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Axial and Pressure Thrust Stiffness of Metal Bellows for Vibration Isolators

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Abstract. Metal bellows are used as a spring element and simultaneously as a container (shell) for a damping medium in vibration isolators, especially in applications where any leakage is inadmissible. Dynamic behaviour of these isolators is affected by axial stiffness of bellows and by a resistance against axial deformation of bellows filled with fluid, which is in this article called pressure thrust stiffness. A method of the pressure thrust stiffness determination is discussed in this study. The method uses FEM model, which has been verified by stiffness measurement of a chosen bellows. Consequently, the sensitivity analysis of bellows dimensions to axial and pressure thrust stiffness was performed to find a dimension parameter of bellows which allows to adjust the ratio between axial and pressure thrust stiffness. Sensitivity analysis shows that the stiffness ratio of metal bellows can be adjusted by two dimensional parameters - mean diameter of bellows and corrugation width.

1 Introduction

Bellows is a flexible shell component which is usually made of stainless steel by welding or forming. Shape, dimensions and number of corrugations (waves) affect mechanical properties of the bellows [1]. Except well know applications such as pipeline systems, flexible couplings etc. [2], the metal bellows have been used in vibration isolators, especially for space applications [3, 4].

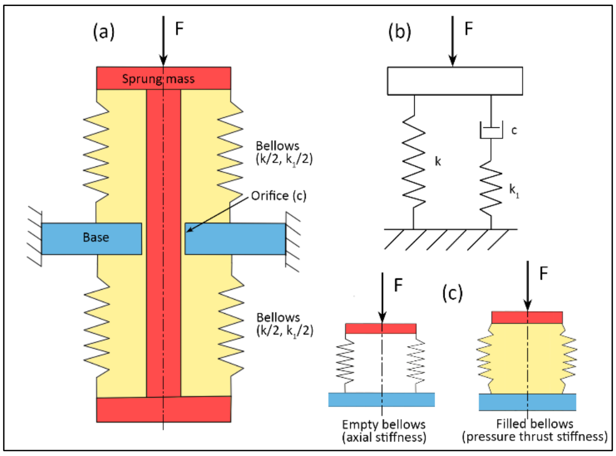

Figure 1. Scheme of vibration isolator with bellows.

The isolators with bellows, see Fig. 1 (a), have several benefits compared to conventional vibration isolators with a piston and a piston rod which must be sealed by sliding seals. The isolators with bellows are sealed by static seals, thus they are frictionless [5]. Therefore, the risk of leakage is minimal. Last but not least, their isolation ability at high frequencies is much better than the isolators with piston [3].

Sum of axial stiffness of both bellows result in primary stiffness of the isolator *k*. The bellows are filled with a damping medium (fluid), see Fig. 1 (b). Flow of the fluid through the orifice causes a damping *c*. The load force *F* increases the pressure of fluid in upper bellows. The pressure increase causes the fluid flow and a pressure thrust (force in axial direction due to pressure), which forces the bellows to extend. Ratio between damping force caused by flow and spring force caused by pressure thrust depends on deformation and velocity of the isolator. Considering that both bellows are connected rigidly due to the red part, the bellows can extend or shorten only because of change their internal volume. Resistance of bellows filled with fluid against compression or tension is in this study called a pressure thrust stiffness, see Fig. 1 (c).

The damper *c* is elastically connected. The secondary stiffness k_1 of the isolator involves the compressibility of the fluid and the pressure thrust stiffness of both bellows. In case of oil as damping medium the compressibility of oil is much higher than the pressure thrust stiffness of metal bellows. Therefore, the bellows pressure thrust stiffness is almost equal to secondary stiffness of the isolator k_1.

Ratio between the secondary and the primary stiffness (1) specifies dynamic behaviour of the isolator [7].

$$N = \frac{k_1}{k} \tag{1}$$

This study was created during a design of vibration isolator for space application. Bellows proved to be the advantageous solution for securing desired stiffness and damping in the vibration isolation system. However, pressure thrust stiffness has not been declared by the bellows manufacturers. Therefore, it was necessary to create FEM model of bellows which allows to determine the pressure thrust stiffness from the bellows dimensions, verify the model by measurement and perform a sensitivity analysis to find dimension parameters which allow to adjust the stiffness ratio. After these steps, it is possible to find the most suitable bellows for the proposed vibration isolator.

2 Methods

The FEM model was compared with stiffness measurement of two bellows with serial number 324125 by Wizenmann Company. Dimensions of both bellows were measured almost identical, but it was slightly different than the values listed in the product list [8]. Measured values of the bellows parameters are summarized in Table 1 and shown in Figure 2. The bellows was made by forming, therefore the wall thickness is lower than the initial thickness of the sheet blank [9]. The value *t* in Table 1 represents average value of the thickness along the bellows corrugation, which is experimentally determined by the manufacturer.

Table 1. Measured parameter of the bellows.

Parameter	Symbol	Value	Unit
Outer diameter	D	36.5	[mm]
Inner diameter	D	23.6	[mm]
Mean diameter	D_m=(d+D)/2	30.05	[mm]
Corrugation width	w=(D-d)/2	6.45	[mm]
Corrugation length	L	3.2	[mm]
Wall thickness	T	0.22	[mm]
Number of corrugations	I	13	[-]

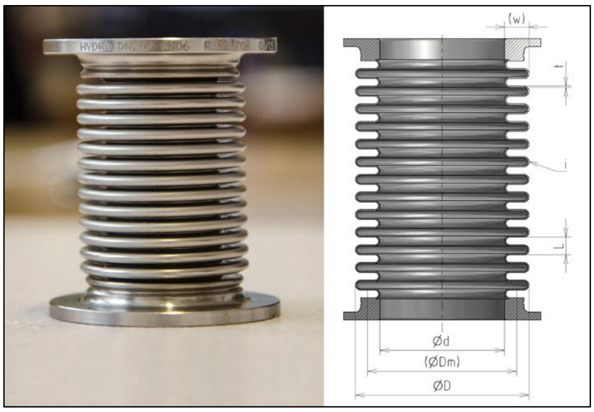

Figure 2. Metal bellows no. 324125 and its dimensions.

Material of bellows is Stainless steel:

Stainless steel	1.4571
Modulus of Elasticity	E = 200 000 MPa
Poisson ratio	μ = 0.28
Yield stress after forming	Re = 500 MPa

Bellows was filled by shock absorber oil:

Shock absorber oil	Paramo TL 15
Volume modulus of Elasticity	K = 2 200 MPa
Density	ρ = 885 kg/m3

Result of axial stiffness simulation was compared with the experiment, calculation provided by manufacturer and also with the product list. The pressure thrust stiffness can be compared only with the measurement.

2.1 FEM Model

The model consists of two parts: wall (steel) and the fluid inside (oil). During determination of axial stiffness the fluid mesh is not considered in the model. The model has following parameters:

Dimensional:	2D
Symmetry:	Axisymmetric (y)
Element type:	SOLID 182 (wall)
	HSFLD 241 (fluid)
Solution:	Non linear

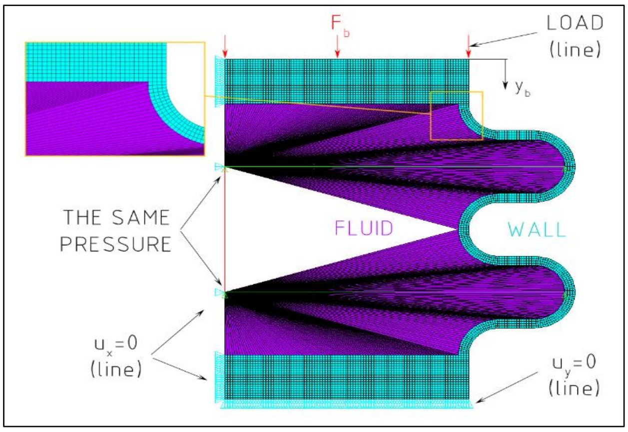

Figure 3. FEM model of metal bellows.

Load force is applied by the pressure on the top line, which corresponds to the force *Fb*. The displacement of the top line y_b is used for the stiffness calculation. The bottom line cannot move in vertical direction *Y*. Nodes located on *Y* axis cannot move in the horizontal direction *X*. There are several points (depends on number of corrugations) with the same pressure in mesh of fluid. It ensures identical pressure in the fluid, as shown in Figure 3.

Both stiffnesses are obtained by interpolation of several points calculated as ratio of Load force F_b and displacement of top line y_b. The dependence of load force and displacement of top line is assumed to be linear.
The difference between pressure thrust and axial stiffness is that the first one is evaluated when the fluid elements are activated. On the other hand, axial stiffness is evaluated when the fluid is not active.

2.2 Measurement

Measurement as well as the simulation was conducted in two configurations. The difference between them was filling and sealing of the bellows. In the case of axial stiffness measurement, the bellows was empty and the sealing was not used. But, when the pressure thrust stiffness was measured, the bellows was sealed and filled by the oil.

2.2.1 Axial stiffness

Two bellows with dimensions corresponding to Table 1 were consecutively compressed by hydraulic workshop press. The force acting on the bellows front surface was measured by the strain gauge load cell HBM - BMT mounted between the press and the front surface of bellows. Linear position transducer Penny & Gilles SLS150 was placed between the force sensor and press table as shown Figure 4. Both sensors were connected to the data acquisition analyzer Dewetron DEWE-800. Each measurement took 30 seconds. During this period, several strokes of hydraulic press were carried out for higher statistical significance. Bellows was slowly pressed in the range from 0 to 10 millimetres with corresponding force 0-230 Newton.

2.2.2 Pressure thrust stiffness

Pressure thrust stiffness measurement was conducted with similar methodology which was used for the axial stiffness, see Figure 4. Steel bellows were pressed in the range from 0 to 1 mm which corresponds to 0 and 560 N respectively.

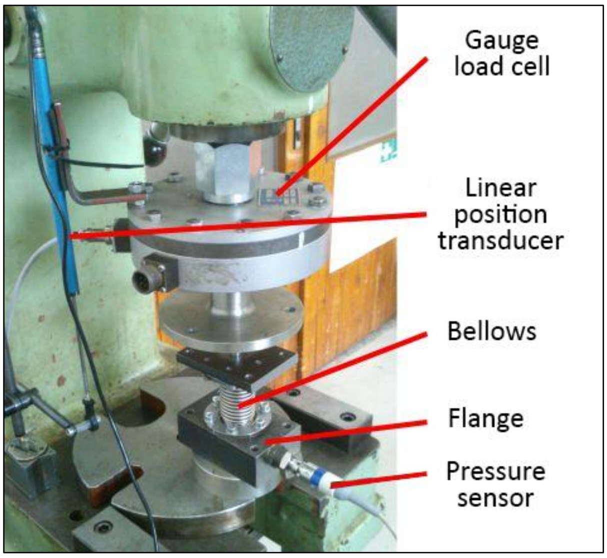

Figure 4. Pressure thrust stiffness measurement.

The measured force is caused by the sum of pressure thrust stiffness and the axial stiffness. Therefore, the pressure thrust stiffness was calculated as a subtraction of measured force and force caused by axial stiffness.
The value of pressure thrust stiffness was similarly to axial stiffness determined as the average of measurements of two bellows.The pressure of the oil inside the bellows was measured by pressure sensor *HBM* 154210274 to check that the pressure inside the bellows did not exceed the allowed value.

3 Results and discussion

Result of axial and pressure thrust stiffness was determined from measured or simulated data by linear approximation. Values of deformation higher than zero corresponds to the compressing of the bellows, deformations lower than zero means tension of bellows.

3.1 Measurement

Force-deformation dependency was measured for two similar bellows and the measured data was linearly approximated by line. The slope of line represents axial or pressure thrust stiffness respectively. Force-deformation dependency of empty bellows, shown in Figure 5, was almost linear in whole range of measurement.

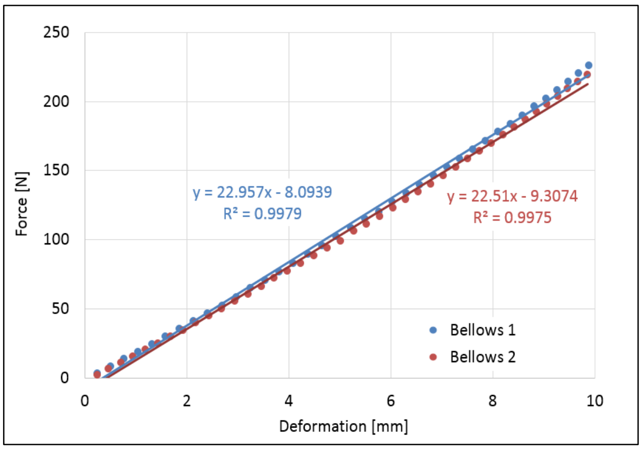

Figure 5. Measured force-deformation dependency for empty bellows (axial stiffness).

Force-deformation dependency of bellows filled by oil is nonlinear at the beginning of bellows compression. This behaviour was probably caused by non-parallel faces of flanges, which are screwed to the bellows. Therefore, the force grew gradually, until the moment when the flanges become parallel to each other. Therefore, the less saturated points in Figure 6 are not included for the approximation.

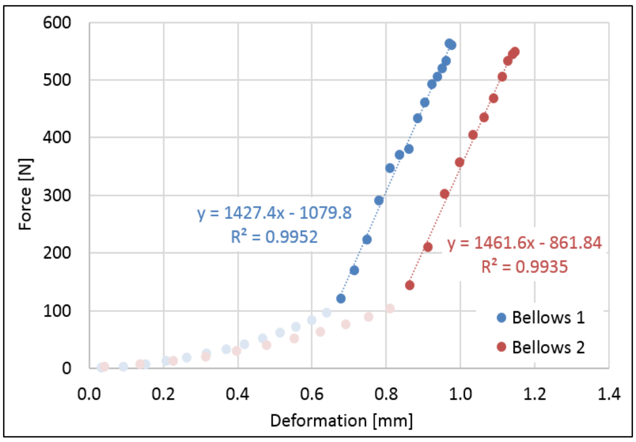

Figure 6. Measured force-deformation dependency for the bellows filled by the oil (pressure thrust stiffness).

3.2 Simulations

The same load force F_b=*300 N* was applied to compare bellows behaviour with or without the filling. Membrane stress in bellows wall is shown in Figure 7. The filling of bellow affects the stiffness, but also the shape of corrugation deformation.

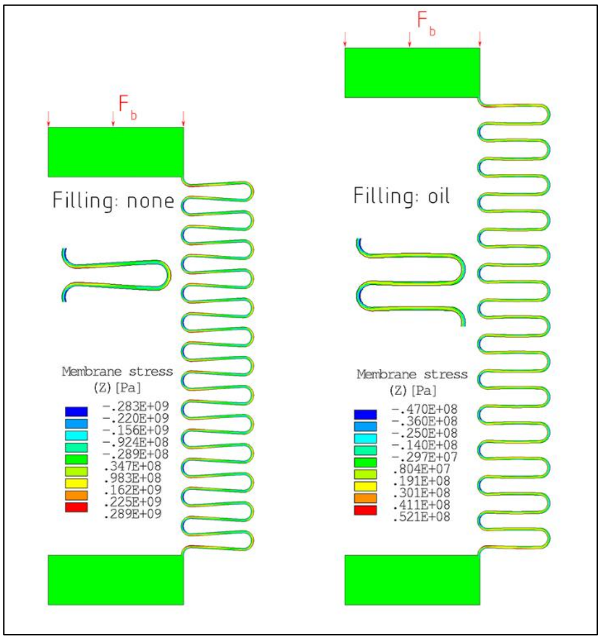

Figure 7. Simulated force-deformation dependency for empty bellows (axial stiffness).

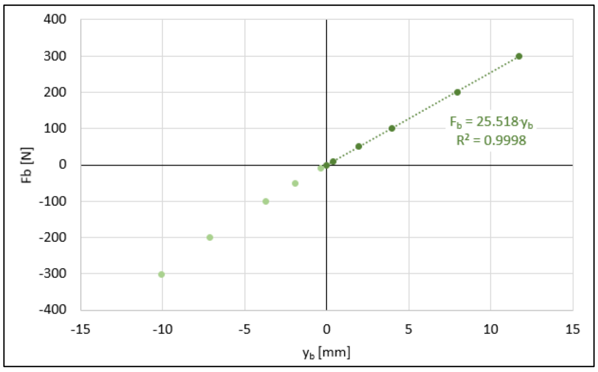

Figure 8. Simulated force-deformation dependency for empty bellows (axial stiffness).

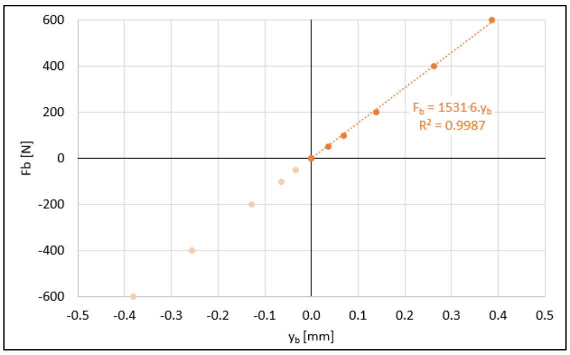

Figure 9. Simulated force-deformation dependency for the bellows filled by the oil (pressure thrust stiffness).

Besides the compression of bellows, the tensile load was simulated too. The results of force-deformation dependency of bellows load by compression and tension differs minimally. However, to achieve the same conditions of simulation and measurement, only the values of force and deformation which are higher than zero (compression of bellows) were compared.

3.3 Results comparison

The results obtained by simulations or measurement were compared. The comparison of axial stiffness was complemented by values from the product list or manufacturer calculations, listed in Table 2.

Table 2. Axial stiffness of bellows.

Procedure	Axial stiffness	Value [N/mm]	Deviation [%]
Product list [8]	k_L	22.3	12.6
Manufacturer calc.	k_C	29.5	15.6
FEM model	k_F	25.52	ref. value
Measurement	k_M	22.7	11

Axial stiffness determined by FEM model differs from all other methods less than 30 %, which is allowed tolerance of axial stiffness, which is guaranteed by manufacturer.

As already mentioned, the pressure thrust stiffness is not declared. Therefore, the pressure thrust stiffness of bellows determined by FEM model k_{1F} was compared only with the measurement k_{1M}, see Table 3.

Table 3. Pressure thrust stiffness of bellows

Procedure	Axial stiffness	Value [N/mm]	Deviation [%]
FEM model	k_{1F}	1531.6	ref. value
Measurement	k_{1M}	1444.5	5.7

3.4 Sensitivity analysis

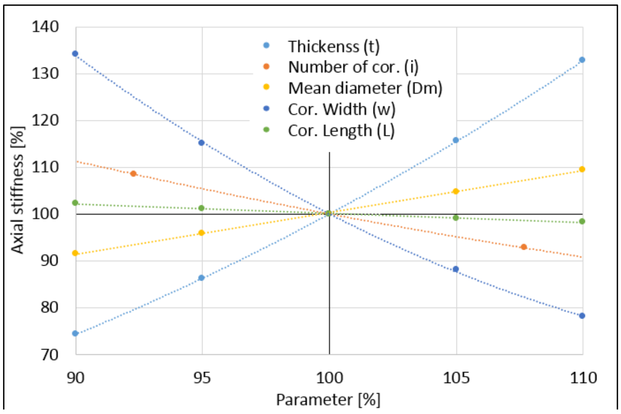

Figure 10. Sensitivity analysis of chosen parameters of bellows to axial stiffness.

The FEM model mentioned above was created for selecting suitable bellows which is going to use in vibration isolator. Therefore, the stiffness ratio *N* is one of important parameter. However, to adjust the stiffness ratio of isolator in Figure 1, it is necessary to find a dimension parameter of bellows which has a different influence on axial and pressure thrust stiffness of the bellows. Therefore, sensitivity analysis of bellows dimension parameters was performed separately for axial and pressure thrust stiffness. Examined parameters are listed in Table 1. Their values were chosen as 90, 95, 105 and 110% of initial value. The stiffness change is also plotted in percent of initial value (100% of each parameter) in Figure 10 - 12.

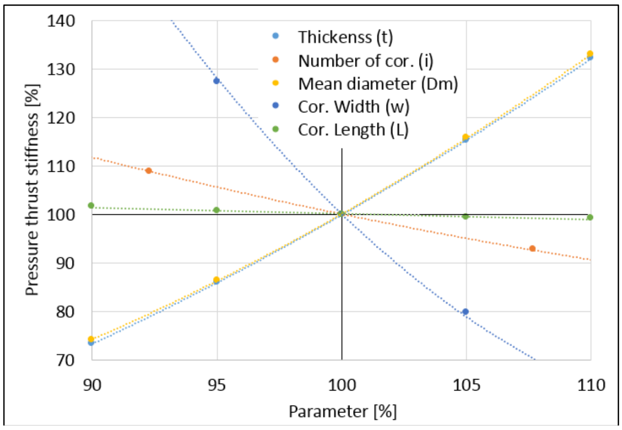

Figure 11. Sensitivity analysis of chosen parameters of bellows to pressure thrust stiffness.

The analysis confirms that the wall thickness *t* has significant influence on the stiffness of bellows. However, the influence is almost the same for axial and pressure thrust stiffness. Similar match was observed for two other parameters: number of corrugation *i* or its length *L*. On the contrary, the analysis revealed that change of the bellows mean diameter D_m or corrugation width *w* has higher influence on the pressure thrust stiffness than on the axial one.

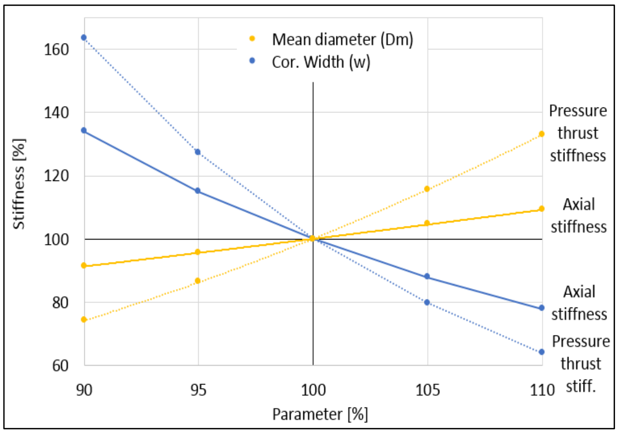

Figure 12. Parameters which allow to adjust the stiffness ratio of isolator.

4 Conclusions

The axial and pressure thrust stiffness of metal bellows have been analyzed in this study. The pressure thrust stiffness (resistance against compression of bellows filled with fluid) is not commonly referenced value. Therefore, the FEM model was created to determine this variable from the bellows dimensions. The model was verified by comparison of axial stiffness obtained by the FEM model, product list, measurement and calculation provided by the bellows manufacturer. The results of axial stiffness obtained by FEM model was 11% higher than the measured value. Simulated pressure thrust stiffness was approximately 5 % higher than value obtained by measurement. This deviation is presumably caused by the imperfect determination of average wall thickness. Moreover, the real thickness of bellows wall is not constant along corrugation.

Sensitivity analysis revealed that the parameters: wall thickness, number of corrugations and its length affect the axial and pressure thrust stiffness almost identically. On the other hand, mean diameter of bellows and corrugations width affect the pressure thrust stiffness more than axial stiffness. Therefore, the last two parameters can be used for adjustment of the ratio between axial and pressure thrust stiffness, which is important for some application of bellows, for example in vibration isolators, which uses the metal bellows as a shell for damping medium. The method mentioned in this study helps to design the most suitable dimensions of the bellows for a specific application.

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