Study of the effect of pressurization on the vibration frequencies of fuselages

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Abstract. In this research, an aerospace vehicle fuselage was modeled as a long-pressurized cylinder. The investigation assessed the presence of high tensile stresses in the structure and their correlation with the values of the undamped free vibration frequencies of the system, which vary according to its geometric stiffness. The modeling was conducted utilizing the Finite Element Method, employing thin shell elements accounting for geometric nonlinearity, as offered in commercial and academic software. Generally, such programs can address the eigenvalue problem associated with this model, using a stiffness matrix considering application of the load, i.e., pressurization. This can originate from the conditioning of the internal atmosphere of commercial aircraft or the presence of large loads of fuel and oxidant in space vehicles (rockets). Another aspect to consider in this analysis is the fact that these vehicles do not have supports, leading to the existence of so-called rigid body modes, with zero vibration frequencies. Ultimately, a maximum variation of 45.29% in the natural frequency value of the investigated structure was observed.

Keywords: geometric nonlinearity, aircraft fuselage, vibration frequency, finite element method.

Introduction

Aerospace vehicles, such as commercial aircraft and rockets, are subject to various mechanical forces during their operation. Understanding the structural behavior and response of these vehicles is crucial to ensure their safety and optimize their performance. Aircraft fuselages, serving as external protective shells, constitute essential aerodynamic structures. Comprising bulkheads and flat truss structures, these components endure diverse loads, including internal pressurization. This phenomenon can result in notable tensile forces, which may significantly impact its structural stiffness, which can be defined as the intrinsic ability of an element or component to withstand deformations when subjected to external forces or loads.

In the context of aircraft component design and dimensioning, such as the fuselage, stiffness plays a pivotal role. It directly influences the component's ability to withstand aerodynamic forces, inertia, and other loads imposed during flight, while ensuring the aircraft's integrity and stability. This, in turn, maintains the aircraft's predefined shapes, preventing excessive deformations that could compromise aerodynamics, efficiency, and flight safety. In fuselage design, for instance, appropriate stiffness minimizes the risk of undesired fluctuations, ensuring the desired dynamic behavior.

Therefore, stiffness analysis is crucial to prevent structural failures, mitigate undesirable vibrations, and ensure the aircraft's extended operational lifespan. Consequently, there exists a necessity to investigate the effects of high tensile stresses on aerospace vehicle fuselages arising from practical scenarios. For instance, commercial aircraft rely on controlled internal atmospheres, and space vehicles such as rockets carry substantial fuel and oxidant loads. Understanding how these factors influence the structural response is indispensable in designing efficient aerospace vehicles. In such a context, scientific investigation provides valuable insights into the phenomena. Research studies like those conducted by Htet [1] and Pagani et al. [2] delves into the optimization of bulkhead stiffness, aiming to enhance dynamic response under critical conditions.

The interaction among pressurization, stiffness, and mass in the bulkheads of fuselages is acknowledged as a complex and pivotal domain in aeronautical engineering. In this research, a spacecraft fuselage was modeled as an internally pressurized long cylindrical shell. The primary objective of this study was to investigate whether the presence of high tensile stresses in the shell could enhance its geometrical stiffness. Accordingly, the hypothesis posits that these stresses could potentially change the values of undamped free vibration frequencies of the system.

1 FEM numerical modeling

For the investigation in this study, the Finite Element Method (FEM) was employed, which is a powerful numerical technique widely used for structural analysis. Simplistically, the methodology of this method involves dividing the structure under analysis into discrete elements, connected at nodes, thereby forming a mesh of finite elements.

Equations of motion are formulated based on the physical characteristics and boundary conditions of each element, resulting in a system of differential equations that describe the oscillations of the structure. The numerical solution of this system provides natural frequencies, vibration modes, and dynamic responses, aiding in the design and assessment of mechanical systems and structures.

In this context, a modal analysis was employed to explore the variation of the structure's natural frequencies, considering a pre-existing loading. Throughout this analysis, the equations of motion were solved through an iterative process, considering geometric nonlinearities. This iteration was carried out in successive steps until convergence was achieved, highlighting its significance in face of substantial changes in vibration modes and natural frequencies of the structure, resulting from these geometric nonlinearity (Wahrhaftig et al. [3-4]).

Once excited, the system is subject to both conservative and dissipative forces. In the absence of excitation, the system enters into free vibrations, with the structure seeking its natural modes of vibration, and the equation of motion takes on a characteristic form.

$$[M]\{\ddot{u}\} + [K]\{u\} = 0 \tag{1}$$

where [M] is the mass matrix; $\{\ddot{u}\}$ is the acceleration vector; [K] is the acceleration vector, comprised of $K = K_0 + K_g$ where K_g is the geometric stiffness matrix, dependent on the magnitude and nature of the normal forces, and $\{u\}$ is the displacement vector.

The solutions of Eq. (1) are vectors Φ, which represent the modes of undamped free vibration where all coordinates of the system vary harmonically in time, all with the same frequency, referred to as undamped free vibration frequency. By differentiating the solution $\{u\} = \Phi\cos(\omega t\text{-}\theta)$ twice with respect to time, substituting into the equation of motion, and canceling the harmonic function, we arrive at a system of homogeneous algebraic equations. For this system to have nontrivial solutions, the determinant of the matrix must be zero, which is the condition.

$$det\big[[K] - \omega^2[M]\big] = 0 \tag{2}$$

being an eigenvalue and eigenvector problem, described by:

$$([K] - \omega^2[M])\Phi = 0 \tag{3}$$

which results in a polynomial equation in ω^2, known as the frequency equation. The *n* solutions ω_i, in this case, are real and positive, and they represent the natural frequencies of the system. An important point to highlight is that the analysis should be conducted while incorporating nonlinear effects.

Case study

In order to explore the previously outlined formulations, which incorporate the effects of geometric nonlinearity in determining the natural frequency of the system, an analysis was conducted on an internally pressurized, long cylindrical shell. This component bears resemblance to structures found in aircraft fuselages, for instance. Due to internal pressurization, the fuselage generates considerable tensile forces in its walls. These forces, in turn, exert a notable influence on the system's vibration frequency. Fig. 1 illustrates the geometric characteristics of the modeled structure.

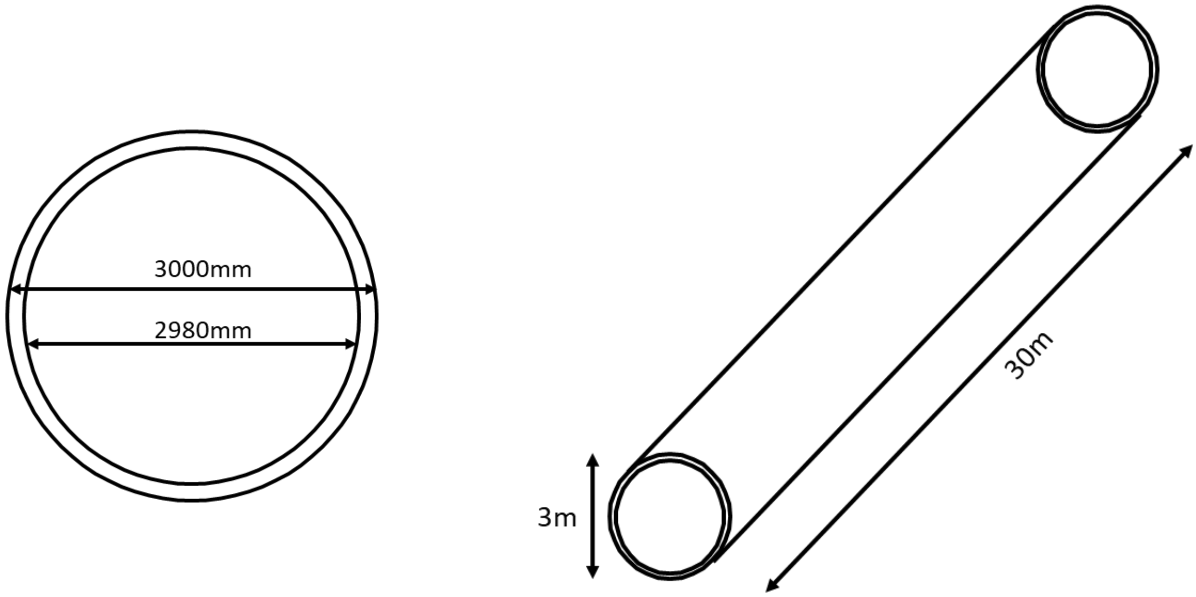

Figure 1. Characteristics of the bulkhead portal frame

The analysis considered a material with a longitudinal modulus of elasticity, E = 360 GPa, density ρ = 3000 kg/m³, and a cross-sectional shape as described earlier. The element was modeled using the thin shell element. The thin shell element is employed in the finite element method to simulate structures with small thickness. It effectively captures structural behavior in terms of bending and shear forces, making it suitable for plate and shell analysis. This element is characterized by having degrees of freedom for translation and rotation at its edges, allowing for an accurate representation of the stiffness and dynamic response of structures.

Figure 2 depicts the model with the mesh employed, utilizing a radial division of 24 elements and a longitudinal length of 50 cm.

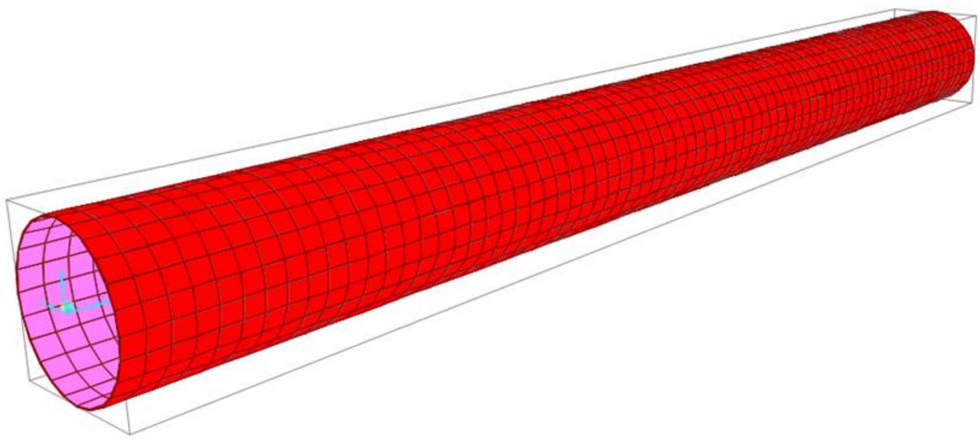

Figure 2. Structure mesh

The applied loading was varied to investigate the influence of pressurization on the vibration frequency of the structure, ranging from zero (initial condition) up to 200 kPa. Figures 3, 4, and 5 display the internal pressures within the tube that were utilized in the analyses.

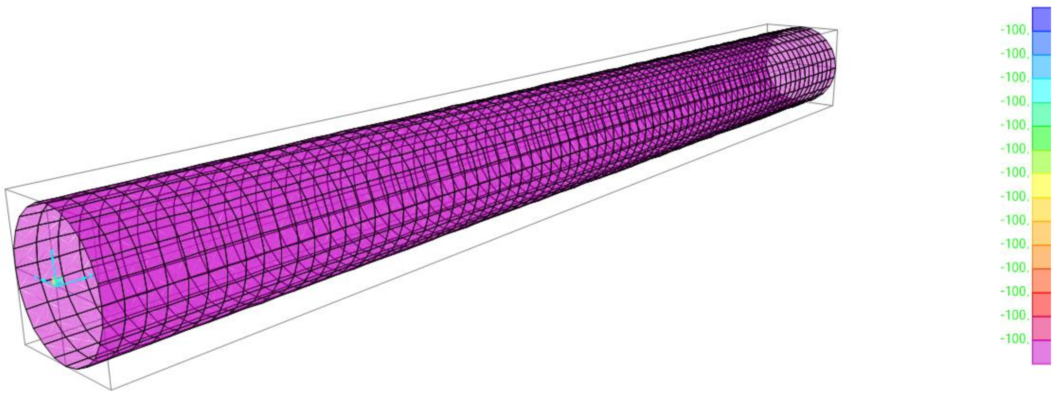

Figure 3. Internal pressure of 100 kPa.

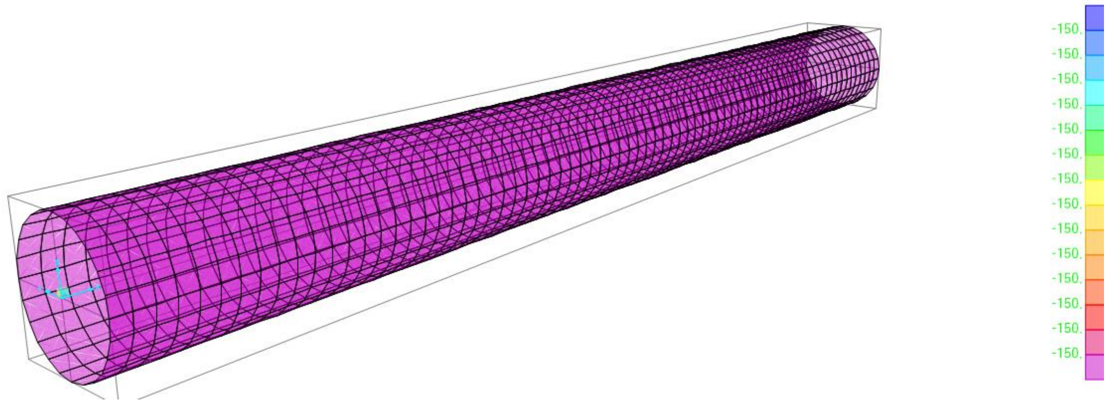

Figure 4. Internal pressure of 150 kPa.

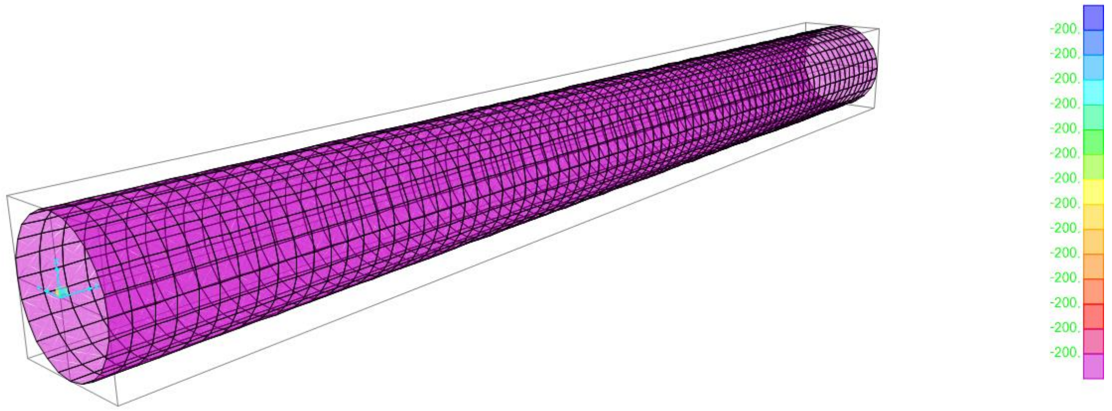

Figure 5. Internal pressure of 200 kPa.

A modal analysis was conducted to ascertain the natural frequencies and vibration modes of the structure, thereby discerning its dynamic characteristics, which can be influenced by factors like geometric stiffness. This allows for an in-depth understanding of the structural vibration behavior. An important consideration in the analysis was the absence of external supports in the structure. This absence gives rise to the existence of rigid body modes, characterized by zero vibration frequencies. Studying the undamped free vibration frequencies provides insights into the dynamic behavior of the fuselage and its resilience against various modes of excitation.

Results and discussions

A modal analysis was employed to investigate the variation in the natural frequencies of the structure, considering a pre-existing load. This load is accounted for through the stiffness matrices. Throughout the analysis, the equations of motion were iteratively solved, incorporating nonlinear effects. The iteration process was repeated in multiple cycles until convergence was achieved. This procedure is of paramount significance, as geometric nonlinearity can induce substantial transformations in the vibration modes and natural frequencies of the structure.

In the current study, the internal pressurization of the element was taken into account, and the variation of the natural frequency of the structure was determined for different conditions. Table 1 presents the results of the structural frequency variation for loadings of 100 kPa, 150 kPa, and 200 kPa.

Table 1. Structure frequency variation results

Condition	Frequency (rad/s)	Variation (%)
Without interne pressure	5,865	-
With 100kPa interne pressure	7,315	24,72
With 150kPa interne pressure	7,941	8,56
With 200kPa interne pressure	8,521	7,30
Total variation (%)	**45,29**	

Table 1 illustrates a substantial increase in the value of the first natural frequency of the structure when comparing the result in the initial state, without internal pressurization, with the state at 200 kPa internal pressure. This increase can be predominantly explained by the structural stiffness gain attributed to the geometric stiffness component of the system, which takes into account the tensile force that the structure is subjected to.

Conclusions

This study delved into the impact of significant tensile stresses prevalent in aircraft fuselages, elucidating the intrinsic relationship with the variation of natural frequencies of the structure. The loads stemming from these stresses increase the geometric stiffness effect, consequently leading to a noticeable change of undamped free vibration frequencies within the investigated system. The employed methodology adopted the Finite Element Method, incorporating thin shell elements and crucially encompassing the consideration of geometric nonlinearity.

In the analyses, a maximum variation in magnitude of 45.29% in the natural frequency was observed, showcasing a noteworthy increment compared to the initial unloaded value. It was also noticed that this variation decreased as internal pressure was increased. This finding robustly underscores the significance of accounting for such tensile stress efforts, which may arise from the internal atmosphere conditioning of commercial aircraft, or the presence of substantial fuel and oxidant loads in space vehicles (rockets), in the dynamic response of the structure.

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