



BSI Standards Publication

Space Engineering — Thermal design handbook

Part 12: Louvers

National foreword

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European Foreword

This document (CEN/CLC/TR 17603-31-12:2021) has been prepared by Technical Committee CEN/CLC/JTC 5 "Space", the secretariat of which is held by DIN.

It is highlighted that this technical report does not contain any requirement but only collection of data or descriptions and guidelines about how to organize and perform the work in support of EN 16603-31.

This Technical report (TR 17603-31-12:2021) originates from ECSS-E-HB-31-01 Part 12A.

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This document has been prepared under a mandate given to CEN by the European Commission and the European Free Trade Association.

This document has been developed to cover specifically space systems and has therefore precedence over any TR covering the same scope but with a wider domain of applicability (e.g.: aerospace).

1

Scope

Thermal louvers are thermal control surfaces whose radiation characteristics can be varied in order to maintain the correct operating temperature of a component subject to cyclical changes in the amount of heat that it absorbs or generates.

The design and construction of louvers for space systems are described in this Part 12 and a clause is also dedicated to providing details on existing systems.

The Thermal design handbook is published in 16 Parts

TR 17603-31-01	Thermal design handbook – Part 1: View factors
TR 17603-31-02	Thermal design handbook – Part 2: Holes, Grooves and Cavities
TR 17603-31-03	Thermal design handbook – Part 3: Spacecraft Surface Temperature
TR 17603-31-04	Thermal design handbook – Part 4: Conductive Heat Transfer
TR 17603-31-05	Thermal design handbook – Part 5: Structural Materials: Metallic and Composite
TR 17603-31-06	Thermal design handbook – Part 6: Thermal Control Surfaces
TR 17603-31-07	Thermal design handbook – Part 7: Insulations
TR 17603-31-08	Thermal design handbook – Part 8: Heat Pipes
TR 17603-31-09	Thermal design handbook – Part 9: Radiators
TR 17603-31-10	Thermal design handbook – Part 10: Phase – Change Capacitors
TR 17603-31-11	Thermal design handbook – Part 11: Electrical Heating
TR 17603-31-12	Thermal design handbook – Part 12: Louvers
TR 17603-31-13	Thermal design handbook – Part 13: Fluid Loops
TR 17603-31-14	Thermal design handbook – Part 14: Cryogenic Cooling
TR 17603-31-15	Thermal design handbook – Part 15: Existing Satellites
TR 17603-31-16	Thermal design handbook – Part 16: Thermal Protection System

2 References

EN Reference	Reference in text	Title
EN 16601-00-01	ECSS-S-ST-00-01	ECSS System - Glossary of terms

All other references made to publications in this Part are listed, alphabetically, in the **Bibliography**.

Terms, definitions and symbols

3.1 Terms and definitions

For the purpose of this Standard, the terms and definitions given in ECSS-S-ST-00-01 apply.

3.2 Symbols

A	Clause 5: bellows effective area, [m ²] Clause 7: contact surface (bourdon sensing element), [m ²]
B	radiosity, [W.m ⁻²]
B*	dimensionless radiosity, $B^* = B/\sigma T^4$
D_i	bellows innermost diameter, [m]
D_o	bellows outermost diameter, [m]
E	modulus of elasticity, [N.m ⁻²]
F	flexibility, [m.Pa ⁻¹]
F_c	coil force constant, [N.m ⁻² .Angular degrees ⁻¹]
H	energy flux impinging on the unit area, [W.m ⁻²]
J	heat flux to the skin arriving from outside, [W.m ⁻²]
K	bellows spring rate, [N.m ⁻¹]
K_c	coil deflection constant, [angular degrees, K ⁻¹]
L	Clause 5: coil active length, [m] Clause 5: length of all convolutions in bellows, [m] Clause 6: louver blade spacing, [m]

L_c	length of a single convolution in bellows measured along the surface, [m]
M	torsional moment of a coil, [N.m]
P	fluid pressure, [Pa]
P_t	proportionality limit pressure in a bourdon, [Pa]
Q	heat transfer to the fluid within the bourdon, [J]
Q_0	heat transfer to the fluid within the bourdon after an infinitely large time, [J]
$R(\theta)$	equivalent thermal resistance of the louver system, it is a function of the optical properties of blades, and inner skin surface, but for a given system R depends only on the blade angle
R_0	coiling radius of a bourdon, [m]
R_m	mean radius of the bellows, [m]
S	heat flux from the space to the skin, [W.m ⁻²]
S_0	solar constant, $S_0 = 1353 \text{ W.m}^{-2}$
T	temperature, [K]
T_c	bourdon filling fluid temperature, [K]
T_0	reference temperature, [K]
ΔT	temperature differential, [K], $\Delta T = T - T_0$
T_{0L}	starting fluid temperature, [K]
T_s	skin temperature, [K]
T^*	local dimensionless temperature, $T^* = T^4/T_{BP}^4$
V	inside volume of bellows, [m ³]
X	sensitivity of a bimetal, [angular degrees, K ⁻¹]
a	semi-major axis of the bourdon tube cross section, [m]
b	Clause 5: semi-minor axis of the bourdon tube section, [m] Clause 6: louver blade width, [m]

c	Clause 5: numerical coefficient given in Table 5-7 under additional data Clause 7: fluid specific heat, [J.kg ⁻¹ .K ⁻¹]
f(θ)	defined as $f(\theta) = 1 - [1/R(\theta)]$
f_{n=1}	fundamental natural frequency, [s ⁻¹]
h	total thermal conductance of a bourdon (sensing element plus fluid, [W.m ⁻² .K ⁻¹])
l	length of a given metallic strip when the temperature is T [m] live length of the bellows, [m]
l₀	length of a given metallic strip when the temperature is T_0 , [m]
m_a	mass of bellows active convolutions, [kg]
m_c	mass of one convolution, [kg]
m_{fa}	mass of fluid trapped in active length at rest, [kg] $m_{fa} = \rho L[0,262(D_o^2 + D_o D_i) - 0,524 D_i^2]$
m_l	mass of liquid within the bellows, [kg]. $m_l = \rho A l$
m₁	mass on bellows free end, [kg]
m₂	bellows mass, [kg]
q	louver heat rejection capability, [W.m ⁻²]
q_{shadow}	heat rejection capability for zero solar input, [W.m ⁻²]
t	thickness of the strip of the coil, [m] wall thickness for bellows or bourdon tube, [m]
w	width of the strip of the coil, [m]
x	coordinate along the louver baseplate, [m]
y,z	Coordinates along the outer and inner faces of the blade, [m]
Φ	sun angle, [angular degrees]
α	absorptance

	numerical coefficient which appears in the expression of bourdon flexibility
α_s	solar absorptance
α_λ	spectral absorptance
β	Clause 5: linear thermal expansion coefficient, [K ⁻¹] Clause 5: numerical coefficient which appears in that expression of bourdon flexibility Clause 6: Dimensionless coordinate along the louver baseplate, $\beta = x/L$
β_H	linear thermal expansion coefficient of the high expansibility component of a bimetal, [K ⁻¹]
β_L	linear thermal expansion coefficient of the low expansibility component of a bimetal, [K ⁻¹]
ε	hemispherical total emittance
ε_I	emittance of the skin inner surface
ε_s	emittance of the skin outer surface
η, ζ	dimensionless coordinates, $\eta = y/L$, $\zeta = z/L$
θ	Clause. 5: angular deflection of a coil, [angular degrees] Clause 6: louver blade angle, [angular degrees]
ν	poisson's ratio
ρ	Clauses 5 and 7: fluid density, [kg.m ⁻³] Clause 6: reflectance
ρ_λ	spectral reflectance
ρ^s	specular reflectance
ψ_0	initial coiling angle in a bourdon, also called mechanical preload angle, [angular degrees]
σ	Stefan-Boltzmann constant, $\sigma = 5,6697 \times 10^{-8}$ W.m ⁻² .K ⁻⁴
τ	time, [s]

Subscripts

B	concerns louver blades
B_I	concerns the inner face of the louver blade
B_O	concerns the outer face of the louver blade
B_P	concerns louver baseplate
eff	effective value

General introduction

Thermal louvers are thermal control surfaces whose radiation characteristics can be varied in order to maintain the proper temperature of a component which experiences cyclical changes in the amount of heat that it absorbs or generates.

Louvers are constituted by five main components: baseplate, blades, actuators, sensing elements, and structural elements.

The baseplate is a surface of low absorptance to emittance ratio which covers the critical set of components whose temperature is being controlled.

The blades, driven by the actuators, are the elements of the louvers which give variable radiation characteristics at the baseplate. When the blades are closed, they shield the baseplate from the surroundings, while when they are fully open, the coupling by radiation of the baseplate to the surroundings is the largest.

The radiation characteristics of the baseplate can be varied in the range defined by these two extreme positions of the blades.

The actuators are the elements of the louvers which drive the blades according to the temperature sensed by sensors placed in the baseplate. Up to now, the actuators of the louvers flown on satellites have been bimetal spirals or bellows, although other types could be used, such as Bourdon spirals, and electrical devices.

In a single actuation system all the blades are driven by the same actuator. In the multiple blade actuator system several actuators are required to operate the system. Generally, bimetals are used as multiple blade actuation system, and bellows as single blade systems.

The sensing element senses the temperature of the baseplate and activates the actuators, which drive the blades according to this temperature. The type of sensing element depends on the kind of actuator. When the actuator is a bimetal, the sensing element is the bimetal itself. If the actuators are bellows or Bourdon, the sensing element can be a tank or a tube, containing a liquid or a liquid-vapor mixture, and soldered to the baseplate.

The different components of the louver system are supported by means of a frame. When bimetallic actuators are used, they are enclosed in a housing to shield the bimetal from the environment. This actuator housing may be a structural part of the frame.

Louver systems can be made for shadow or sunlight operation. In the first case heat is radiated through the louver to the outer skin of the spacecraft, while in the second the excess heat is transferred from the emitting baseplate to the outer space.

Louvers do not consume power except those that are electrically actuated.

Components of a louver

5.1 Blades

Louver blades are normally of rectangular plan form. Trapezoidal plan forms are preferred for circular assemblies.

Each blade is mounted around a shaft. This provides the torsional stiffness required to transmit the actuator torque:

Characteristics of blades used in several existing configurations are given in Table 5-1.

Table 5-1: Blade Characteristics of Existing Louver Assemblies
R: Rectangular, T: Trapezoidal

PRODUCER	SPACECRAFT	α_s	BLADE MATERIAL	CONFIGURATION
	LAUNCH DATE	ε		DIMENSIONS x10 ³ [m]
	MARINER 2	0,12	0,508x10 ⁻³ m thick Polished Aluminium	R
	8/26/1962	0,04		
COMMENTS: Louver blades are center pivoted.				
	O.G.O.	0,12	Two layers of 0,127x10 ⁻³ m thick Polished Aluminium	R
	9/4/1964	0,04		500x45
COMMENTS: The blade is a rectangular center-rotating member constructed of two formed aluminium sheets spot-welded together along the two edges. Plastic end fittings are provided at each end of the blades.				
	MARINER 4	0,12	Two layers of 0,127x10 ⁻³ m thick Polished Aluminium	R
	11/28/1964	0,04		150x30
COMMENTS: Each louver blade is a rectangular center-pivoted member consisting of an aluminium tube whose square cross section has a side of 3,5x10 ⁻³ m.				
Fairchild Hiller	PEGASUS II	0,11	Polished Aluminium 5052	R
	5/25/1965	0,05		200x50
COMMENTS: Each louver blade is a rectangular center-pivoted member constructed from Aluminium Alloy 5052.				
Louver for shadow operation.				
GENERAL	NIMBUS 1 & 2	0,15	32 Layers of 6,35x10 ⁻⁶ m	R

PRODUCER	SPACECRAFT	α_s	BLADE MATERIAL	CONFIGURATION
	LAUNCH DATE	ε		DIMENSIONS x10 ³ [m]
ELECTRIC	(SENSORY SUBSYSTEM)		thick embossed preshrunk aluminized Mylar	
	1-8/28/1964 2-5/15/1966	0,03		
COMMENTS: The blades are side pivoted and are covered by a layer of Mylar 2,54x10 ⁻⁵ m thick not embossed, to maintain specular external surface.				
GENERAL ELECTRIC	NIMBUS 1 & 2 (CONTROL SUBSYSTEM)	0,20	11 Layers of 6,35x10 ⁻⁶ m thick matted glass fiber paper	R
	1-8/28/1964 2-5/15/1966	0,80		
COMMENTS: The blades are covered on both sides by an additional layer of glass fiber paper, and are enclosed with a 5,08x10 ⁻⁵ m thick woven glass fiber fabric that is impregnated with Teflon. The blades are diffuse.				
Fairchild Hiller	ATS	0,17 ^a	Polished Aluminium with a whitepaint strip (6% of area)	R
	5/30/1974	0,05 ^a		
COMMENTS: Blades are sandwiched with a BR-34 polyimide adhesive bond. A white paint strip (DC 92-007) was added to the top of each blade along its entire length to lower the blade temperature during operation in a solar environment.				
^a Values measured before the white strip was added.				
Fairchild Hiller	O.A.O.	0,12	Two stamped sheets of Polished Aluminium	R
		0,06		
COMMENTS: Louver for shadow operation.				
TRW-Systems	PIONNER IV	0,15-0,20	0,076x10 ⁻³ m Aluminium foil sheets (1100-H 18)	T
	3/3/1959	0,04		Length = 267. Width at the large end = 76,2. Width at the narrow end = 25,4.
COMMENTS: To obtain the appropriate stiffness and longitudinal rigidity, sheet blades are formed into 6,35x10 ⁻³ m thick rectangular cross section, containing a hollow-internal shaft. Circular system.				
SNIAS		0,10	Polished Aluminium (A 9)	R
		0,04		123x38
COMMENTS:				
ERNO	HELIOS		Uncoated Aluminium Sandwich	T
	12/10/1974			Length = 220 Width at the large end =

PRODUCER	SPACECRAFT	α_s	BLADE MATERIAL	CONFIGURATION
	LAUNCH DATE	ε		DIMENSIONS x10 ³ [m]
				100
COMMENTS:				
RCA			Foam with glued aluminized Mylar	R
COMMENTS: Louver made per blade, actuated by bimetal. Price: US \$ 2100 per blade.				

5.2 Actuators

5.2.1 Bimetals

5.2.1.1 Introduction

Bimetal is a composite material having two or more metallic layers of different thermal expansion coefficients, that are permanently bonded together. If the bimetal temperature raises, the metal layer with the higher thermal expansion coefficient (high expansion component) tends to expand more than the one with the lower coefficient (low expansion component). The differences in thermal expansion cause the bending of the bimetal. If one end of the bimetal is fixed, the displacement at the free end can be used for operating electrical contacts or tripping a mechanism.

In order to achieve large deflections, the bimetal is frequently used in the form of helicoidal spring. If this spring is fixed at its outer extremity, the inner end may be attached to a shaft which will then rotate when the temperature changes. The available forces will depend both on the material mechanical and thermal characteristics, and on the spring dimensions.

Bimetals have been used in many spatial louver systems such as: Mariner, ATS, OGO, Pegasus, Pioneer, etc.. In these systems the bimetal is thermally coupled to the nearest portion of the radiator plate, and is, therefore, used as actuator and as sensing element.

5.2.1.2 Materials

Materials which are used in the manufacture of the bimetals for low expansion components or for high expansion components are given in Table 5-2.

Table 5-2: Materials Used

	MATERIAL	ALLOYS WITH LARGEST β
		ALLOYS WITH SMALLEST β
LOW EXPANSION COMPONENT	INVAR, Also called; NILO 36, NILEX, NILVAR, and INDILATANS	
HIGH EXPANSION COMPONENT	BRASSES	CARTRIDGE BRASS
		RED BRASS
	AUSTENITIC ALLOY STEELS	STAINLESS STEEL 347
		STAINLESS STEEL 310
	NICKEL-MANGANESE-CHROMIUM ALLOYS	NIMONIC ALLOY PE 16
		NIMONIC ALLOY PK 33

Thermal Expansion Coefficient

Values of the relative linear thermal expansion of the above alloys are plotted as functions of temperature in Figure 5-1 to Figure 5-4.

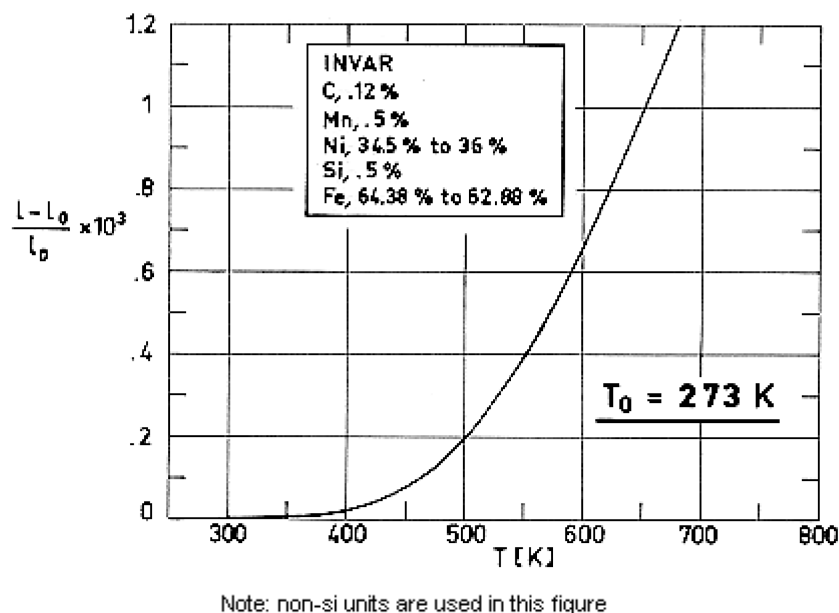


Figure 5-1: Relative linear thermal expansion vs. temperature in the case of Invar.
 $T_0 = 273 \text{ K}$. From THE MOND NICKEL CO [35].

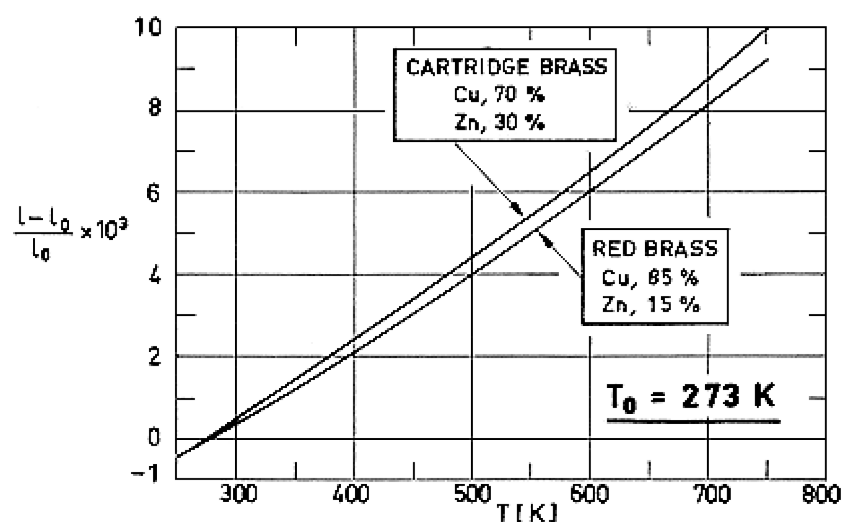


Figure 5-2: Relative linear thermal expansion vs. temperature in the case of brasses.
 $T_0 = 273 \text{ K}$. After Baldwin (1961) [3].

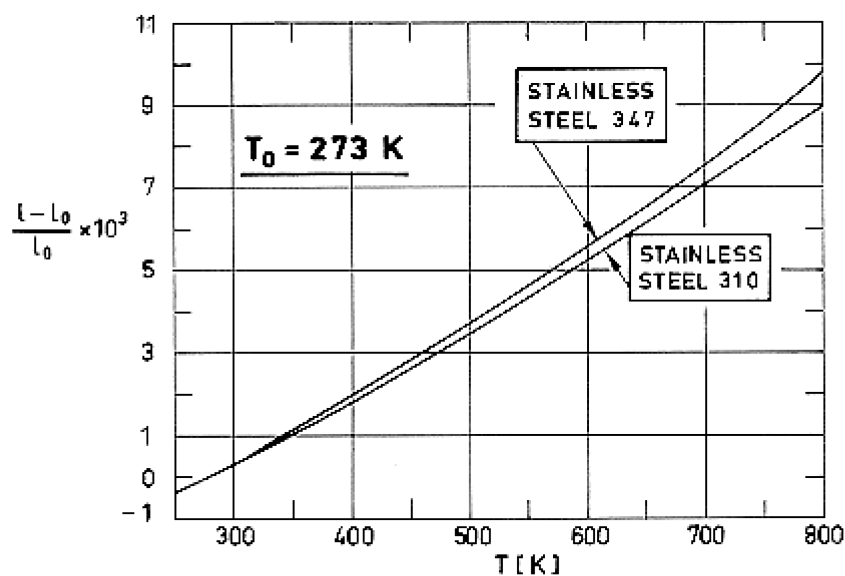


Figure 5-3: Relative linear thermal expansion vs. temperature in the case of austenitic steels. $T_0 = 273 \text{ K}$. After Zapffe (1961) [39].

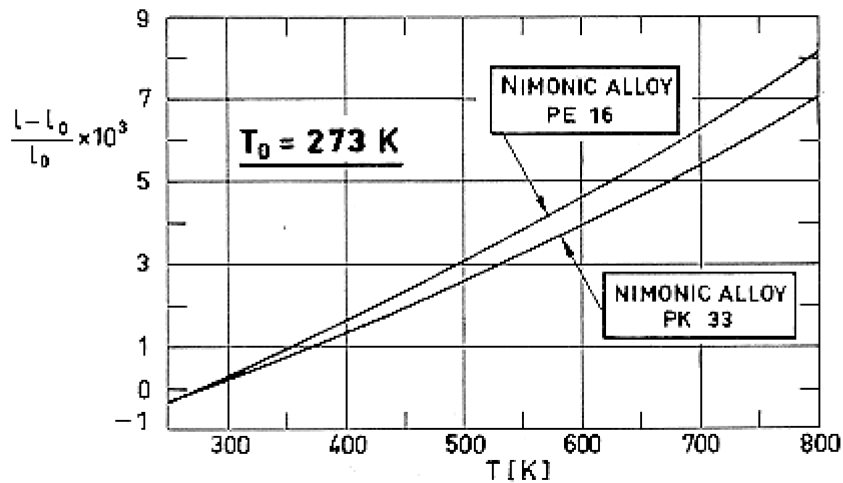


Figure 5-4: Relative linear thermal expansion vs. temperature in the case of Nimonic alloys. $T_0 = 273$ K. After WIGGIN & Co. (1967) [38].

This relative linear thermal expansion is defined as

$$(l-l_0)/l_0 = \beta \Delta T$$

Figure 5-5 is a summary of the data given in the four foregoing figures.

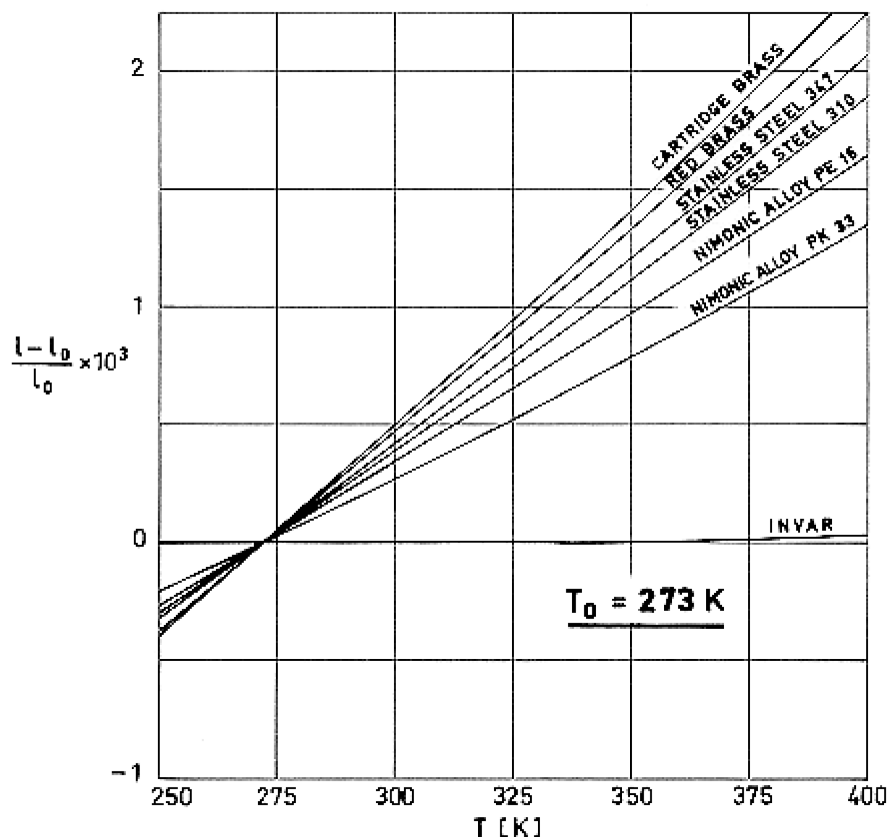


Figure 5-5: Relative linear thermal expansion vs. temperature for different alloys. $T_0 = 273$ K. After Baldwin (1961) [3], Zapffe (1961) [39], WIGGIN Co. (1967) [38].

5.2.1.3 Deflection of spirals and helical coils. sensitivity

Bimetalic spirals and helical coils deflected rotationally when the temperature changes. The deflection is given by

$$\theta = \frac{K_c \Delta T L}{t} \quad [5-1]$$

where the coil deflection constant, K_c , may be written as:

$$K_c = \frac{3}{4} \frac{360}{\pi} (\beta_H - \beta_L) = \frac{270}{\pi} (\beta_H - \beta_L) \quad [5-2]$$

The sensitivity, X , of spirals and helical coils is:

$$X = \frac{\theta}{\Delta T} = \frac{K_c L}{t} \quad [5-3]$$

Although the above expressions are always valid, it should be pointed out that K_c depends on the temperature and it is really constant only when the relative linear thermal expansion is a linear function of temperature.

Typical values of K_c for different bimetals are from 5×10^{-4} to 25×10^{-4} Angular Degrees. K^{-1} .

Figure 5-6 gives the ΔT required to achieve a given rotation θ , for different sensitivities, X , while Figure 5-7 shows X as a function of the bimetal slenderness, L/t , for different values of the deflection constant K_c .

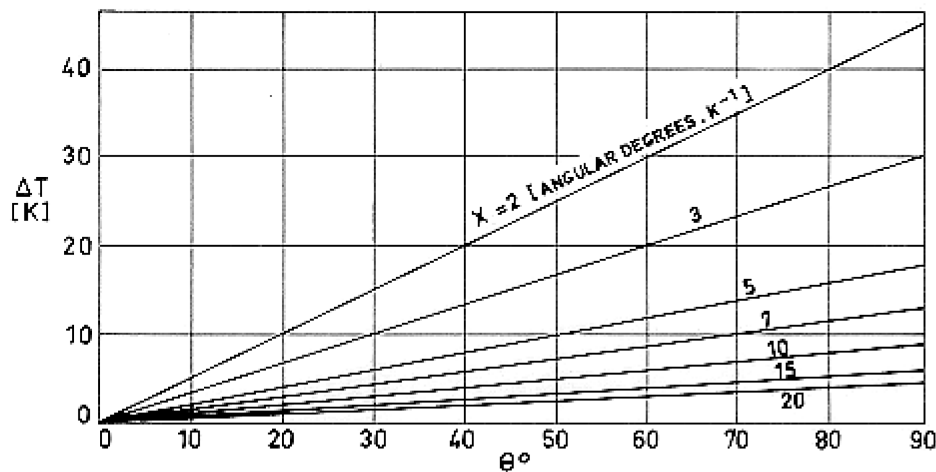


Figure 5-6: Difference of temperature, ΔT , vs. angle of rotation of the free end, θ , for several values of the sensitivity, X . After Martin & Yarworth (1961) [21], KAMMERER (1971) [16].

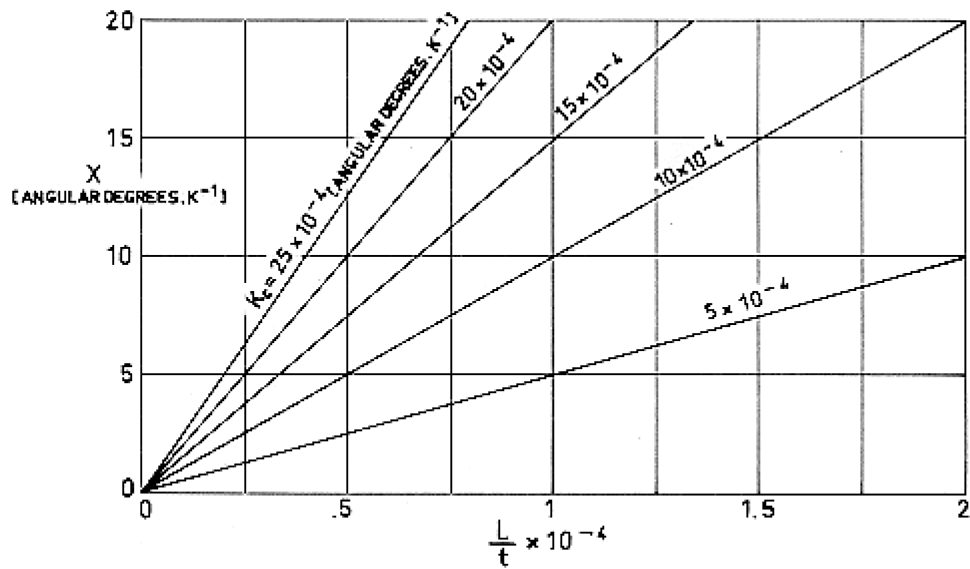


Figure 5-7: Sensitivity vs. ratio L/t , for different values of K_c . After Martin & Yarworth (1961) [21], KAMMERER (1971) [16].

References: Martin & Yarworth (1961) [21], KAMMERER (1971) [16], Trylinski (1971) [37].

5.2.1.4 Torsional moment of spirals and helical coils

The Torsional Moment of spirals and helical coils is given by

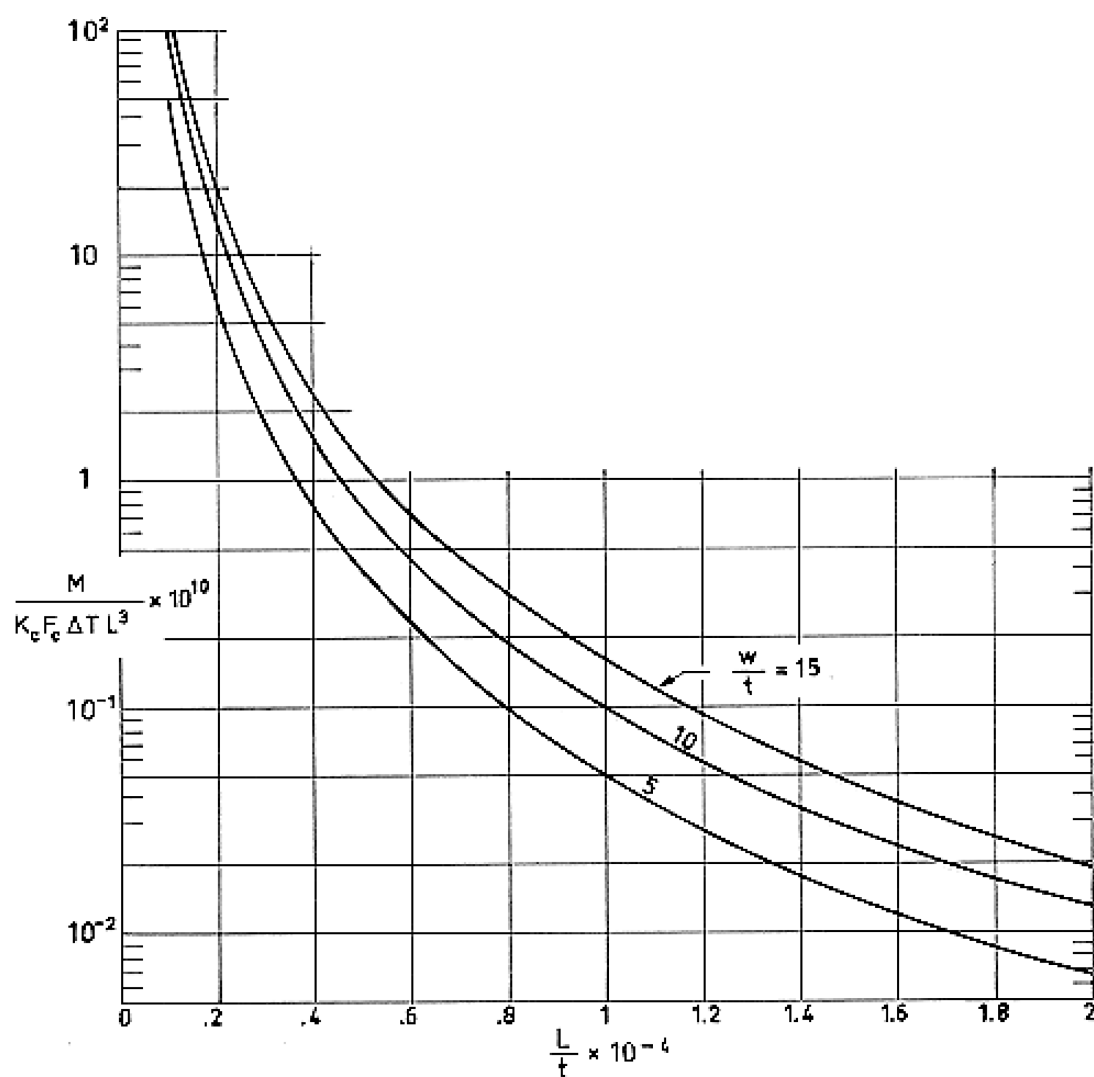
$$M = K_c F_c \Delta T w t^2$$

where the so called thermal force of the spiral, $K_c F_c$, is:

$$K_c F_c = \frac{37}{216} E (\beta_H - \beta_L) \quad [5-4]$$

Typical values of $K_c F_c$, for different bimetals are of order of 1×10^5 to $5 \times 10^5 \text{ N.m}^{-2}.\text{K}^{-1}$.

The Figure 5-8 gives the ratio $M/K_c F_c \Delta T L^3$ versus L/t , for different values of w/t .



Note: non-si units are used in this figure

Figure 5-8: Dimensionless ratio $M/K_c F_c \Delta T L^3$ vs. L/t , for several values of w/t . After Martin & Yarworth (1961) [21], KAMMERER (1971) [16].

5.2.2 Bellows

5.2.2.1 Introduction

Bellows are flexible, thin-walled, circumferentially corrugated cylinders with open or closed ends.

The principle of operation of the bellows is simple: an inner to outer pressure difference causes a change in the bellow length, unless both ends are clamped. If an end is clamped while the other is free, the bellows can behave as an actuator.

Bellows serve many different functions, either as independent units or as integral parts of more complex components. Filled with a liquid they are used as measuring devices. Louvers of the NIMBUS spacecraft are actuated by bellows containing a liquid-vapor mixture of Freon (Freon-11 for the louvers of the control subsystem and Freon-114 for those of the sensory subsystem).

Bellows constituted by one or more layers of materials are called respectively one-ply or multi-ply bellows.

5.2.2.2 Materials

Both metallic and non-metallic materials can be used to manufacture the bellows. Metallic bellows can be either formed, welded, machined, or deposited. In the last method the metal is deposited by electroplating or chemically onto machined aluminium mandrels which are later dissolved.

The characteristics of the metallic and non-metallic materials more used in the manufacture of bellows are summarized in the following pages.

Table 5-3: Typical Alloy Used in Bellows
D: Deposited, F: Formed, W: Welded

MATERIAL			TYPE	OUTSTANDING CHARACTERISTICS
COPPER ALLOYS	BRASS, BRONZE		F D	HIGH PROPORTIONAL LIMIT. GOOD TOUGHNESS.
	BERYLLIUM COPPER			
	ZIRCONIUM COPPER			
ALUMINIUM ALLOYS	5083		F	HIGH STRENGTH-WEIGHT RATIOS. GOOD TOUGHNESS AT LOW AND INTERMEDIATE STRESS LEVELS AT TEMPERATURES AS LOW AS 20 K.
	6061			
	7075			
NICKEL AND CUPRO-NICKEL ALLOYS	NICKEL 200		F D	GOOD CORROSION RESISTANCE. LOW MAGNETIC PERMEABILITY.
	MONELS	400 404 K 500		
TITANIUM ALLOYS	Ti - 75 A		F	HIGH STRENGTH AND STRENGTH TO WEIGHT RATIO. GOOD CREEP STRENGTH FROM 530 K TO 640 K.
	Ti - 6 Al - 4 V			
LOW-ALLOY STEELS	4130		F	EXTREMELY HIGH STRENGTH. HIGH PROPORTIONAL LIMIT. HIGH FATIGUE STRENGTH. GOOD CREEP RESISTANCE.
STANDARD AUSTENITIC STAINLESS STEELS	304, 304 L 310, 316 321, 347		F W	EXCELLENT TOUGHNESS TO 20 K. GOOD FATIGUE AND CREEP STRENGTH. GOOD NEUTRON RADIATION RESISTANCE. GOOD CORROSION AND OXIDATION RESISTANCE.
PRECIPOTATION-	17-4 PH, 17-7 PH		F W	HIGH STRENGTH. GOOD CREEP

MATERIAL		TYPE	OUTSTANDING CHARACTERISTICS
HARDENING STAINLESS STEELS	PH-15-7 Mo, AM350		STRENGTH. HIGH FATIGUE STRENGTH.
OTHER IRON-BASE ALLOYS	19 - 9 DL	F W	HIGH STRENGTH. GOOD CREEP STRENGTH. HIGH FATIGUE STRENGTH PLUS SEALABILITY TO HARD GLASS (KOVAR).
	A - 286		
	KOVAR		
NICKEL-BASE ALLOYS GROUP I	INCOELS 600, 625, X-750, 718	F W	GOOD HIGH TEMPERATURE STRENGTH. GOOD FATIGUE STRENGTH. GOOD TOUGHNESS. GOOD CREEP RESISTANCE. GOOD STRENGTH-TO RUPTURE.
	INCOLOY 825		
	HASTELLOY C		
NICKEL-BASE ALLOYS GROUP II	M252: WASPALOY	W	
	UDIMET 700		
	RENE 41 AND 62		
COBALT-BASE ALLOYS	L 605	W	
REFRACTORY METALS	COLUMBIUM	W	
OTHER ALLOYS	INVAR, (Ni-Span-C)	W	

NOTE From TRW (1970) [36].

Table 5-4: Typical Nonmetallic Materials Used in Bellows

	BUNA-N	NEOPRENE	RUBBER COMPOUNDS		SILICONE RUBBER	TEFLON
			MODIFIED ISOMERIZED RUBBER	CHLORINATED		
Temperature Range without significant changes in Properties [K]	200-500	250-360				200-525
Density [kg.m ⁻³]	1000	1230	1060	1640	1666	2160
Specific Heat [J.kg ⁻¹ .K ⁻¹]	2000	1674	2092	1550 to 1800		1670
Thermal Conductivity [W.m ⁻¹ .K ⁻¹]	0,158 to 0,213	0,209	0,109 to 0,121	0,126	0,177 to 0,277	0,242
Thermal Expansion Coefficient [K ⁻¹]	9x10 ⁻⁵ to 2x10 ⁻⁴	9x10 ⁻⁵ to 2x10 ⁻⁴	7,5x10 ⁻⁵	1,2x10 ⁻⁴	3,6x10 ⁻⁴	(1,6±0.2) x10 ⁻⁵
Solar Radiation Effects	NONE	NONE		DARKENS	NONE	NONE
Acid Effects	None except strong acids	None	None for weak acids, and ClH, SO ₄ H ₂	None	None except strong acids	None
Organic Dissolvent Effects	None except ketones and esters	None except oxygenated dissolvents and aromatic hydrocarbons	None except aromatic and aliphatic hydrocarbons	None except ketones, esters, and aromatic hydrocarbons	None except esters, and aromatic and aliphatic hydrocarbons	None
Alkali Effects	None		None	None	None except strong alkalies	None
Mineral Oil and Fuel Effects	None	None	Attacked	None	None	None

NOTE References: Burton (1949) [5], Stern (1954) [34].

Actuating Fluids

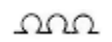
Table 5-5: Typical Fluids Used in Bellows

NAME	FORMULA	DENSITY [kg.m ⁻³]	MELTING POINT [K]	BOILING POINT [K]
Butane	CH ₃ (CH ₂) ₂ CH ₃	600 (T = 273 K)	138	272,6 to 272,9
Ethyl Chloride (Chloroethane)	CH ₃ CH ₂ Cl	921,4 (273 K)	134,5	285,3
Freon 11	CClF ₃		162	248
Freon 21	CHCl ₂ F	1421 (273 K)	146	282
Methyl Chloride (Chloromethane)	CH ₃ Cl	1008 (243 K) 960 (273 K)	175,5	249

NOTE From Hodgman (1953) [14].

5.2.2.3 Convolutions and characteristics

Table 5-6: Bellows Convolutions and Relevant Characteristics

	CONVOLUTION SHAPE	AXIAL SPRING RATE	LONG STROKE CAPABILITY	RESISTENCE TO DIFFERENTIAL PRESSURE
FORMED				
SEMITOROIDAL		VERY HIGH	VERY POOR	VERY GOOD
U-SHAPED, STRAIGHT WALL		MEDIUM	FAIR	FAIR
U-SHAPED, EXTERNAL RING SUPPORT		HIGH	FAIR	VERY GOOD
U-SHAPED, INTERNAL RING SUPPORT		HIGH	FAIR	VERY GOOD
U-SHAPED, EXTERNAL T-RING SUPPORT		HIGH	FAIR	VERY GOOD
S-SHAPED		MEDIUM	FAIR	FAIR
S-SHAPED EXTERNAL RING SUPPORT		HIGH	FAIR	VERY GOOD
TOROIDAL EXTERNAL		VERY HIGH	POOR	EXCELLENT

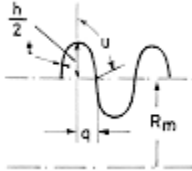
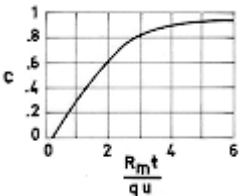
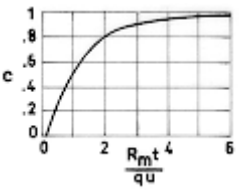
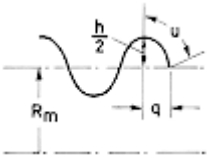
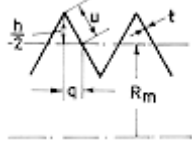
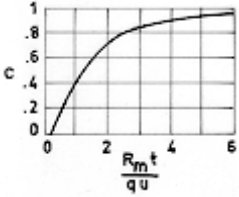
	CONVOLUTION SHAPE	AXIAL SPRING RATE	LONG STROKE CAPABILITY	RESISTENCE TO DIFFERENTIAL PRESSURE
PRESSURE				
TOROIDAL INTERNAL PRESSURE		VERY HIGH	POOR	EXCELLENT
NESTING (SINGLE SWEEP)		MEDIUM	GOOD	GOOD
WELDED				
FLAT CONICAL PLATE		MEDIUM	FAIR	GOOD
STEPPED FLAT PLATE		LOW	GOOD	FAIR
CURVED (SINGLE SWEEP)		MEDIUM	GOOD	GOOD
CORRUGATED (NESTING)		VERY LOW	EXCELLENT	POOR
CORRUGATED (NON- NESTING)		LOW	GOOD	POOR
TOROIDAL		VERY HIGH	POOR	EXCELLENT
DEPOSITED				
U-SHAPED (CAN BE VARIED)		LOW	GOOD	FAIR
MACHINED				
RECTANGULAR		HIGH	FAIR	EXCELLENT

NOTE From TRW (1970) [36].

5.2.2.4 Spring rate

The spring rate, K , is the ratio of the applied force to the resulting deflection. In the case of bellows the spring rate ranges from $2 \times 10^3 \text{ N.m}^{-1}$ to $3 \times 10^5 \text{ N.m}^{-1}$. Formulae to calculate K in several cases can be found in Table 5-7 below.

Table 5-7: Spring Rate for Several Bellows

SHAPE	SPRING RATE	ADDITIONAL DATA
<p>ELLIPTICAL</p> 	$k = 6,92 \frac{ER_m t^3}{uh^2} \frac{q}{L_c} \left(\frac{1}{c} \right) \cdot \left[\frac{q + h/2}{2q + h/2} \right]$ $L_c = 4u$	 $m_c = 6,63 \rho t D_m \sqrt{3,3h^2 + 2qh + 3,3q^2}$
<p>CONICAL FLAT PLATE</p> 	$k = 6,92 \frac{ER_m t^3}{uh^2} \frac{q}{L_c} \left(\frac{1}{c} \right)$ $L_c = 4u$	 $m_c = 6,28 \rho t D_m \sqrt{h^2 + 4q^2}$
<p>SINE WAVE</p> 	$k = 6,92 \frac{ER_m t^3}{uh^2} \frac{q}{L_c} \left(\frac{1}{c} \right) \cdot \left[\frac{q + h/2}{1,6q + h/2} \right]$ $L_c = 4u$	 $m_c = 12,57 \rho t D_m u$

NOTE From TRW (1970) [36].

The flexibility, F , is the ratio of the deflection to the applied pressure difference.

5.2.2.5 Effective area

Effective area of a bellows is the equivalent surface area on which pressure acts to produce the axial force. Typical range of effective area of the bellows is from 6×10^{-4} to $30 \times 10^{-4} \text{ m}^2$.

Effective area on both formed and welded bellows can be approximated to an accuracy of 3 percent by the following relationship:

$$A = \pi/16(D_o + D_i)^2$$

References: FIAT (1970) [12], TRW (1970) [36], Trylinski (1971) [37].

5.2.2.6 Volume

The inner volume of the bellows may be obtained from the following expression:

$$V = 0,262 L (D_o^2 + D_o D_i + D_i^2)$$

Reference: TRW (1970) [36].

5.2.2.7 Response

Response of a bellows is the time required to move it against its own inertia and spring force, through its operating stroke.

Typical values of gas filled bellows response vary from 3×10^{-3} to 50×10^{-3} s, depending on the bellows geometry. Bellows with large effective areas and low spring rates have faster response times. Bellows that require long deflections are generally slow. Liquid filled bellows may have response times of one to three seconds.

Reference: TRW (1970) [36].

5.2.2.8 Vibrations

Life of the bellows under vibration depends upon the stresses induced, the level and frequency of vibration, and the amount of damping within the system.

The vibration frequency can be estimated by use of the following formulae.

Table 5-8: Frequency of Bellows Vibration

FREQUENCY MODE	FORMULA	CONDITIONS OF CALCULATION	APPROXIMATION TO EXACT VALUE
LONGITUDINAL	$f_{n=1} = 3,13 \sqrt{\frac{K}{m_1 + \frac{m_2}{3}}}$	BELLOW EMPTY. ONE END FREE.	GOOD
LONGITUDINAL (ACCORDION)	$f_{n=1} = 19,825 \sqrt{\frac{K}{m_{fa} + m_a}}$	BOTH ENDS CLAMPED. DIFFERENTIAL PRESSURE LESS THAN $6,9 \times 10^3$ Pa.	GOOD
LATERAL (TRANSVERSE OR BEAM)	$f_{n=1} = 2,22 \sqrt{\frac{KD_o^2}{l^2(m_a + m_l)}}$	BOTH ENDS CLAMPED. DIFFERENTIAL PRESSURE LESS THAN $6,9 \times 10^3$ Pa.	POOR
TORSIONAL	VERY HIGH FREQUENCY AND VERY LOW AMPLITUDE IT IS NOT A PROBLEM.		
FLOW-INDUCED	THEY ARE NOT SIGNIFICANT UNDER SPACE CONDITIONS.		

NOTE From TRW (1970) [36].

5.2.2.9 Summary table concerning existing bellows