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Research Article

Numerical and Analytical Approach in Predicting Vibrational Analysis of Metallic Expansion Bellows Under Varying Geometrical Condition

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Abstract:

Metal bellows are flexible components that can expand in vacuum or get compressed when subjected to external pressure. Because of their special property of energy absorption and structural displacement accommodation, they find extensive use in applications like bridges, industrial actuators, piping systems, and safety-critical components in aerospace and medical industries. The bellows used in this research are from the product portfolio of Aeroflex Industries Limited (a market leader in flexible flow solutions). Aeroflex Industries Limited provided the design data and physical prototypes for investigation purpose along with the support in project through funding and technical collaborations. This research explores the dynamic performance of metal expansion bellows using a combined analytical-numerical strategy. Three bellows of varying sizes (¼", 2", and 12") having different geometries are under investigation. The examination is carried out for two boundary conditions: (i) both ends are fixed, and (ii) one end is fixed while the other end is free. Natural frequencies of the bellows are calculated with both analytical equations and finite element analysis. The simulated natural frequency is found to converge when the mesh is refined, and optimal frequency values are achieved with particular mesh sizes that trade-off computational efficiency and accuracy. The investigation also compares the maximum deformation felt by each bellow under the aforementioned conditions through numerical simulations. The findings emphasize the role of mesh resolution and boundary constraints on the metal bellows' dynamic response, providing insight useful for design and application in high-performance engineering systems.

1. Introduction

In various industrial applications such as oil and gas, chemical processing, aerospace, automotive, HVAC, etc., flexible flow solutions are critical components due to their requirements of durability and adaptability. Aeroflex Industries Limited is one of the market leaders in providing flexible flow solutions for over 25 years. It has been initiated and funded to research the advanced design and performance of bellows; it is one of the key products in their portfolio. The collaboration enabled to fabricate and test the prototype of bellows focusing on existing challenges in manufacturing and its application.

A bellows is a flexible structure that can be compressed or extended when pressure is applied. These elastic vessels return to their original shape once the pressure or vacuum is released. Bellows are widely utilized in both hot and cold piping systems. As fluids move through the pipelines, they cause the system to expand and contract, leading to pressure fluctuations. These fluctuations can result in axial or angular movements within the piping setup. In scenarios like fossil fuel transportation or nuclear power generation, changes in temperature or mechanical motion frequently cause the system to elongate or contract. To address these variations, expansion joints are essential. These joints incorporate flexible connections, similar to bellows, that accommodate the dimensional changes resulting from thermal expansion and contraction in pipeline systems, ducts, or vessels. The primary function of these joints is to ensure flexibility within piping systems, allowing for the accommodation of both axial and angular movements. Bellows are designed to endure high internal pressures while still providing the necessary axial or angular flexibility. They are widely utilized in various industrial settings, including modern thermal and nuclear power plants, where corrugated pipes serve as expansion joints. Typically, bellows are produced with thinner walls compared to cylindrical shells, enhancing their flexibility and range of movement. Based on manufacturing methods, bellows can be categorized into three main types: formed bellows, which are produced by hydraulically shaping thin-walled tubes; welded edge bellows, which are assembled by welding together thin diaphragm-like discs; and electroformed bellows, which are created by electrodepositing metal onto a mandrel for high precision and thin-walled flexibility. These types differ in terms of strength, precision, and suitability for various applications. The bellows are capable of absorbing various types of movements, including axial movement, angular rotation, longitudinal and lateral deflection, and torsional movement. Axial movement occurs parallel to the centerline axis of the bellows and can involve either expansion or contraction, while lateral movements occur perpendicular to the bellows axis. Additionally, bellows can withstand torsional stress and angular motions. The effectiveness of expansion joints hinges significantly on the design parameters of the bellows, including material selection, geometric features, manufacturing techniques, and performance testing methods. Therefore, it's essential to examine various design aspects of bellows to grasp their mechanical and thermal behaviors in different conditions. Numerous researchers have explored how various geometrical parameters, and operating conditions impact a bellows' performance [13–17]. Designing bellows involves a range of considerations, such as estimating pressure capacity, fatigue life, stress from deflection, spring focus, and stability. Additionally, heat transfer analysis under various operating conditions requires careful attention. This paper offers a comprehensive review of the key design and analysis elements associated with bellows. From a design perspective, it highlights critical geometric variables, including the inside and outside diameters, shape and number of convolutions, height, pitch of convolutions, number of piles, etc. Several studies have been presented to analyze and evaluate these design aspects of bellows [10-12]. A key component of the expansion joint is the bellows, which feature uniform convolutions. These convolutions can be designed in numerous shapes, including flat circular rings, U-shaped, S-shaped, semi-toroidal, rectangular flanged, and various reinforced rings. Expansion joints can be categorized based on their applications and operational conditions into several types: a. single bellow, b. universal bellow, c. hinged bellow, d. gimbal expansion. A representation of bellows in expansion joint is available in Fig. 1.

***Figure 1.** representation of bellows in expansion joint*

Air conditioning equipment, industrial facilities, hose pipes, vacuum systems, and aerospace equipment are just a few of the many applications for metal bellows [18]. To create extremely flexible and strong bellows, the right materials, designs, and production techniques are employed. Bellows that can handle the system's axial, radial, and rotational displacements as well as the combined effects of thermal expansion and vibrations. Bellows must be made to be both longitudinally flexible and circumferentially sturdy in order to withstand pressure and accommodate deflections [19].Metal bellows are typically produced using forming, bulging, and drawing processes. While stainless steel is the most frequently used material, certain applications may call for specialized options like Inconel or aluminum. The design of bellows can vary significantly, including shapes such as U-shaped, semi-toroidal, toroidal, S-shaped, flat, stepped, single sweep, and nested ripple[*]. When designing new bellows, it's important to consider several fundamental parameters and their implications. Factors such as vibration effects, connection points of the bellows, thermal stresses, flow analysis, fatigue life, and the selection of materials and shapes must all play a role in the design process. Compliance with the standards set by the Expansion Joint Manufacturers Association (EJMA) is also essential.

2. Literature Review

Research conducted by Shaikh et al. [3] examined the failure of AM350 steel bellows that were used in the controlled rod drive mechanism of a fast breeder test reactor, involving experimental investigations. Broman et al. [4] suggested utilizing I-DEAS software for the simulation of metal expansion bellows, emphasizing that this method could be adapted to different software platforms where users can set specific parameters for optimization in line with overall design requirements. Li [5] explored the stress impact of the elliptic degree of Ω-shaped bellows, comparing ideal and elliptic toroids under conditions of internal pressure and deflection, ultimately evaluating stress distribution. Their findings indicated that the elliptic degree influences the magnitude of the stresses induced and those arising from axial deflection. Additionally, Broman et al. [4] analyzed the dynamic characteristics of bellows by adjusting certain parameters of beam finite elements, while Jakubauskas and Werner [6] looked into the transverse vibrations of fluid-filled double-bellows expansion joints. Jha et al. [7] investigated stress corrosion cracking in stainless steel bellows within satellite launch vehicle propellant tank assemblies, and Zhu et al. [8] studied the effects of environmental conditions on the fatigue life of U-shaped bellows expansion joints.Gawande et al. [9] conducted a thorough analytical and numerical investigation to analyze the stress characteristics in U-shaped bellows under varying internal pressures of 1MPa to 2MPa. They utilized finite element analysis with ANSYS 14 to explore the properties of these metal expansion bellows. Additionally, they developed a mathematical model to determine the axial natural frequency of the bellows. Their work included performing numerical and modal analyses to assess the natural frequency of axial vibrations and comparing the analytical findings with experimental data. Gawande et al. [9] conducted a thorough analytical and numerical investigation to analyze the stress characteristics in U-shaped bellows under varying internal pressures of 1MPa to 2MPa. They utilized finite element analysis with ANSYS 14 to explore the properties of these metal expansion bellows. Additionally, they developed a mathematical model to determine the axial natural frequency of the bellows. Their work included performing numerical and modal analyses to assess the natural frequency of axial vibrations and comparing the analytical findings with experimental data. A review of existing literature reveals that numerous researchers have explored various aspects of bellows, including their applications under different working conditions, comparative analyses, manufacturing processes, and some efforts towards enhancing fatigue life [9]. However, there remains a critical need to focus on the selection of appropriate materials for specific bellow applications, effective design considerations, induced stress assessments, fatigue life analysis, and failure predictions. Additionally, further investigations into the characteristics of different bellows and the impact of vibrations are warranted.According to industry surveys, the probability of bellow failures often stems from flow-induced vibrations. Therefore, a thorough examination of how these vibrations affect the dynamic characteristics of metal expansion bellows is essential. Currently, researchers are engaged in efforts to extend the life of bellows, and if strategies to minimize failure risks associated with vibrations are successfully implemented, it could significantly enhance the longevity of bellows.

Problem Statement and Objective of Research

Recent industrial surveys indicate that bellows are a crucial component in heat expansion joints. Their primary role is to accommodate both regular and irregular expansion and contraction within the system. Given the extreme working conditions that bellows often operate under, there is a risk of failure due to high stresses, vibrations, and fatigue. Discussions with industry experts suggest that the study presented in this paper requires a thorough understanding of the effects of vibration and the natural frequency associated with it.

This research focuses on the vibrational effects and delves into the numerical and modal analysis of the axial natural frequency of vibration. It aims to explore the selection of materials for bellows used in specific applications, ensuring their design is optimal, and assessing how vibrations impact the dynamic characteristics of metal expansion bellows. Key factor considered in this study is natural

[*] EJMA, Standards of Expansion Joint Manufacturers Association, 9th edition, New York, 2008.

frequency using Finite Element Analysis & Analytical calculations.

3. Methodology

During this study, we examine three distinct bellows with varying geometries for our analysis. For designing the geometry, the u-shaped corrugated pipes with design parameters like sheet thickness, corrugation space, Hose OD, Hose ID, Pitch etc. are utilized (Fig 2) The specifications for the (¼", 2", and 12") bellows are outlined in Tables 1, 2, and 3, respectively. The values of various design parameters—such as wall thickness, convolution height, and pitch—tend to increase with the nominal diameter of the bellows. The bellow with a nominal diameter of 12’’ exhibits the largest values among the three bellows in key design parameters such as wall thickness, convolution height, and pitch (Fig. 3–5). Our analysis unfolds in two stages. First, we discuss the analytical results of the bellows, followed by an explanation of the numerical results. For the analytical part, we identify the natural frequencies of the bellows under two boundary conditions: in the first condition, both ends of the bellows are fixed, while in the second condition, one end is fixed and the opposite end is free.

$$AE\frac{\omega_i}{a}\cos\omega_i\sqrt{\frac{G}{gK_n}}-\frac{W_0}{g}\omega_i^2\sin\omega_i\sqrt{\frac{G}{gK_n}}+K_s\sin\omega_i\sqrt{\frac{G}{gK_n}}=0\ldots\ldots(1)$$

The axial natural frequencies of the bellows can be calculated by using the above equation with different end conditions.

Condition 1: One end of the bellows is fixed and other end free

i.e. $W_0 = 0$ and $K_s = 0$;

Substituting the values in equation (1) we get;

$$\cos\omega_i\sqrt{\frac{G}{gK_n}}=0$$

$$\Rightarrow \omega_i\sqrt{\frac{G}{gK_n}}=\frac{(i-1)\pi}{2}$$

$$\Rightarrow \omega_i=\frac{(i-1)\pi}{2}\sqrt{\frac{gK_n}{G}}$$

Where ' i ' is known as the order number of natural frequency, i = 1,2,3,4 ....

$$\therefore f_i=\frac{\omega_i}{2\pi}$$

$$\Rightarrow f_i=\frac{\frac{(i-1)}{2}\sqrt{\frac{gK_n}{G}}}{2\pi}$$

Substituting the value of $g = 9806.65$ mm/s 2 the frequency equation is;

$$f_i=49.5(i-0.5)\sqrt{\frac{K}{G}}.\ldots\ldots(2)$$

Condition 2: Both ends of the bellows are fixed i.e. $W_0 = 0$ and $K_s = \infty$;

Substituting the values in equation (1) we get;

$$\sin\omega_i\sqrt{\frac{G}{gK_n}}=0$$

$$\Rightarrow \omega_i\sqrt{\frac{G}{gK_n}}=\frac{i\pi}{2}$$

$$f_i=\frac{\omega_i}{2\pi}=49.5i\sqrt{\frac{K_n}{G}}.\ldots\ldots(3)$$

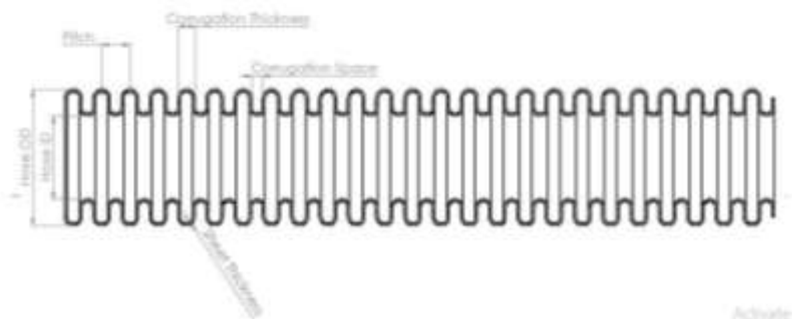

Figure 2. *General Geometry of Expansion bellow*

Table 1. *Specifications of bellow with size of ¼’’*

Sr. no	Parameters	Values	Units
1	Hose ID	6.2	mm
2	Hose OD	9.6	mm
3	Sheet Thickness	0.16	mm
4	No of Plies	1	
5	Pitch	2	mm
6	Corrugation Thickness	1.2	mm
7	Corrugation Space	0.8	mm
8	No of Corrugation	15	
9	Material	SS321	
10	Mass	0.002	Kg

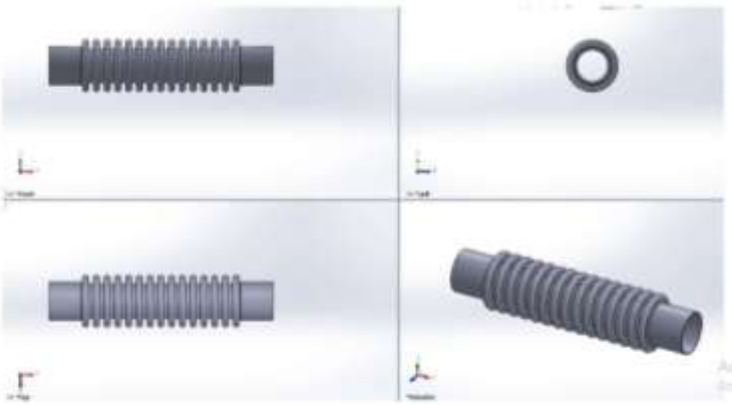

Figure 3. *Geometry of ¼'' Bellow*

Table 2. *Specification of Bellows with size of 2''*

Sr. no	Parameters	Values	Units
1	Hose ID	60.3	mm
2	Hose OD	76.9	mm
3	Sheet Thickness	0.4	mm
4	No of Plies	1	
5	Pitch	8.77	mm
6	Corrugation Thickness	4.78	mm
7	Corrugation Space	3.98	mm
8	No of Corrugation	18	
9	Material	SS321	
10	Mass	0.28	Kg

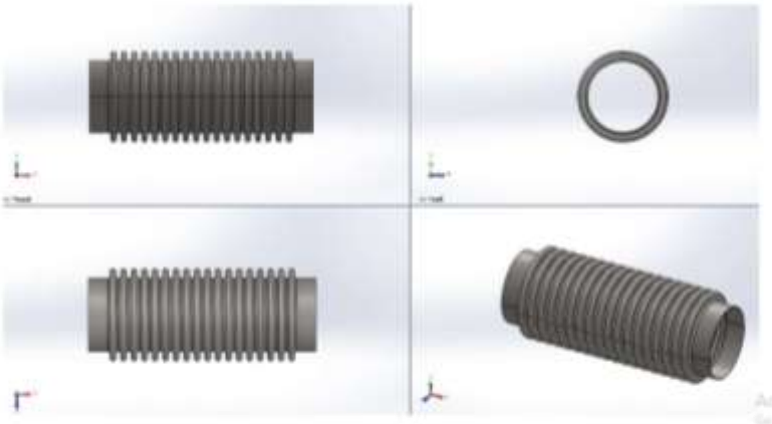

Figure.4 *Geometry of 2'' Bellow*

Table 3. *Specification of Bellows with size of 12''*

Sr. no	Parameters	Values	Units
1	Hose ID	300.2	mm
2	Hose OD	336	mm
3	Sheet Thickness	0.6	mm
4	No of Plies	1	
5	Pitch	18.2	mm
6	Corrugation Thickness	9	mm
7	Corrugation Space	9.2	mm
8	No of Corrugation	15	
9	Material	SS321	
10	Mass	3.21	Kg

Figure 5. *Geometry of 12 '' Bellow*

4. Result And Discussion

During this study, three different bellows, with different geometries are considered for the analysis. The geometry of (¼", 2", and 12") bellows are provided in the Table 1, Table 2 and Table 3 respectively.

A. ¼" inch

For the ¼'' bellow, natural frequencies were first computed analytically under fixed-fixed and fixed-free boundary conditions. The analytical method, based on existing literatures, yielded values of 3912.2 Hz and 1961.7 Hz respectively.

Subsequently, FEA simulations were conducted in ANSYS, with mesh sizes varying from 0.2 mm to 0.8 mm and element counts from 1.2 lakh to 3.5 lakh. The simulated natural frequencies were found to converge as the mesh was refined. The optimum frequency values were 4131.5 Hz for the fixed-fixed case and 1926 Hz for the fixed-free case at a mesh size of 0.4 mm. The FEA results showed good agreement with the analytical values, with an error difference of approximately 5.65 % (Fixed Fixed) and 1.50(Fixed Free) respectively

Table 4. *Result of Axial natural frequencies for the bellow with size of 1/4''*

Sr.no	Mesh Size	No. of element	Boundary Condition	Simulated Natural Freq	EJMA Results	Error
	mm	Lakh		Hz	Hz	
1	0.2	3.5	Both End Fixed	4126.7	3910.8	6
			One End Free	1924	1955.4	-2
2	0.3	2	Both End Fixed	4131.2	3910.8	6
			One End Free	1926	1955.4	-2
4	0.4	1.5	Both End Fixed	4131.5	3910.8	6
			One End Free	1926	1955.4	-2
5	0.5	1.41	Both End Fixed	4157.2	3910.8	6
			One End Free	1939.8	1955.4	-1
6	0.8	1.2	Both End Fixed	4165.2	3910.8	7
			One End Free	1941.3	1955.4	-1

Results of Mesh Convergence (¼" size)

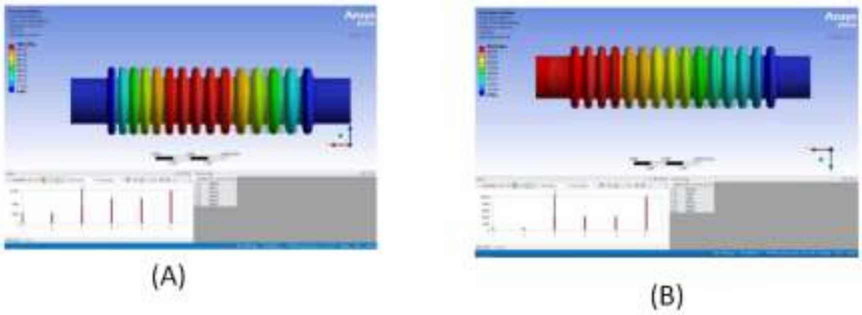

Figure 6. *Maximum deformation of bellow with size of 1/4'' for both end fixed (A) and one end fix and other end free (B)*

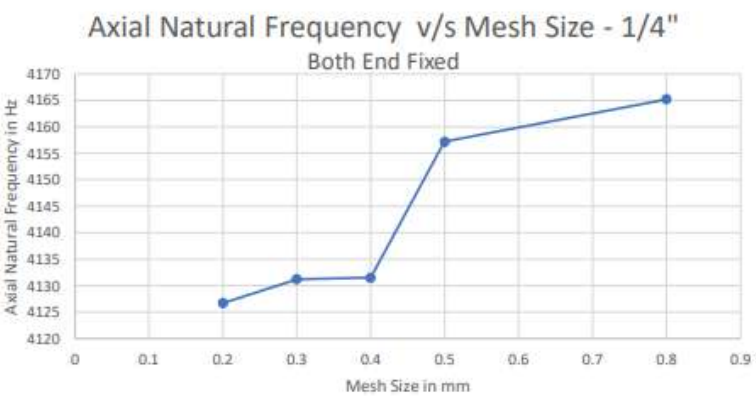

Figure 7. *Variation in simulated natural frequency with mesh size for both end fixed condition in ¼" Bellow*

Table 5. *Result of Axial natural frequencies for the bellow with size of **2”***

Sr.no	Mesh Size	No of elements	Boundary Condition	Simulated Natural Freq	EJMA Results	Error
	mm	Lakh		Hz	Hz	%
1	0.6	16.5	Both End Fixed	329	313.6	5
			One End Free	158.6	156.8	1
2	0.8	9.23	Both End Fixed	329.5	313.6	5
			One End Free	158.9	156.8	1
3	1	6.9	Both End Fixed	329.9	313.6	5
			One End Free	159.1	156.8	1
4	1.2	5.52	Both End Fixed	329.9	313.6	5
			One End Free	159.1	156.8	1
5	1.5	4.25	Both End Fixed	331.7	313.6	6
			One End Free	159.9	156.8	2

Results of Mesh Convergence (2’’size)

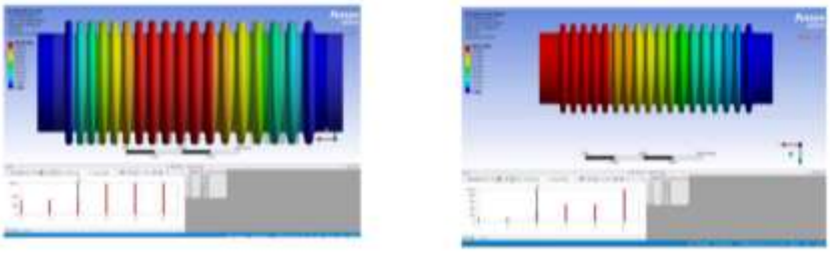

Figure 8. *Maximum deformation of bellow with size of 2’’ for both end fixed (A) and one end fix and other end free (B)*

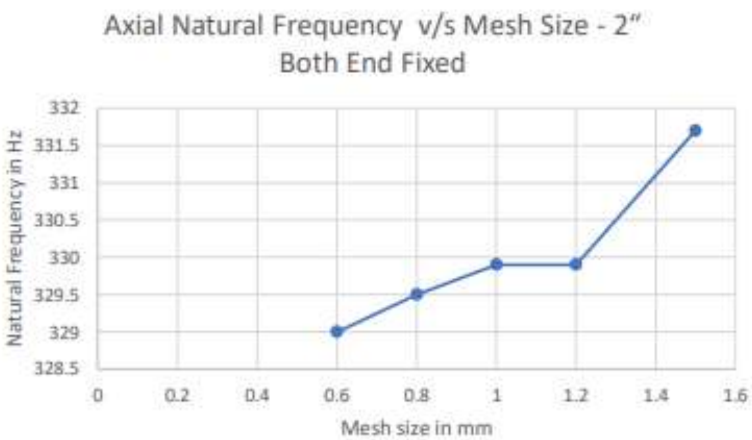

Figure 9. *Variation in simulated natural frequency with mesh size for both end fixed condition in 2” Bellow*

12” Inches

Table 6. *Result of Axial natural frequencies for the bellow with size of 12”*

Sr.no	Mesh Size	No. of element	Boundary Condition	Simulated Natural Freq	EJMA Results	Error
	mm	Lakh		Hz	Hz	
1	1.5	22.6	Both End Fixed	120.3	110.85	9
			One End Free	59.399	55.42	7
2	2	13.4	Both End Fixed	120.71	110.85	9
			One End Free	59.587	55.42	8
3	2.5	10.4	Both End Fixed	121.15	110.85	9
			One End Free	59.813	55.42	8
4	3	8.9	Both End Fixed	121.23	110.85	9
			One End Free	59.85	55.42	8

2" Inches

The analytical values for the 2'' bellow under fixed-fixed and fixed-free conditions were found to be 313.6 Hz and 156.8 Hz. In the FEA analysis, mesh sizes ranged from 0.6 mm to 1.5 mm, and the number of elements varied between 4.25 lakh and 16.5 lakh. The natural frequency values obtained from FEA converged to 329.9 Hz (fixed-fixed) and 159.1 Hz (fixed-free) at a mesh size of 1 mm. The FEA results showed good agreement with the analytical values, with an error difference of approximately 6 % (Fixed Fixed) and 1 % (Fixed Free) respectively

For the 12'' bellow, the analytical approach produced frequency values of 110.85 Hz and 55.42 Hz under the two boundary conditions. FEA was performed using mesh sizes from 1.5 mm to 3 mm and the number of elements varied between 22.6 lakh and 8.9 lakh. The highest accuracy was observed at a mesh size of 2 mm, where the FEA returned frequencies of 120.71 Hz (fixed-fixed) and 59.58 Hz (fixed-free). The FEA results showed good agreement with the analytical values, with an error difference of approximately 9 % (Fixed Fixed) and 7 % (Fixed Free) respectively

Results of Mesh Convergence (12''size)

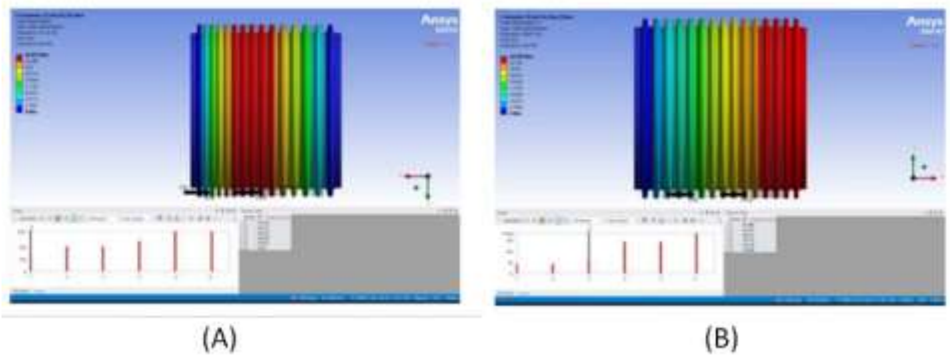

***Figure 10**. Maximum deformation of bellow with size of 12'' for both end fixed (A) and one end fix and other end free (B)*

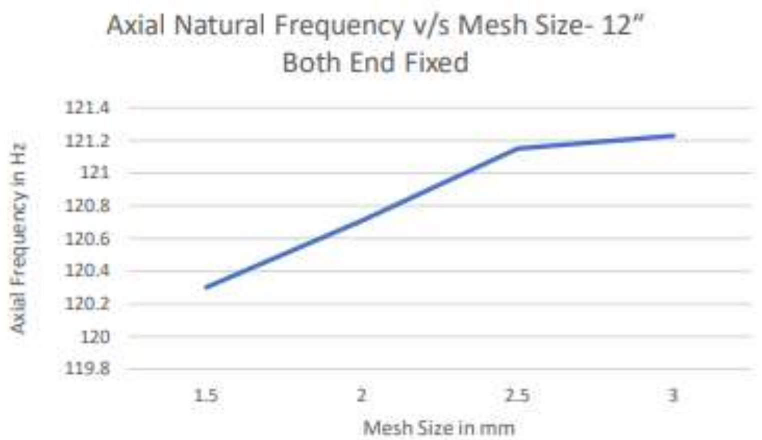

***Figure 11.** Variation in simulated natural frequency with mesh size for both end fixed condition in 12" Bellow*

5. Conclusion

The dynamic characteristics of expansion bellows were evaluated using both analytical calculations and finite element simulations. Three different bellows with nominal diameters of ¼", 2", and 12" were analyzed under two boundary conditions: (i) both ends fixed, and (ii) one end fixed and the other end free.The analytical (EJMA-based) natural frequencies were determined using standard formulations provided by the Expansion Joint Manufacturers Association (EJMA) [2]. serve as theoretical reference values.

In contrast, the numerical (FEA-based) natural frequencies were obtained by performing simulations in ANSYS. The finite element analysis was conducted with varying mesh sizes and element counts to assess convergence and accuracy.

1. For the ¼'' bellow, the EJMA-based analytical frequencies were 3910.8 Hz (fixed-fixed) and 1955.4 Hz (fixed-free). The FEA results at a mesh size of 0.4 mm showed close agreement, yielding 4131.5 Hz and 1926 Hz, with error differences of approximately 5.65% and 1.50%, respectively.
2. For the 2'' bellow, the analytical frequencies were 313.6 Hz (fixed-fixed) and 156.8 Hz (fixed-free). The FEA simulations, optimized at a mesh size of 1 mm, produced values of 329.9 Hz and 159.1 Hz, resulting in errors of 5 % and 1 %.
3. For the 12'' bellow, the analytical frequencies were 110.85 Hz (fixed-fixed) and 55.42 Hz (fixed-free). FEA simulations with a mesh size of 2 mm returned values of 120.71 Hz and 59.58 Hz, corresponding to error differences of 9 % and 7%, respectively.
4. These comparisons confirm that the FEA simulations align well with the EJMA-based analytical results, particularly when mesh refinement is adequately performed. The study highlights the value of combining both methods: EJMA equations provide quick estimations, while FEA allows for detailed behavior analysis under real-world constraints.

Author Statements:

- **Ethical approval:** The conducted research is not related to either human or animal use.
- **Conflict of interest:** The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper
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- **Data availability statement:** The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

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