this report.

Table 1: VISTA Requirements

AD01 Section	**Description**	**Criteria**
10.4.4 (b)	81 actuators arrange per AD02	Design
10.4.4 (c)	Accommodate position changes in AD22	Design
10.4.4 (d)	Use of Bellofram™ diaphragm	Design
10.4.4 (e)	Range of travel	≥ ±2mm
10.4.4 (f)	Actuator force range	5 to 900N
10.4.4 (g)	Absolute accuracy, individual support	≤ ± 2 N
10.4.4 (h)	RMS error of all supports and definers	< 0.6 N rms
10.4.4 (m)	Repeatable lateral force at piston	≤ 4.5 N rms
AD02 Section		
4.2.1	Compression operation, not fixed to M1	Design
4.2.3	Low stiffness in all directions	Design
4.2.4	Interface is a pair of plane surfaces	Design

3.4.3 Verification by Design

3.4.3.1 AD01 Section 10.4.4(b)

Per Section 10.4.4 (b), the Axial Support system shall consist of 81 supports arranged in concentric rings below the M1 Mirror. The M1 Cell Structure controls the mounting locations of the supports and is being designed per the support positions defined in AD03.

3.4.3.2 AD01 Section 10.4.4(c)

Conformance with this requirement is based on having one design that will function in each of the 81 positions. One design has been developed that can be placed universally in any of the 81 M1 Cell structure positions. Tolerance control of both the Axial Support and M1 cell structure will ensure compatibility between positions.

3.4.3.3 AD01 Section 10.4.4(d)

Force actuators used in the conceptual design featured a rolling element Bellofram diaphragm. A Bellofram diaphragm suited for the target force and pressure parameters was selected and implemented into the design. Specifications for the diaphragm are as follows:

Part Number: 4C-200-22-015-PN
Material: EPDM
Fabric: 301 Polyester
Working Pressure: 14.2 bar
Burst Pressure: 58.4 bar
Effective Pressure Area: 17.2 cm^2

Pressure and force parameters based on this diaphragm are discussed in detail in Section 4.4.3.5 and calculations are shown in Section 4.5.

3.4.3.4 AD01 Section 10.4.4(e)

The range of travel shall be greater than ± 2.0 mm. The axial support design has an overall travel of 8 mm ± 0.5mm. The dimensions of the components shown in Figure 2 determine the allowable travel. Dimension tolerances of these parts will be maintained to ensure that the range of travel meets the design requirement.
With respect to the Cassegrain interface (machining datum for the M1 structure), the tolerance stack-up for height of the axial support, the structure mounting face, and the mounting bucket impact the effective range of travel. The Table 2 lists the tolerances for these items.

Figure 2: Travel Limits

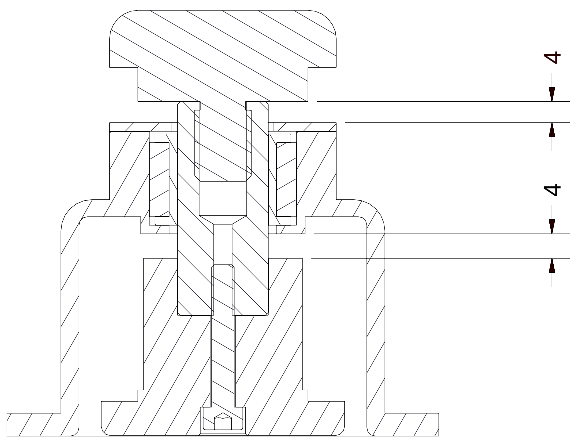


Table 2: Axial Support Tolerance Stack-Up

Support Component	Tolerance [mm]	Comments
Load Cell	0.1	Overall height
Actuator Body	0.05	Overall height
Diaphragm	0.1	Flange thickness
Upper Housing	0.05	Overall height
Bearing Retainer	0.05	Thickness
Contact Button	0.05	Thrust bearing to contact surface
Thrust Bearing	0.5	Overall thickness of bearing and races
Thrust Bearing Base	0.05	Shaft mating surface to thrust bearing
M1 Cell		
Cassegrain to Mounting Bucket	0.5	Conservative budgetary estimate
Mounting Bucket	0.1	Mounting plate to structure interface
Total	**1.55**	

Combining the total from table 2 with the available travel and the travel tolerance yields an effective travel of 5.95mm. The axial maintenance pads will also consume travel by the compression of the compliant rest pad. A budgetary compression distance of 1mm for the rest pad and 1 mm for clearance leaves a minimum of 3.95mm or ± 1.98mm for actuator travel.

3.4.3.5 AD01 Section 10.4.4(f)

The force output range of the Axial Support shall be 5 to 900 N. The force output is a linear function of piston area, pressure, and spring force. For input pressures of 0 to 69 kPa, the force output is zero due to the spring preload, and for input pressures of 69 kPa and above, the following equation applies:

$F = (P \times A) - K(\Delta x)$

where F = Force Output
P = Pressure In
A = Effective Piston Area (17.23 cm^2)
K = Spring Rate (6.48 N/mm)
Δx = Spring compression from free length

The following table indicates the pressures required for the high and low end of the required force range at varying stroke positions. Force output is linear between 5 and 900 N for any given stroke.

Table 3: Force Output

Force Output	At Zero Stroke	At Mid-Stroke (4mm)	At Full Stroke (8mm)
5 N	72 kPa	87 kPa	102 kPa
900 N	590 kPa	606 kPa	620 kPa

Conformance with the 5 to 900 N range requirement demands that the air input be controllable through a minimum range of 72 to 620 kPa. The control valve selected shall provide a controlled output from 50 kPa or less to greater than 690 kPa.

3.4.3.6 AD01 Section 10.4.4 (g)

Section 10.4.4(g) requires that the absolute accuracy of an individual support be better than 2.0 N. Recalling that the load cell is in series with the pneumatic section of the support, all of the force output is reacted through the load cell. Therefore, the accuracy of the support is governed by the accuracy of the load cell.

Table 4: Load Cell Accuracy

Term	%F.S	Error Value
Static error band	0.08%	0.8 N
Temperature Effect on span	0.004% / °C	0.6 N
Temperature Effect on zero	0.004% / °C	0.6 N
	RSS Total	**1.17 N**

3.4.3.7 AD01 Section 10.4.4 (h)

Section 10.4.4(h) requires that the RMS error of all supports be less than 0.6 N rms at any instant. Table 5 shows the terms error terms that contribute to the system error budget. Refer to VIS-TRE-03001-9702, Design Report for Axial Support Control for the complete error budget.

Table 5: Axial Support / Definer Error

Type	Static Error Band	Peak Force Error
Static Error Band	0.08%	0.8 N
Temperature (span)	0.004% FS/°C	0.6 N
Temperature (zero)	0.004% FS/°C	0.6 N

3.4.3.8 AD01 Section 10.4.4(m)

Section 10.4.4(m) requires that the repeatable lateral force measured at the piston not exceed 4.5 N. Repeatable lateral force contributions are expected from the following areas:

- Lateral displacement of the mirror pad relative to the support as a result of structural deformation over the altitude range (≈33µm from FEA model, 18 Sept 03).
- Lateral displacement of the mirror pad relative to the support as a result of thermal expansion (114µm, 5°C over 1.9m at 12µm/m-°C).
- Parallelism between the piston face and the mirror pad. The force generated by the diaphragm is perpendicular to the face of the piston. A lateral component is generated for any non-zero angle between the normal to the piston face and the z-axis.
- Off axis spring force. Test data has shown that the spring does not had a significant contribution to lateral forces at the mirror interface

Table 6 indicates the force values for the individual contributions.

Table 6: Repeatable Lateral Force Budget

Source	Value [N]	Comments
Lateral Displacement	2.5	Thrust Bearing to accommodate 147µm of displacement (M1 flex + thermal expansion)
Parallelism	1.5	Piston to contact surface
Spring	0.0	Estimated value from testing
Total	**3.50**	

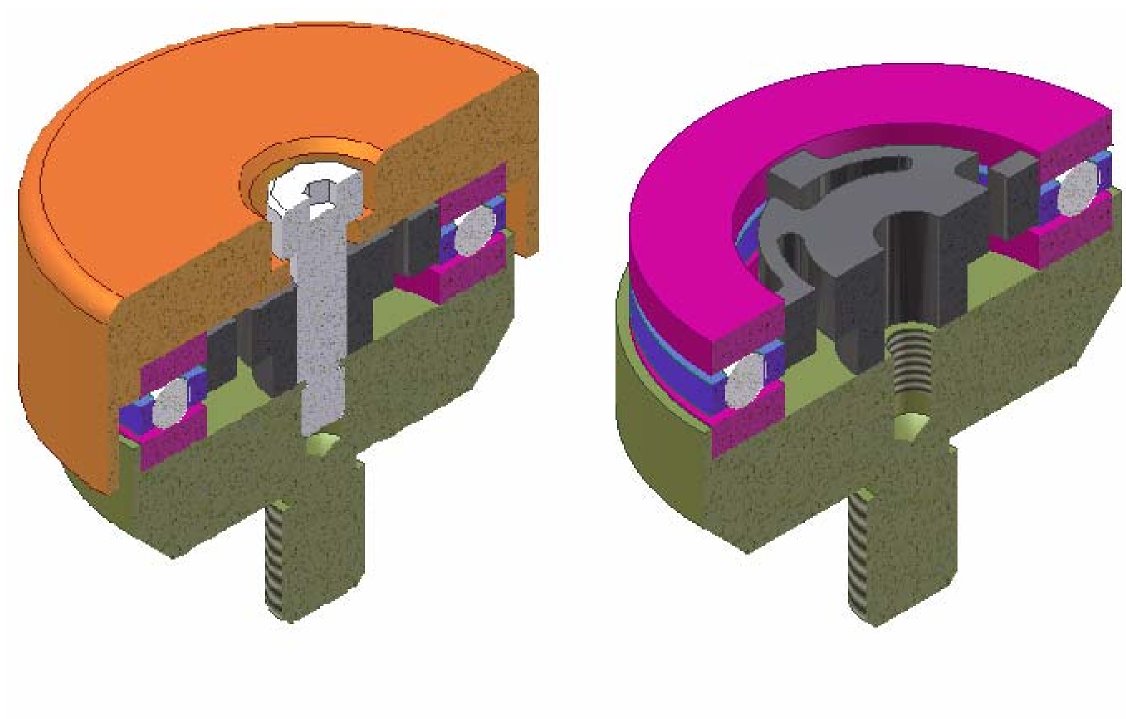
3.4.3.9 AD02 Section 4.2.1

Per Section 4.2.1, the axial support was designed for operation in compression conditions. The interface with the mirror pads is planar and is not fixed to them.

3.4.3.10 AD02 Section 4.2.3

This requirement states that the Axial Supports shall exhibit low stiffness in all directions and have a small centring action in the lateral plane. Since the design is pneumatic, stiffness in the axial direction is governed by the compressibility of air and is low by default. Low lateral stiffness is achieved through the use of a thrust bearing and a centring flexure. Referring to Figure 3, the contact pad is seated on the top race of the thrust bearing to allow lateral translation between the mirror pad and the support. Lateral displacement during operation is approximately 0.15 mm. The centring flexure provides a maximum of 2 N centring force at 0.015 mm to re-align the thrust bearing and contact pad when the support is de-activated.

Figure 3: Thrust Bearing and Flexure



3.4.3.11 AD02 Section 4.2.4

The section 4.2.4 requirement states that the interface shall be a pair of planar surfaces. The contact surface of the axial support is a flat circular surface. The surface finish indicated on the mating wedges (VIS-DWG-ATC-02000-0003 through 0006) is also reflected on the Axial Support's contact surface.

3.5 Calculations

www.marshbellofram.com
Nancy Tate (sales)
Part Number: 4C-200-22-015-PN
Material: EPDM
Fabric: 301 Polyester
Working Pressure: 14.2 bar
Burst Pressure: 58.2 bar

$D_c := 50.8 \cdot mm$ Cylinder Diameter

$D_p := 42.93 \cdot mm$ Piston Diameter

$H := 5.59 \cdot mm$ Overall Height

$W_{sw} := 0.381 \cdot mm$ Side wall thickness

$A_e := 17.23 \cdot cm^2$ Effective Piston Area

$C := 3.94 \cdot mm$ Convolution

$S_A := 4.06 \cdot mm$ Maximum Half Stroke

Spring Specifications

Manufacturer: Century Spring
Part Number: 72795S

$L_f := 50.8 \cdot mm$ Free Length

$L_s := 17.02 \cdot mm$ Solid Height

$K := 6.48 \cdot \frac{N}{mm}$ Spring Rate

For 68.9 kPa preload

$P_{preload} := 68.9 \cdot 10^3 \cdot Pa$ Piston preload pressure

$F := P_{preload} \cdot A_e$ Force to overcome preload at zero stroke

$F = 119N$

$\Delta L_{preload} := \frac{F}{K}$ Spring deflection required for preload force

$\Delta L_{preload} = 18.32mm$

$L_{preload} := L_f - \Delta L_{preload}$ Spring compressed length for preload

$L_{preload} = 32.48mm$

Discussion:
This is the compressed length of the spring at zero stroke. 8 mm of additional compression will occur through the travel range of the piston.

Actuator Force Output (at a given stroke)

$F_{spring}(x) := K \cdot \left(\Delta L_{preload} + x\right)$ Force required to overcome the spring as a function of stroke

$P_{spring}(x) := \frac{F_{spring}(x)}{A_e}$ Pressure required to overcome the spring as a function of stroke

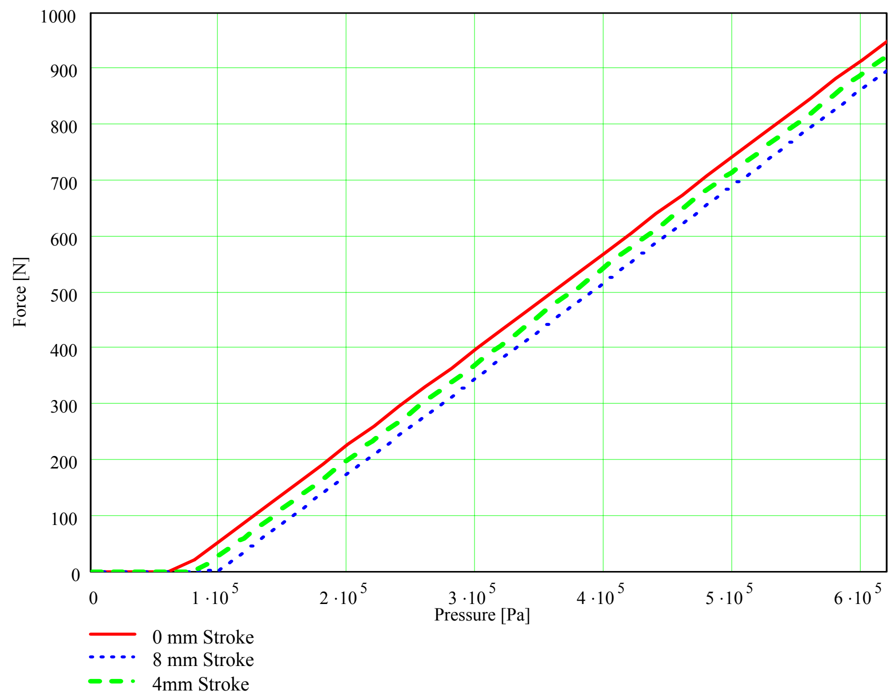
$x := 4 \cdot mm$ Set the stroke to required to contact the mirror pad to 4 mm

$P := 0 \cdot kPa, 20 \cdot kPa .. 620 \cdot kPa$ Input pressure range 0 to 620 kPa

$$F(P,x) := \begin{cases} 0 \cdot N & \text{if } P < P_{spring}(x) \\ P \cdot A_e - F_{spring}(x) & \text{otherwise} \end{cases}$$

Force output as a function of pressure. Note that force is zero until the actuator piston contacts the mirror at position x = 4 mm

Force Output vs Pressure



Discussion:
The force output is a linear function of pressure and spring compression. Once contact is made between the support and the mirror pad, spring force remains constant leaving only a linear relationship between pressure and force.

Pressure Range for Force at Given Stroke Positions

$$P(F,x) := \frac{F + K\cdot\left(\Delta L_{preload} + x\right)}{A_e}$$

Pressure as a function of desired force (F) and stroke position (x)

At Zero Stroke:

$$P(5\cdot N, 0\cdot mm) = 72 kPa$$

$$P(900\cdot N, 0\cdot mm) = 591 kPa$$

At Mid-Stroke:

$$P(5\cdot N, 4\cdot mm) = 87 kPa$$

$$P(900\cdot N, 4\cdot mm) = 606 kPa$$

At Full Stroke:

$$P(5\cdot N, 8\cdot mm) = 102 kPa$$

$$P(900\cdot N, 8\cdot mm) = 621 kPa$$

Discussion:
The controlled operating pressure occurs range is bounded by the lowest force at the zero stroke and the highest force at maximum stroke (72 to 621 kPa).

3.6 Conclusions

Lateral forces, both repeatable and non-repeatable, are understood to be key performance items for the axial support. The design modifications (thrust bearing and centring flexure) that have been implemented since Issue A of this document specifically targeted these requirements.

The design for the axial support conforms to the remaining requirements in Table 1. Where possible, these requirements will also be verified by testing as indicated in the verification plan (AD11).

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