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Development of Bellows Design Software using MATLAB

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Abstract

Bellows product is an important part in the area of plant engineering, shipbuilding, and petrochemistry. For safety and durability, it is necessary to consider many factors when designing it. This research developed a U-shaped metal bellows design software based on the EJMA 9th Edition manual. We developed this GUI software using MATLAB software to be able to design four types of bellows: Unreinforced Single Bellows, Unreinforced Double Bellows, Reinforced Single Bellows, and Reinforced Double Bellows. We designed the already proven bellows model to verify this software. We investigated the behavior while changing the thickness of the bellows. As the thickness of the bellows increases, the spring rate, thrust force, and stress increase, and fatigue life decreases. This software will help design engineers save time and effort.

Keywords: Bellows, EJMA, Fatigue Life, MATLAB GUI, Stress

1. Introduction

The bellows product is an important part in the area of plant engineering, shipbuilding, and petrochemistry. It is installed to protect pipelines from deformation due to thermal expansion of the tube and ground subsidence.

For safety and durability, it is necessary to consider many factors when designing bellows. In the design process, there is considerable difficulty in obtaining the data required for the design because of the complex shape. The bellows designer has to change the values of a number of parameters to design a product, and perform an iterative calculation for a long time. This inconvenient design process results in degradation in reliability of the product, due to the inefficiency of the design. Therefore, we need to develop a reliable automatic bellows design software[1].

This research developed the U-shaped metal bellows design software based on the EJMA 9th Edition manual. We developed this GUI software using MATLAB software to be able to design four types of bellows: Unreinforced Single Bellows, Unreinforced Double Bellows, Reinforced Single Bellows, and Reinforced Double Bellows. We designed the already proven bellows model to verify the software. We investigated the behavior while changing the thickness of the bellows. As the thickness of bellows increases, the spring rate, thrust force, and stress increase, and fatigue life decreases. This software will help design engineers save time and effort[2–4].

2. Design Theory (EJMA 9th Edition)

In this paper, we describe an important equation from the design equations provided in EJMA, which are proven with a variety of experiences. The most important factors are the axial strain per waveform, spring constant, axial force, lateral force, moment, stress, and fatigue life.

Figure 1 shows the information on the geometry of the bellows, where L_t is the bellows tangent length; L_b is the bellows convoluted length; w is the convolution height; q is the convolution pitch; t is the bellows nominal material thickness of one ply; and n is the number of bellows material plies of thickness t.

We calculate the axial movement per convolution in the x-axis direction resulting from imposed axial movement x, lateral movement y, and angular rotation θ on the basis of the following EJMA design equation.

$$e_x = \frac{x}{N},\ e_y = \frac{3D_m y}{N\left(L_b \pm x\right)},\ e_\theta = \frac{\theta D_m}{2N}$$

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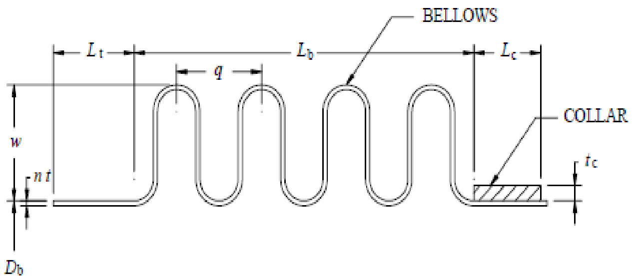

Figure 1. Geometric parameters of bellows.

where, e_x is the axial movement per convolution resulting from imposed axial movement x. This movement may be measured as compression or extension; e_y is the axial movement per convolution resulting from the imposed lateral deflection y; e_θ is the axial movement per convolution resulting from the imposed angular rotation θ; x is the applied axial movement in compression or extension; N is the number of convolutions in one bellows; and D_m is the mean diameter of bellows convolutions, with $D_m - D_b + w + n_t$.

To obtain the axial force, lateral force and moment, we have to calculate the spring constant in advance, as shown in Equations. (2) and (3).

$$f_i = 1.7\frac{D_m E_b t_p^3 n}{\omega^3 C_f}$$

$$f_w = f_i \text{ for } S_t < 1.5S_y$$
$$= 0.67 f_i \text{ for } S_t > 1.5S_y$$

where, f_i is the bellows theoretical initial axial elastic spring rate per convolution; f_w is the bellows working spring rate per convolution; E_b is the modulus of elasticity at design temperature, unless otherwise specified, for bellows material; t_p is the bellows material thickness for one ply, corrected for thinning during forming, and $t_p = t\sqrt{\frac{D_b}{D_m}}$ for bellows formed from tubes with inside diameter equal to D_b; C_f is a factor used in specific design calculations to relate the U-shaped bellows convolution segment behavior to a simple strip beam; $S_t = 0.7(S_3 + S_4) + (S_5 + S_6)$; S_y is the yield strength at design temperature, unless otherwise determined, of the actual bellows material after completion of bellows forming and any applicable heat treatment, where $S_y = \frac{0.67 C_m S_{ym} S_{yh}}{S_{yc}}$; S_{ym} is the yield strength at room temperature of the actual bellows material in the annealed condition from the certified test report; S_{yh} is the yield strength at design temperature of the bellows material in the annealed condition from the applicable code or standard reference; S_{yc} is the yield strength at room temperature of the bellows material in the annealed condition from the applicable code or standard reference; and C_m is a material strength factor.

The axial force at the end of the convoluted length of an expansion joint resulting from axial deflection x, F_a is:

$$F_a = f_w e_x$$

where, f_w is the bellows working spring rate per convolution; and e_x is the axial movement per convolution resulting from the imposed axial movement x.

The lateral force at the ends of the convoluted length of the expansion joint resulting from lateral deflection y, V_l is:

$$V_1 = \frac{f_{wD_m} e_y}{2(L_b \pm x)} \left(\textit{for lateral movement}\right)$$

The moment at the ends of the convoluted length of the expansion joint resulting from lateral deflection y, M_l is:

$$M_1 = \frac{f_{wD_m} e_y}{4} \left(\textit{for lateral movement}\right)$$

The moment at the ends of the convoluted length of the expansion joint resulting from angular rotation θ, M_θ is:

$$M_\theta = \frac{f_{wD_m} e_\theta}{4} \left(\textit{for angular rotation}\right)$$

The bellows tangent circumferential membrane stress due to pressure, S_1 is:

$$S_1 = \frac{P(D_b + nt)^2 L_t E_b k}{2\left(ntE_b L_t (D_b + nt) + t_c k E_c L_c D_c\right)}$$

where, P is the pressure; L_t is the bellows tangent length; k is a factor that considers the stiffening effect of the attachment weld and the end convolution on the pressure capacity of the bellows tangent, and $k = \frac{L_t}{\left(1.5\sqrt{D_b t}\right)}$ if $k \geq 1$, use $k = 1$; t_c is the bellows tangent reinforcing collar material thickness; E_c is the modulus of elasticity at design temperature, unless otherwise specified, for the bellows tangent reinforcing collar material; L_c is the bellows tangent collar length; and D_c is the mean diameter of the bellows tangent reinforcing collar, where $D_c - D_b + 2nt + t_c$.

The bellows circumferential membrane stress due to pressure, S_2 is:

$$S_2 = \frac{PD_m K_r q}{2A_c}$$

where, A_c is the cross-sectional metal area of one bellows convolution.

The bellows meridional membrane stress due to pressure, S_3 is:

$$S_3 = \frac{Pw}{2nt_p}$$

The bellows meridional bending stress due to pressure, S_4 is:

$$S_4 = \frac{P}{2n}\left(\frac{w}{t_p}\right)C_p$$

The bellows meridional membrane stress due to deflection, S_5 is:

$$S_5 = \frac{E_b t_p^2 e}{2w^3 C_f}$$

The bellows meridional bending stress due to deflection, S_6 is:

$$S_6 = \frac{5E_b t_p e}{3w^2 C_d}$$

where, C_d, C_f, C_p are factors used in specific design calculations to relate the U-shaped bellows convolution segment behavior to a simple strip beam; and e is the total equivalent axial movement per convolution.

The fatigue life, the number of cycles to failure, N_c is:

$$N_c = \left(\frac{c}{S_t - b}\right)^a$$

where, S_t is the total meridional stress, where st = 0.7(S_3 + S_4) + (S_5 + S_6); and a, b, and c are material and manufacturing constants.

3. Bellows Design Software

The purpose of this study is to develop a bellows design software, Bellows Designer, using MATLAB GUI. Expansion Joints can be divided into the Unreinforced Single Type, Unreinforced Double Type, Reinforced Single Type, and Reinforced Universal Type. We developed the Bellows Designer to design the bellows for the above four conditions[5].

Figure 2 shows the initial screen of the bellows design software that appears when a user uses Bellows Designer. The initial screen is composed of parameter input sections for the bellows, fastener, collar ring, and reinforcing ring.

The left side of Figure 2 shows the area of inputting parameters such as material, size, whether there is heat treatment of the bellows, temperature, and pressure. The right side of Figure 2 shows the area of inputting parameters of the collar ring, the reinforcing ring, and the fastener, and whether or not to use a reinforcing ring. It is possible to select the material for the bellows, collar ring, reinforcing ring, and fastener in the red boxes in Figure 2. The data on stress and Young's modulus of material that is frequently used for bellows have been stored as a MATLAB file and Microsoft Excel file. Selecting the material in Figure 2 automatically updates the data on stress and Young's modulus of the material.

Figure 3 shows the Bellows Design Analysis screen that automatically opens when a user presses the 'Run & See Reports' button in Figure 2.

If a user chooses the bellows type as shown in Figure 3, important stresses are automatically calculated and displayed to inform whether or not it meets the design criteria. The calculated stress should be evaluated for pressure capacity as follows.

$$S_1 \;\&\; S_2 \le C_{wb} W_b S_{ab}$$

$$S_3 + S_4 \le C_m S_{ab} \ \left(\textit{below the creep range}\right)$$

$$S_3 + \left(\frac{S_4}{1.25}\right) \le S_{ab} \ \left(\textit{in the creep range}\right)$$

where, C_{wb} is the longitudinal weld joint efficiency factor from the applicable code for bellows; W_b is the elevated temperature weld joint strength reduction factor from the applicable design code for bellows; S_{ab} is the allowable material stress at design temperature, unless otherwise specified, from the applicable code for bellows; and C_m is the material strength factor at temperatures below the creep range.

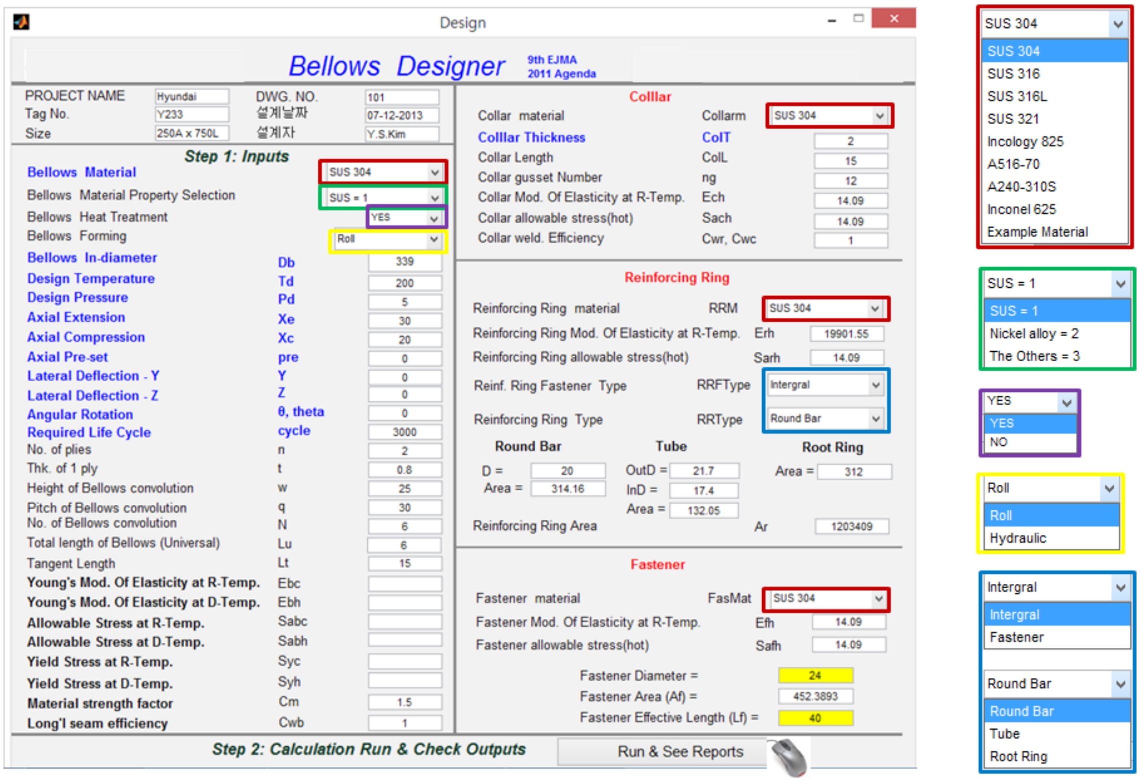

Figure 2. Parameters input process.

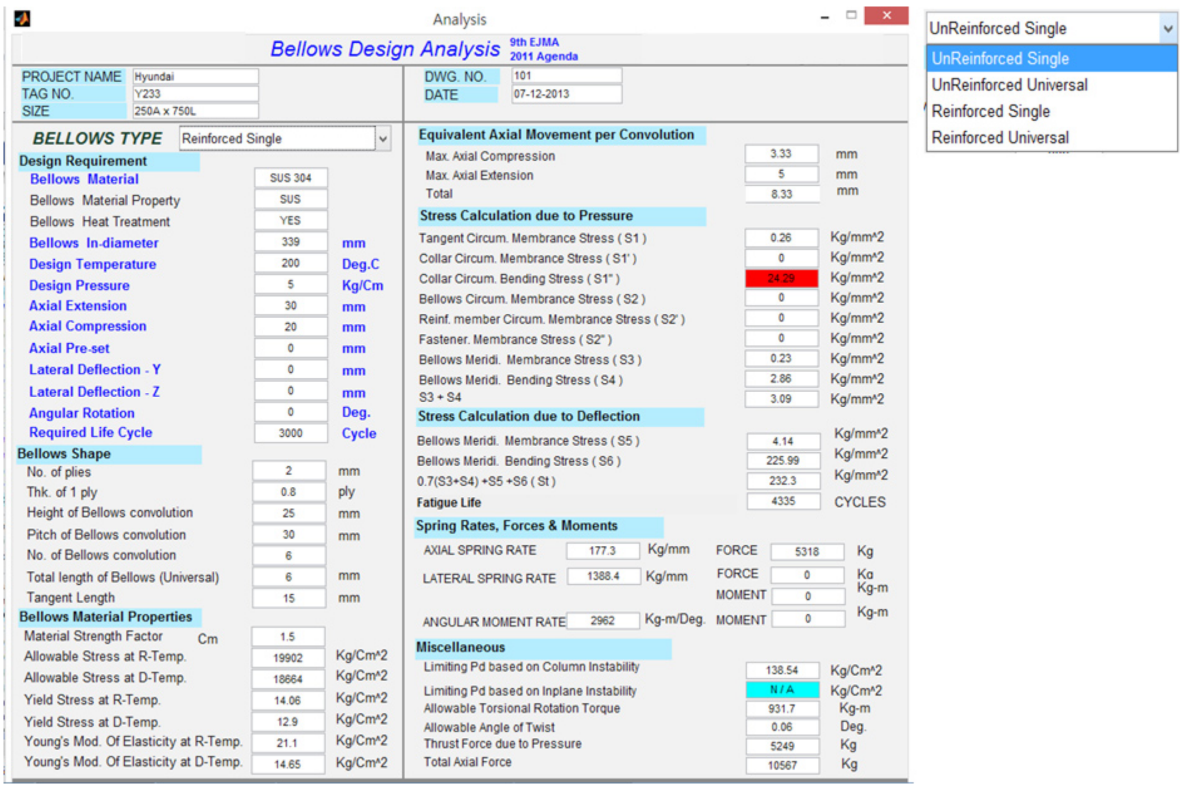

Figure 3. Analysis and calculation process.

If the calculated stresses do not meet the above criteria, warning signs are displayed in red. Also, if the fatigue life does not meet the initial conditions that were entered, warning signs are displayed in red. In this case, the bellows can be redesigned by changing the design condition, by reverting to the previous step.

4. Verification of the Design Software

Figure 4 shows the proven bellows model that we selected to verify the software, by looking at the bellow's behavior.

Table 1 shows the fatigue life, thrust force, axial spring rate, lateral spring rate, and stress due to the thickness change. Their units are respectively cycle, kgf, $\frac{kgf}{mm}$, and $\frac{kgf}{mm^2}$.

Equation 2 above shows that the spring constant increases in proportion to the cube of the thickness. Therefore, as Figures 5 and 6 shows, as the thickness increases, the spring constant of the bellows increases. This causes both the axial force and the stress to increase, as shown in Figures 7 and 8. Equation 14 above shows that the fatigue life is inversely proportional to the total stress S_t. That is, when the thickness of bellows increases, the stress increases; therefore, as Figure 9 shows, the fatigue life drastically decreases.

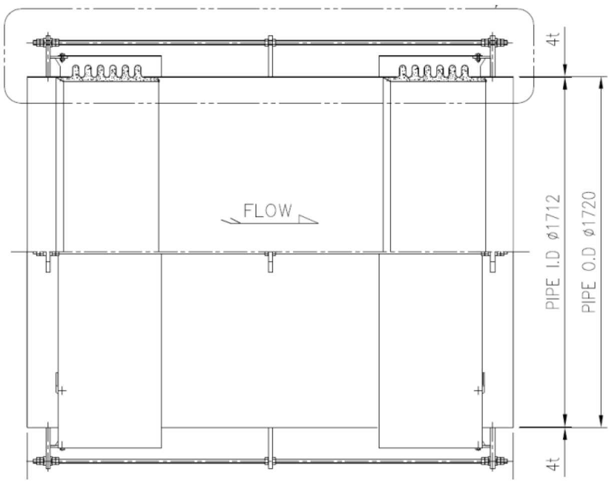

Figure 4. Bellows model.

Table 1. Calculation result

Thickness	0.8	1	1.2	1.4	1.6
Fatigue Life	283295	59690	19941	9013	4706
Thrust Force	4936.7	4937.8	4938.9	4940	4941.1
Axial Spring Rate	4.948	9.277	15.582	24.477	36.222
Lateral Spring Rate	5.791	10.858	18.243	28.664	42.427
Total Stress	70.58	89.52	109.12	127.83	146.75

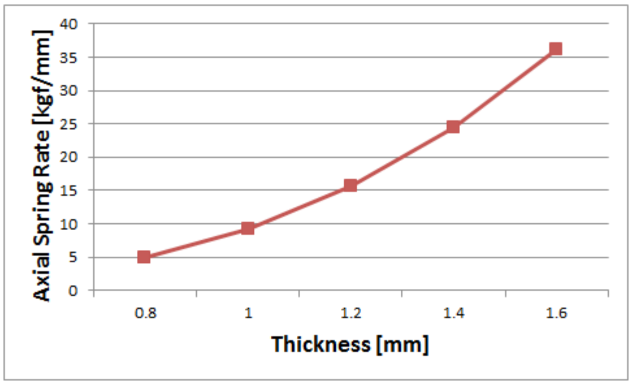

Figure 5. Axial spring rate with varying thickness.

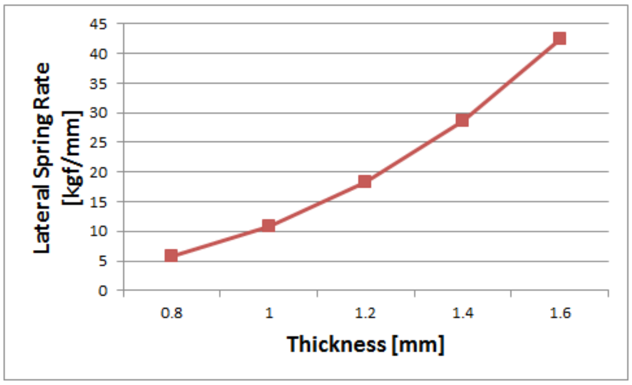

Figure 6. Lateral spring rate with varying thickness.

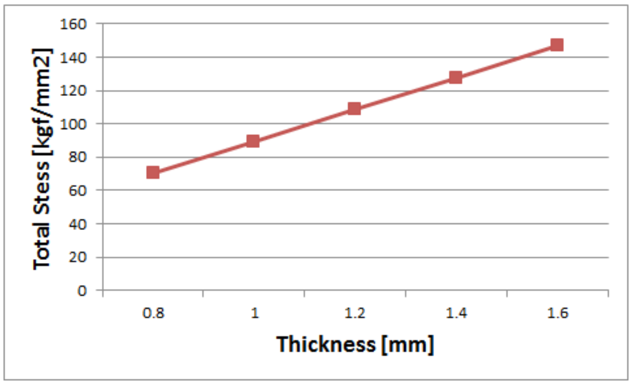

Figure 7. Thrust force with varying thickness.

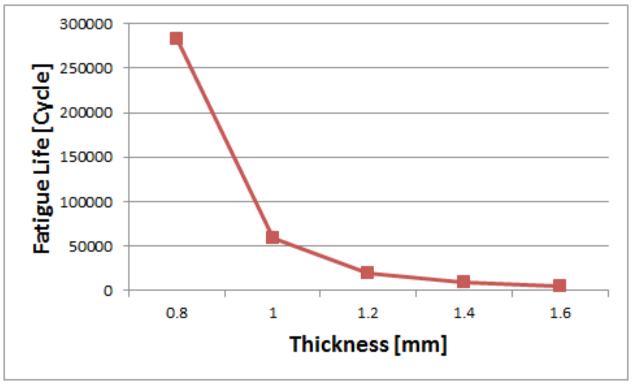

Figure 8. Total stress with varying thickness.

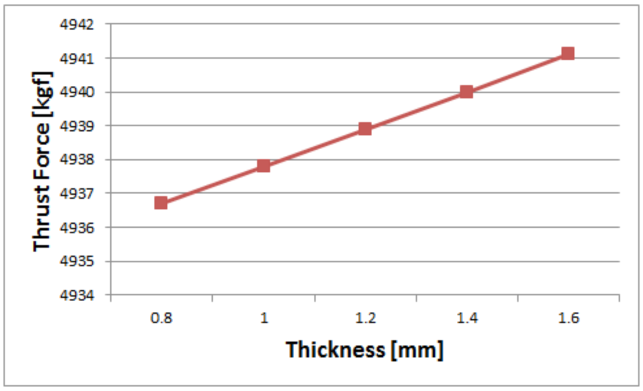

Figure 9. Fatigue life with varying thickness

5. Conclusion

In this study, we develop the bellows automatic design software, Bellows Designer, based on the design formula of EJMA 9th Edition. This software uses the MATLAB GUI to make access to the program code easy, to enhance security, and to reduce the possibility of program errors.

Bellows Designer enables engineers to design bellows of the following four types: Unreinforced Single Bellows, Unreinforced Universal Bellows, Reinforced Single Bellows, and Reinforced Universal Bellows.

We verify the software developed in this study by looking at the behavior of the bellows when selecting a proven bellows model. We find that as the thickness of the bellows increases, the spring constant and thrust force increase, and the fatigue life decreases. This software will help design engineers save time and effort.

6. Acknowledgement

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