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Effects of Geometric Nonlinearities on the Dynamic Characteristics of Portal Frames

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Abstract. In this paper, we present a study of the effects of the presence of large compressive axial forces applied to members of portal frames on their vibration frequencies. It is a well-known fact that axial forces in structural members may affect the so-called geometric stiffness. If they are compressive, the overall stiffness will decrease, and, as a consequence, the vibration frequencies also.

Our structural model is a simple portal frame composed of two upright columns fixed at their bases supporting a horizontal beam pinned at both ends. We suppose a motor to be mounted at the beam mid span. The natural frequencies of vibration of the structure will usually be set far away from the machine nominal operational speed to avoid possible resonance due to motor unbalance. But if large axial forces are applied to the portal frame members changing their geometric stiffness and frequencies, unexpected resonances may occur, potentially dangerous.

Two analysis are carried out. First, a simplified mathematical model is derived using simple Rayleigh's Method considerations. Next, a more refined Finite Element model is implemented. Results agree reasonably well.

Keywords: geometric stiffness, modal analysis, Rayleigh's Method, Finite Element Method.

1 Introduction

The initial stiffness of a structure, calculated in its unloaded state, is affected by the applied forces, the so-called geometric stiffness. The compressive forces reduce the stiffness and the vibration frequencies and can cause "buckling", loss of stability, when the frequencies tend to zero. Traction forces, on the other hand, increase stiffness and, consequently, vibration frequencies.

In this research, a numerical study is presented, using both a Raleigh's Method approximation and the finite element method, of the effects of geometric nonlinearities on the vibrations of rotating machine support structures. These phenomena tend to be more important in modern structural engineering, especially in aerospace applications, due to the use of thin members, more efficient materials and powerful analysis tools.

Here we study the models of a metal portal frame under compression, supporting a rotary engine. The original design foresaw natural frequencies far from the excitation frequency. However, the presence of large axial compression forces will reduce the beam stiffness and its natural frequencies, which can lead to unexpected and potentially dangerous states of resonance. This paper is a continuation of references [2] and [3].

2 Methodology

2.1 Physical Model

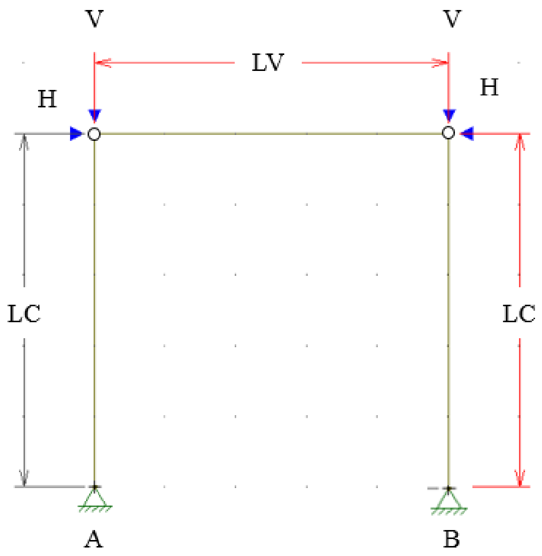

Figure 1. Frame Model

The model represented in Figure 1 represents a three beams frame, under compressive H and V forces.

3 Results

We first present an approximate Rayleigh solution, with 3rd degree polynomial shape functions, for the first two frequencies, as, for example [1].

Elastic beam stiffness

$$K_e = \frac{48EI}{LV^3} \tag{3.1}$$

Geometric beam stiffness

$$K_g = \frac{24H}{5LV} \tag{3.2}$$

Equivalent beam mass

$$M = \frac{34A\rho LV}{70} \tag{3.3}$$

$$\omega_2 = \sqrt{\frac{K_e - K_g}{M}} \text{ em rad/s} \tag{3.4}$$

Elastic column stiffness

$$K_e = \frac{6EI}{LC^3} \tag{3.5}$$

Geometric column stiffness

$$K_g = \frac{12V}{5LC} \tag{3.6}$$

Equivalent column mass

$$M = \frac{33A\rho LC}{140} + A\rho LV \tag{3.7}$$

$$\omega_1 = \sqrt{\frac{K_e - K_g}{M}} \text{ in rad/s} \tag{3.8}$$

Next, Finite Element models are simulated, with various mashes. As expected, more elements lead to better approximation to Rayleigh's solution. It is also important to note that changing the thickness of the beams sections does not change the shape of the curve which describes the frequencies vs the applied load in Figs. 4 and 7.

3.1 Beam compression

Figures 2-4 show results of a MATLAB MEF routine to obtain the first two frequencies, comparing with the approximate Rayleigh solution, for the case of compression H forces applied to the beam. Beam sections are rectangular 100x50 mm with 2 mm and 4 mm wall thickness.

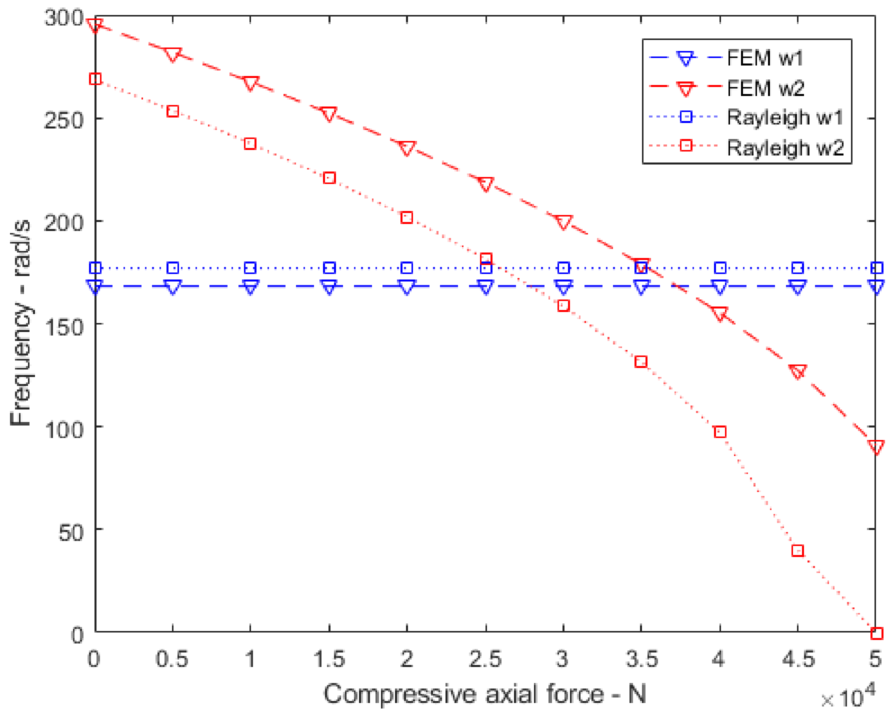

Figure 2. Simulating compressive loads in the beam, structure mesh 2 nodes in the columns and 2 nodes in the beam. FEM w1 and FEM w2 represent the first and second frequencies, respectively, obtained via FEM. Rayleigh w1 and Rayleigh w2 represent the first and second frequencies, respectively, obtained through Rayleigh's method.

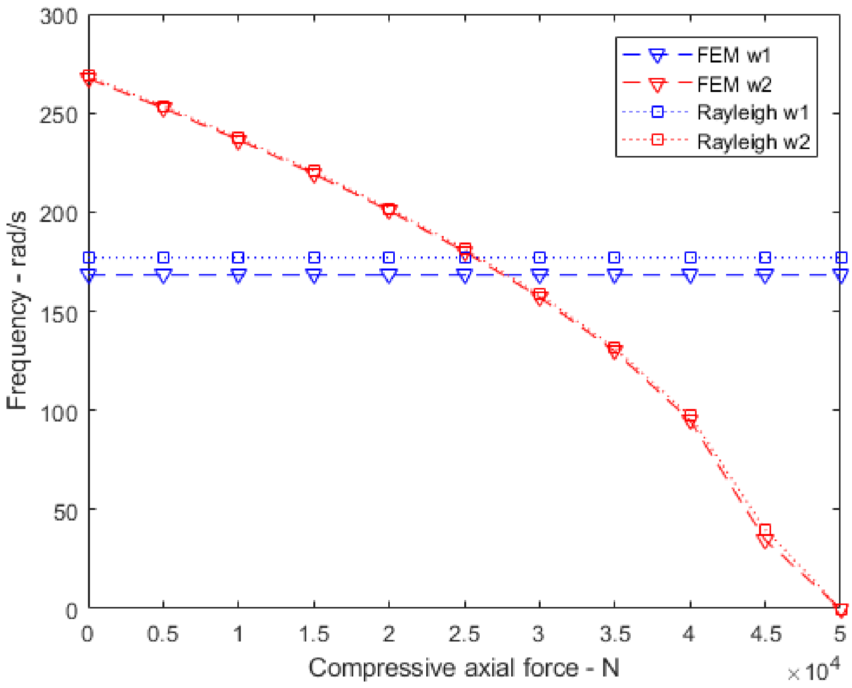

Figure 3. Simulating compressive loads in the beam, structure mesh 2 nodes in the columns and 3 nodes in the beam. FEM w1 and FEM w2 represent the first and second frequencies, respectively, obtained via FEM. Rayleigh w1 and Rayleigh w2 represent the first and second frequencies, respectively, obtained through Rayleigh's method.

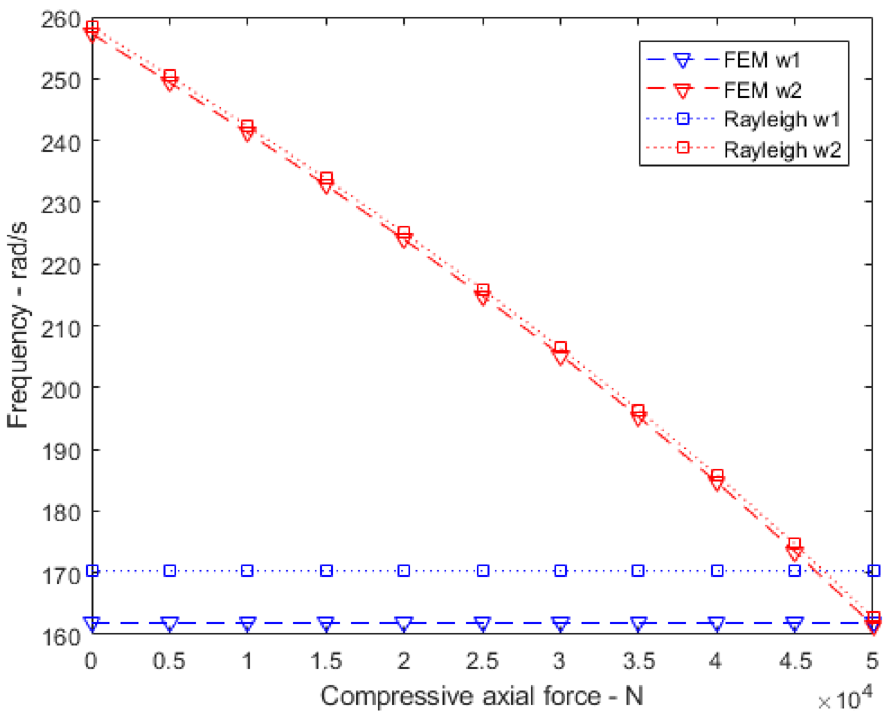

Figure 4. Simulating compressive loads on the beam, mesh structure 3 nodes on the columns and 3 nodes on the beam, with a 4 mm profile. FEM w1 and FEM w2 represent the first and second frequencies, respectively, obtained via FEM. Rayleigh w1 and Rayleigh w2 represent the first and second frequencies, respectively, obtained through Rayleigh's method.

3.2 Column compression

Figures 5-7 show results of a MATLAB MEF routine to obtain the first two frequencies, comparing with the approximate Rayleigh solution, for the case of compression V forces applied to the columns. Beam sections are rectangular 100x50 mm with 2 mm and 4 mm wall thickness.

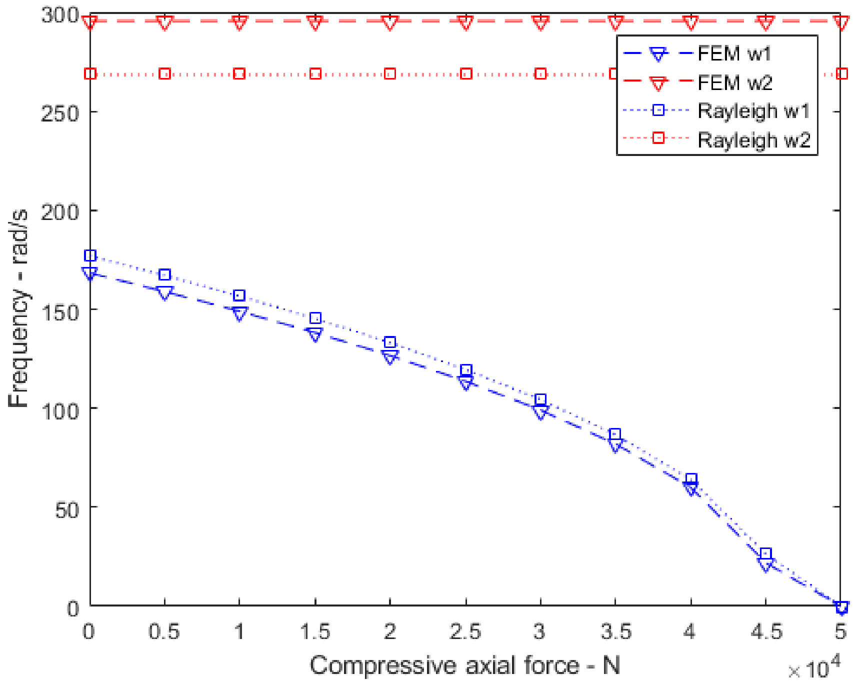

Figure 5. Simulating compressive loads on the columns, mesh structure 2 nodes on the columns and 2 nodes on the beam. FEM w1 and FEM w2 represent the first and second frequencies, respectively, obtained via FEM. Rayleigh w1 and Rayleigh w2 represent the first and second frequencies, respectively, obtained through Rayleigh's method.

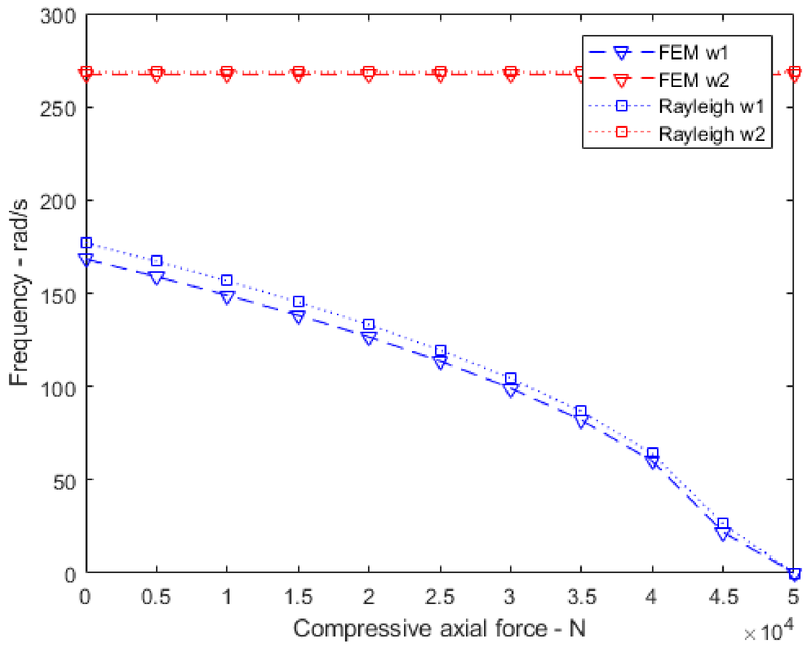

Figure 6. Simulating compressive loads on the columns, mesh structure 2 nodes on the columns and 3 nodes on the beam. FEM w1 and FEM w2 represent the first and second frequencies, respectively, obtained via FEM. Rayleigh w1 and Rayleigh w2 represent the first and second frequencies, respectively, obtained through Rayleigh's method.

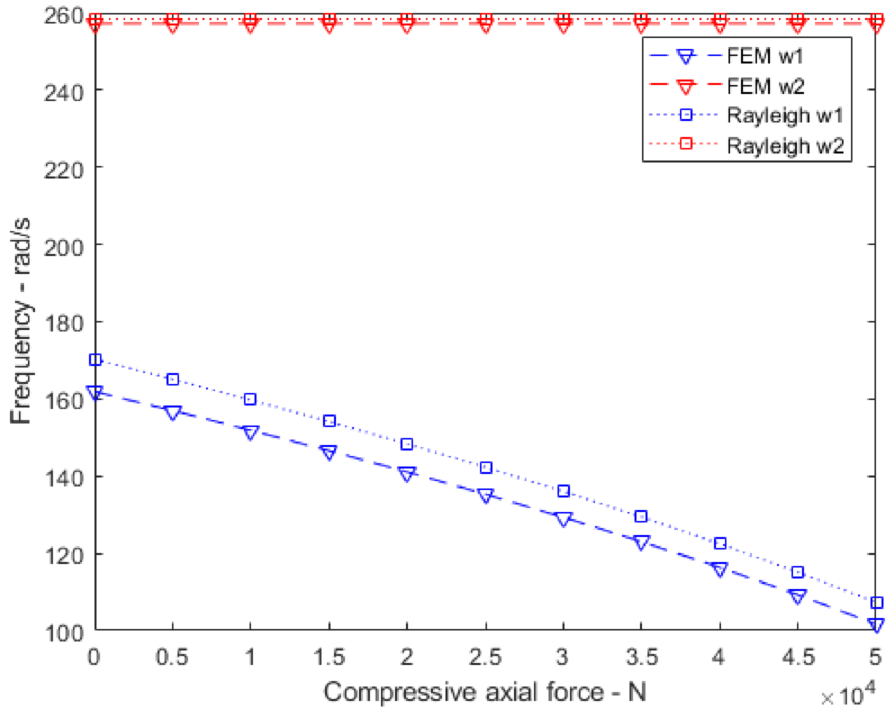

Figure 7. Simulating compressive loads in the columns, structure of the structure 3 nodes in the columns and 3 nodes in the beam, with a thickness profile of 4 mm. FEM w1 and FEM w2 represent the first and second frequencies, respectively, obtained via FEM. Rayleigh w1 and Rayleigh w2 represent the first and second frequencies, respectively, obtained through Rayleigh's method.

4 Conclusions

This work showed the comparison between the finite element method and Rayleigh's approximate solution of the problem. As one of the objectives was to develop a routine in MATLAB capable of providing results as close as possible to Rayleigh's approximate solution, in a simple way. This comparison was necessary to validate the results obtained. It was possible to observe that it is not necessary to make a high discretization of the structure to obtain very close results. This shows the importance of knowing what is behind the commercial software of finite elements, which are basically these routines that were developed here. Finally, it was possible to verify that compression forces in a structure may lead to unexpected potentially dangerous resonance states.

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