

Hybrid Finite Element and Spectral Approach for Random Dynamic Response Prediction of an Axisymmetric Aircraft Fuselage Section

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Abstract: This study investigates the dynamic behavior of an aircraft fuselage structure subjected to random vibratory excitations using a hybrid finite element and spectral analysis approach. The study focuses on a simplified axisymmetric section representative of the fuselage of the Airbus A330-300. A numerical model was developed using Autodesk Simulation Mechanical 2015 under a two-dimensional plane strain formulation. First, a modal analysis was performed to extract the natural frequencies and mode shapes of the structure. The obtained results revealed the presence of global deformation modes at low frequencies and localized vibration modes at higher frequencies. Due to the limitations of the finite element software regarding direct power spectral density (PSD)-based random vibration analysis, the modal results were exported to MATLAB for spectral reconstruction of the random dynamic response. The response spectrum exhibited resonance peaks corresponding to the identified natural frequencies, confirming the dominant contribution of low-frequency modes to the overall structural response. The root mean square (RMS) displacement remained relatively low under the considered excitation conditions, indicating moderate vibratory levels. However, the study also highlights the limitations associated with the simplified axisymmetric model and the use of an approximate excitation spectrum. The proposed methodology provides a computationally efficient framework for preliminary vibration assessment of aircraft fuselage structures.

Keywords: Aircraft Fuselage; Random Vibration; Modal Analysis; Finite Element Method; Power Spectral Density; Dynamic Response; Axisymmetric Model; MATLAB; Autodesk Simulation Mechanical 2015.

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I. INTRODUCTION

Aircraft fuselage structures are continuously subjected to complex dynamic loading environments during service operations. These excitations originate from multiple sources, including atmospheric turbulence, engine-induced vibrations, aerodynamic pressure fluctuations, and structural interactions occurring during flight maneuvers. Because these excitations exhibit significant random characteristics, the structural response of aircraft fuselages must be analyzed within a stochastic dynamic framework rather than through purely deterministic approaches [1,2].

The prediction of vibratory behavior is a major issue in aerospace engineering because excessive dynamic response levels may lead to passenger discomfort, acoustic fatigue, local structural damage, and long-term degradation of structural integrity [3]. In thin-walled cylindrical structures such as aircraft fuselages, the interaction between global

deformation modes and localized panel vibrations may significantly amplify stress concentrations, particularly near resonant frequencies [4]. Consequently, accurate identification of modal characteristics and dynamic amplification mechanisms remains essential for ensuring structural reliability and durability.

Over the past decades, the finite element method (FEM) has become one of the principal numerical tools used for the dynamic analysis of aerospace structures. Numerous studies have investigated modal behavior, structural vibrations, and aeroelastic phenomena in aircraft components using finite element formulations [5–7]. Modal analysis is commonly employed as a first step for identifying the natural frequencies and mode shapes governing the dynamic response of fuselage structures [8]. However, while commercial FEM software packages provide efficient modal extraction capabilities, several platforms remain limited in their ability to directly

perform advanced random vibration analyses based on Power Spectral Density (PSD) formulations.

Random vibration analysis based on PSD functions constitutes one of the most widely adopted approaches for evaluating structural response under stochastic excitations [9]. In aerospace applications, PSD-based methods are frequently used to represent turbulence-induced loading and broadband vibratory environments [10]. The response is generally characterized through statistical quantities such as root mean square (RMS) displacement, stress, and acceleration levels [11]. Several authors have demonstrated the relevance of spectral methods for predicting the vibratory behavior of aerospace structures subjected to broadband excitation [12,13].

Despite the availability of advanced three-dimensional modeling approaches, simplified axisymmetric models continue to offer important advantages in preliminary structural investigations due to their reduced computational cost and numerical efficiency [14]. Nevertheless, such simplifications also introduce limitations, particularly regarding the representation of non-axisymmetric deformation modes and localized structural discontinuities.

In this context, the present work proposes a hybrid numerical methodology combining finite element modal analysis and spectral reconstruction of the random dynamic response. A simplified axisymmetric section representative of

the fuselage of the Airbus A330-300 is modeled using Autodesk Simulation Mechanical 2015 under a two-dimensional plane strain formulation. The modal characteristics obtained from the finite element analysis are subsequently used within a MATLAB-based spectral framework to estimate the random vibration response of the structure.

The results highlight the dominant contribution of low-frequency modes to the global dynamic response and demonstrate the capability of the proposed approach to identify resonance-sensitive frequency regions. The study also discusses the limitations associated with simplified excitation spectra and axisymmetric modeling assumptions.

II. MATERIALS AND METHODS

➤ Geometrical Model of the Fuselage Structure

A simplified numerical model representative of an aircraft fuselage section was developed in order to investigate the dynamic behavior of thin-walled cylindrical structures subjected to vibratory excitation. The study focused on a section inspired by the geometry of the Airbus A330-300 fuselage.

To reduce computational complexity while preserving the dominant structural behavior, the fuselage section was modeled using a two-dimensional axisymmetric representation (see Figure 1).

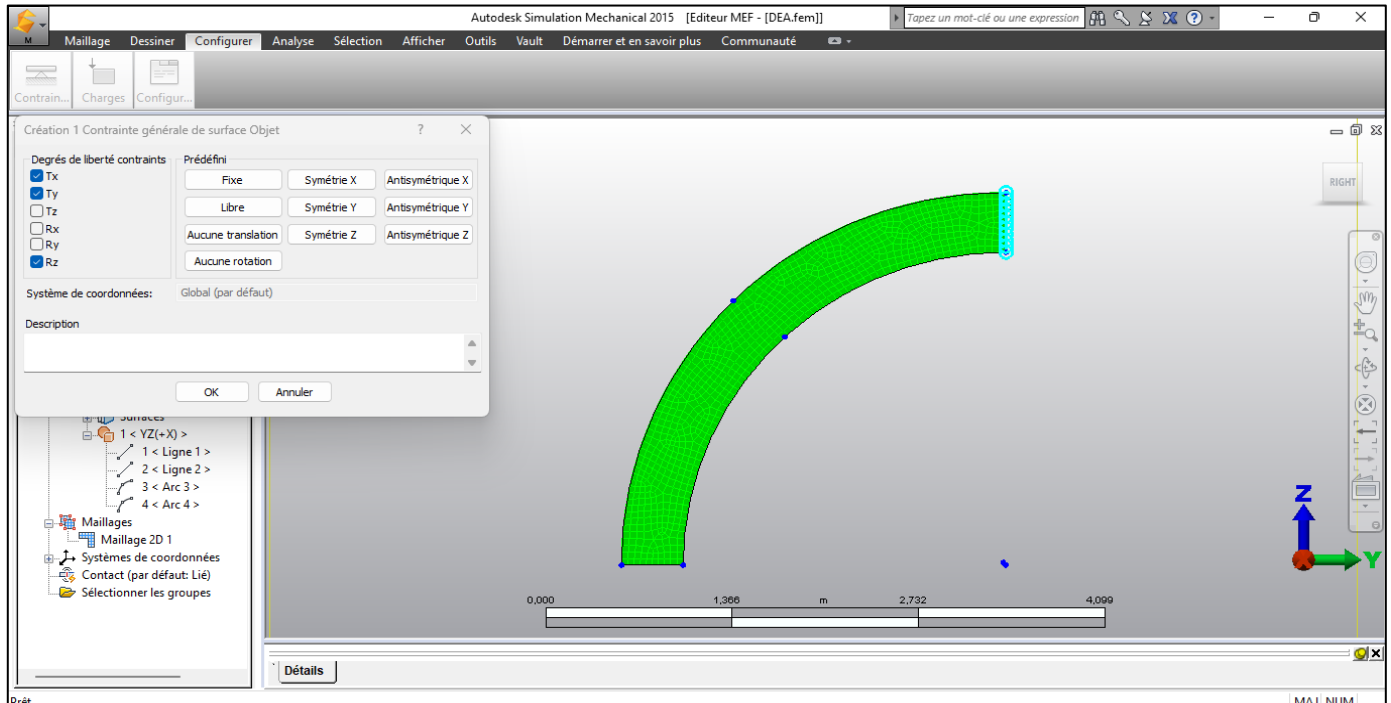


Fig 1 Représentation Du Modèle Axisymétrique D'un Fuselage D'avion.

The geometry consists of a curved annular section defined by two concentric arcs corresponding to the inner and outer surfaces of the fuselage shell. The adopted dimensions were derived from the external fuselage diameter of the A330-300 reported in the literature and publicly available aircraft specifications [15].

The geometric construction was implemented in Autodesk Simulation Mechanical 2015 using arc-based contour generation. The inner and outer radii were defined to represent the fuselage skin thickness under a simplified shell approximation. This axisymmetric formulation enables

efficient numerical computation while retaining the principal stiffness characteristics of the cylindrical structure.

➤ *Finite Element Modeling*

The finite element model was developed under a two-dimensional plane strain formulation. This assumption was adopted because the fuselage section is characterized by a large longitudinal extent compared to the local shell thickness, allowing the out-of-plane strain to be neglected in the simplified representation.

Quadrilateral 2D finite elements were employed for spatial discretization of the structure. The mesh was generated using structured quadrilateral elements with a characteristic element size of 0.05 m. Additional mesh parameters included a mesh transition ratio of 1.25 and a maximum mesh angle of 15°. These parameters were selected to improve numerical stability and mesh regularity.

The material behavior was assumed to be homogeneous, isotropic, and linearly elastic. The mechanical properties adopted in the simulations are representative of conventional aerospace aluminum alloys commonly used in

fuselage structures [4]. The material parameters used in the simulations are summarized in Table 1.

Table 1 Mechanical Properties Used in the Finite Element Model.

Property	Value
Young’s modulus, E	70 GPa
Poisson’s ratio, ν	0.33
Density, ρ	2700 kg/m ³

The model was subjected to simplified boundary conditions intended to maintain global structural stability while minimizing rigid body motion. The loading conditions consisted of equivalent pressure loading applied normal to the fuselage surface in order to simulate internal and external pressurization effects.

The general workflow adopted for the finite element analysis performed in Autodesk Simulation Mechanical 2015 is illustrated in Figure 2. The procedure includes geometrical modeling, material definition, meshing strategy, boundary condition application, modal extraction, and post-processing stages.



Fig 2 General Architecture of the Finite Element Analysis Procedure Implemented in Autodesk Simulation Mechanical 2015.

➤ *Modal Analysis Procedure*

A free vibration modal analysis was first conducted to identify the natural frequencies and corresponding mode shapes of the structure. The generalized eigenvalue problem solved by the finite element formulation can be expressed as:

$$[K - \omega^2 M]\phi = 0 \tag{1}$$

Where *K* is the global stiffness matrix, *M* is the mass matrix, ω represents the natural circular frequencies, and ϕ denotes the eigenvectors associated with the mode shapes.

The first ten natural frequencies were extracted because low-order modes generally dominate the dynamic response of large aerospace structures subjected to broadband excitation [8].

➤ *Random Dynamic Response Analysis*

Because Autodesk Simulation Mechanical 2015 does not directly support advanced Power Spectral Density (PSD)-based random vibration analysis for the adopted modeling configuration, the modal results were exported to MATLAB for post-processing and spectral reconstruction of the random response.

The overall numerical procedure adopted in the present study, including finite element modal extraction and MATLAB-based spectral reconstruction, is summarized in Figure 3.

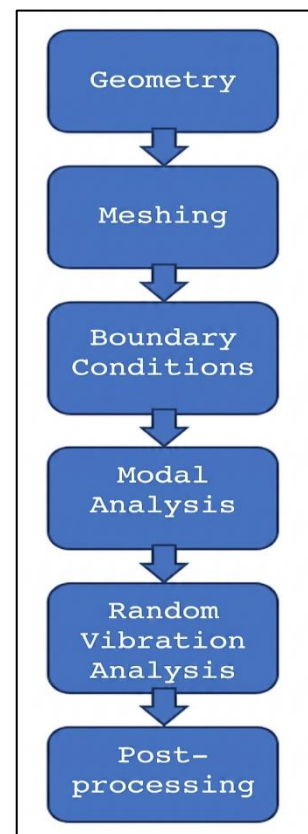


Fig 3 Flowchart of the Numerical Simulation Procedure Used for Modal and Random Vibration Analyses.

The excitation was modeled using a simplified PSD representation intended to approximate broadband stochastic excitation conditions:

$$S_f(f) = \frac{S_0}{1 + (f/f_c)^2} \quad (2)$$

Where S_0 is the reference spectral amplitude and f_c is the cut-off frequency.

The frequency response function associated with each mode was computed according to:

$$H_i(\omega) = \frac{1}{\omega_i^2 - \omega^2 + j2\zeta_i\omega_i\omega} \quad (3)$$

Where ω_i denotes the modal frequency and ζ_i represents the modal damping ratio.

The response Power Spectral Density was then estimated using modal superposition:

$$S_x(\omega) = \sum_{i=1}^n |H_i(\omega)|^2 S_f(\omega) \quad (4)$$

The global vibratory level was quantified using the root mean square (RMS) displacement defined by:

$$X_{RMS} = \sqrt{\int_0^{\infty} S_x(f) df} \quad (5)$$

This methodology enabled the identification of resonance-sensitive frequency regions and the estimation of the overall dynamic response of the fuselage section under stochastic excitation.

➤ *Software and Data Availability*

The finite element simulations were performed using Autodesk Simulation Mechanical 2015, while the spectral response analysis and post-processing were carried out in MATLAB.

No experimental datasets were used in this study. The numerical data generated during the simulations are available from the authors upon reasonable request.

Generative artificial intelligence tools were used exclusively for language refinement and manuscript drafting assistance. No AI-based tool was used for numerical simulation, data generation, or scientific interpretation.

III. RESULTS

➤ *Modal Characteristics*

The first ten natural frequencies obtained from the finite element model are presented in Table 2.

Table 2 Natural frequencies obtained from the modal Analysis.

Mode Number	Natural Frequency (Hz)
1	41,88466
2	215,591
3	312,93
4	473,788
5	689,157
6	785,971
7	1131,27
8	1270,15
9	1495,85
10	1867,05

The modal analysis performed using Autodesk Simulation Mechanical 2015 allowed the identification of the principal dynamic characteristics of the fuselage structure. The first natural frequency was obtained at approximately 41.88 Hz and corresponds to the fundamental global deformation mode of the structure.

This low-frequency mode is mainly associated with global bending behavior of the cylindrical shell. In practical aerospace applications, such low-frequency modes are particularly important because they may be excited by atmospheric turbulence, engine-induced vibrations, and low-frequency aerodynamic fluctuations [4].

As the modal order increases, a progressive increase in modal density is observed. Starting from approximately 700 Hz, the extracted modes exhibit increasingly localized deformation patterns. This transition from global to local structural behavior is characteristic of thin-walled cylindrical structures and is commonly reported in shell vibration studies [14].

The relatively high frequencies obtained in the present study compared with complete fuselage numerical models can mainly be attributed to the simplified axisymmetric representation adopted in the analysis. The absence of structural discontinuities such as windows, doors, stiffeners, and assembly joints contributes to an increase in the global stiffness of the model.

➤ *Mode Shape Analysis*

The mode shapes associated with the extracted natural frequencies are illustrated in Figures 3 and 4.

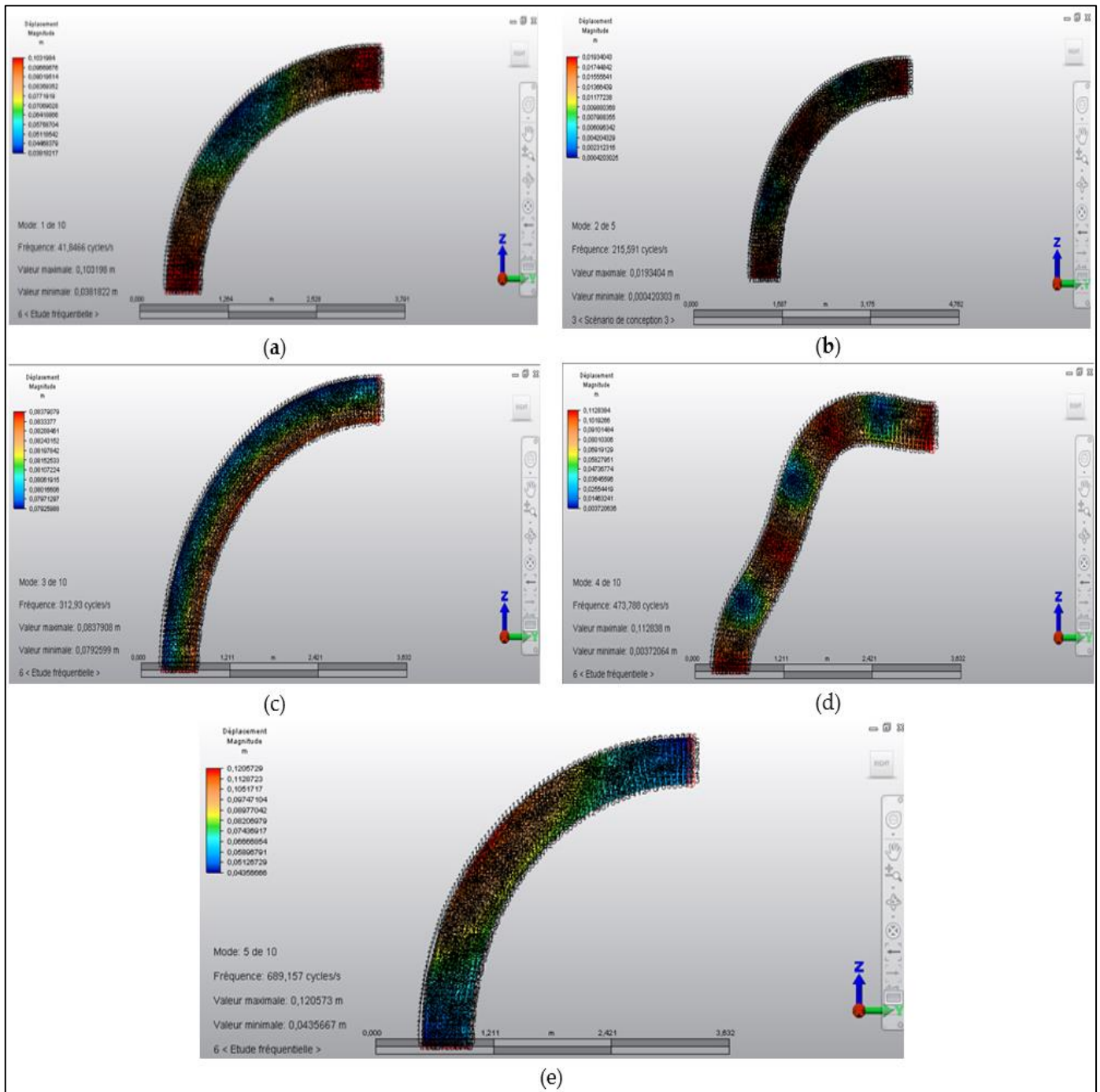


Fig 4 First Five Mode Shapes Obtained from the Finite Element Modal Analysis.

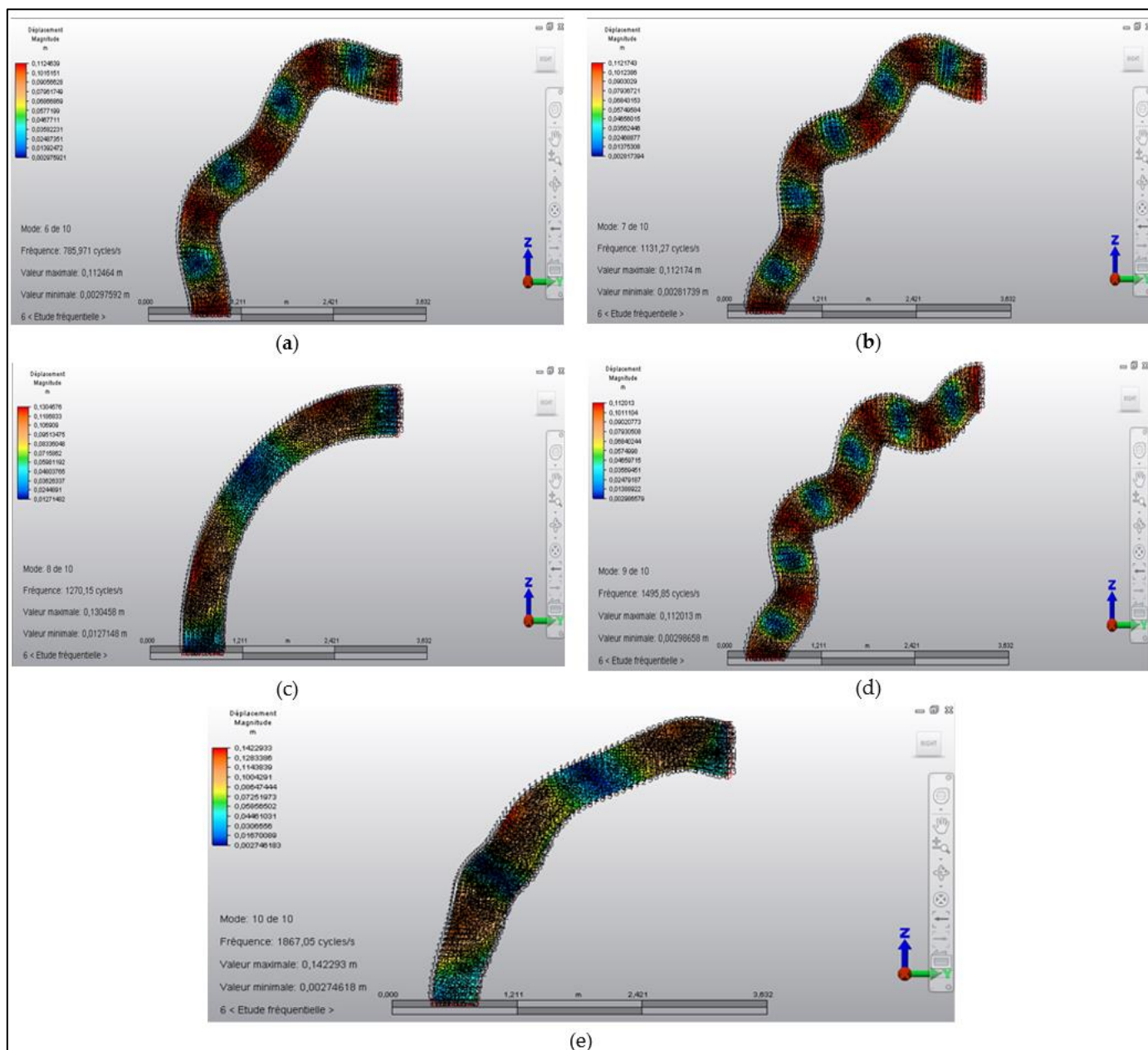


Fig 5 Higher-Order Mode Shapes Associated with Localized Structural Deformation.

The first vibration modes are characterized by global deformation patterns involving the overall motion of the fuselage section. These modes present relatively smooth displacement distributions with limited curvature localization.

The lower-order modes are primarily governed by the global stiffness and mass distribution of the structure. Consequently, they strongly influence the global dynamic response under broadband excitation.

In contrast, the higher-order modes exhibit localized deformation lobes and shell breathing behavior. These deformation patterns are associated with higher curvature gradients and localized strain concentrations. Such localized vibration modes are known to contribute significantly to fatigue-sensitive regions in thin shell aerospace structures [3].

The appearance of localized deformation regions at higher frequencies indicates a transition toward local panel-type vibration mechanisms. These modes are particularly important in aerospace applications because they may induce high-frequency stress fluctuations capable of accelerating structural fatigue damage.

It should be emphasized that the displacement amplitudes displayed in modal analysis do not represent physical displacement levels. These amplitudes are normalized quantities associated with the eigenvector scaling procedure adopted by the numerical solver.

➤ *Random Dynamic Response*

The random dynamic response reconstructed from the modal data using MATLAB is presented in Figure 5.

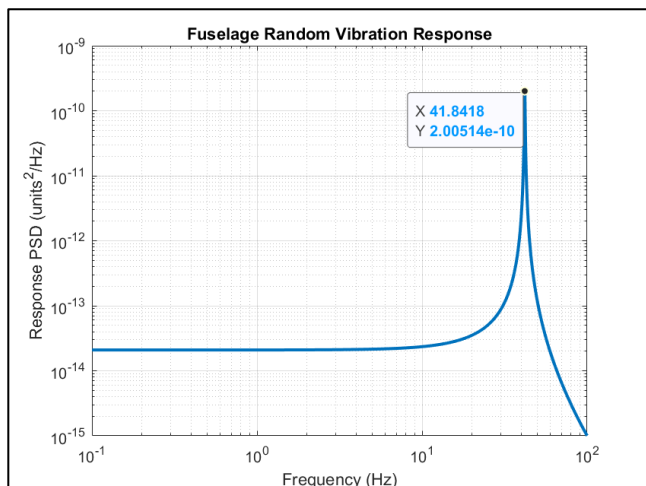


Fig 6 Power Spectral Density Response of the Fuselage Structure Under Stochastic Excitation.

The response spectrum exhibits several pronounced resonance peaks located at approximately 42, 214, 312, 474, 688, and 788 Hz. These frequencies coincide with the natural frequencies identified during the modal analysis, confirming the dominant contribution of resonance phenomena to the dynamic behavior of the structure.

The spectral response indicates that the vibratory behavior is primarily governed by the lower-frequency modes. These modes concentrate most of the vibratory energy because of their larger modal participation and broader dynamic influence on the global structural motion.

The estimated root mean square (RMS) displacement obtained from the spectral reconstruction is given by:

$$X_{RMS} = 1.17 \times 10^{-5} \text{ m}$$

This relatively low RMS value suggests moderate global vibration levels under the considered excitation conditions. Nevertheless, this result must be interpreted cautiously because the response strongly depends on the adopted Power Spectral Density (PSD) model.

The excitation spectrum used in the present study represents a simplified approximation of operational stochastic loading conditions. In real aerospace environments, turbulence-induced excitations are generally modeled using experimentally validated spectral models such as the Dryden or von Kármán turbulence spectra [10].

Furthermore, the present analysis does not explicitly include realistic modal participation factors or fluid–structure interaction effects. Consequently, the obtained results should be interpreted as a preliminary estimation of the random dynamic response rather than a complete operational prediction.

➤ *Structural Response under Pressure Loading*

The displacement and stress distributions obtained under pressure loading are presented in Figures 6 and 7.

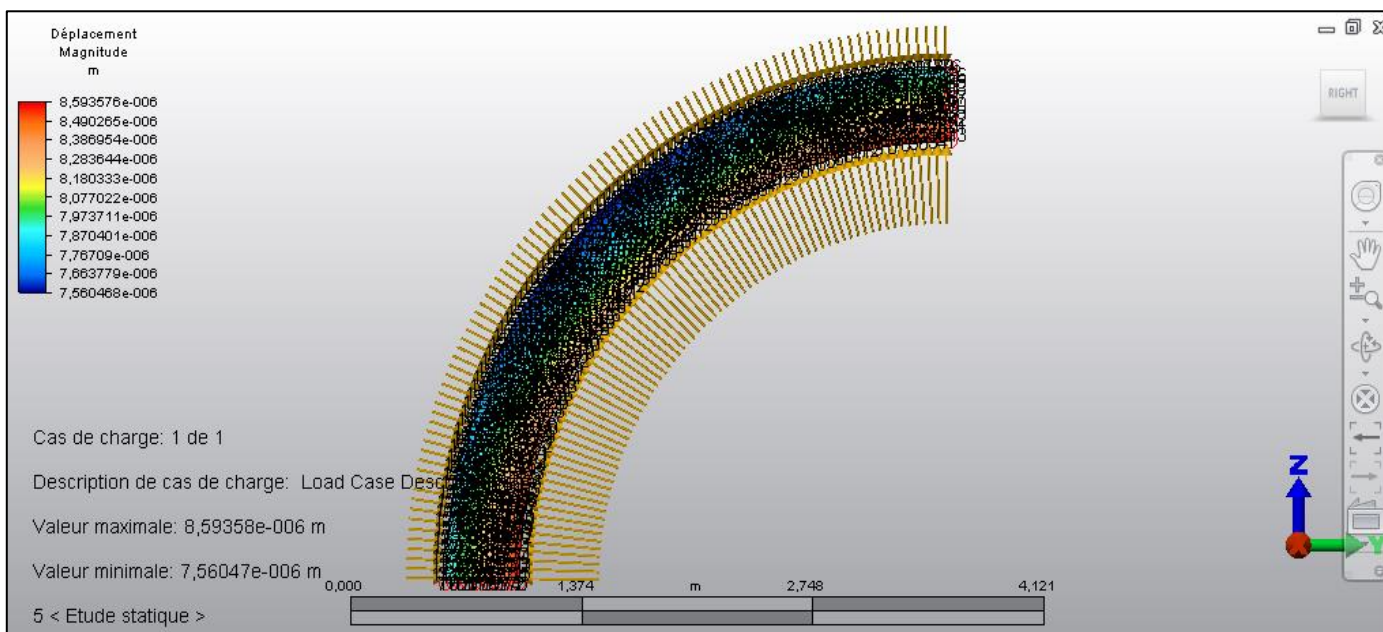


Fig 7 Displacement Distribution of the Fuselage Section Under Pressure Loading.

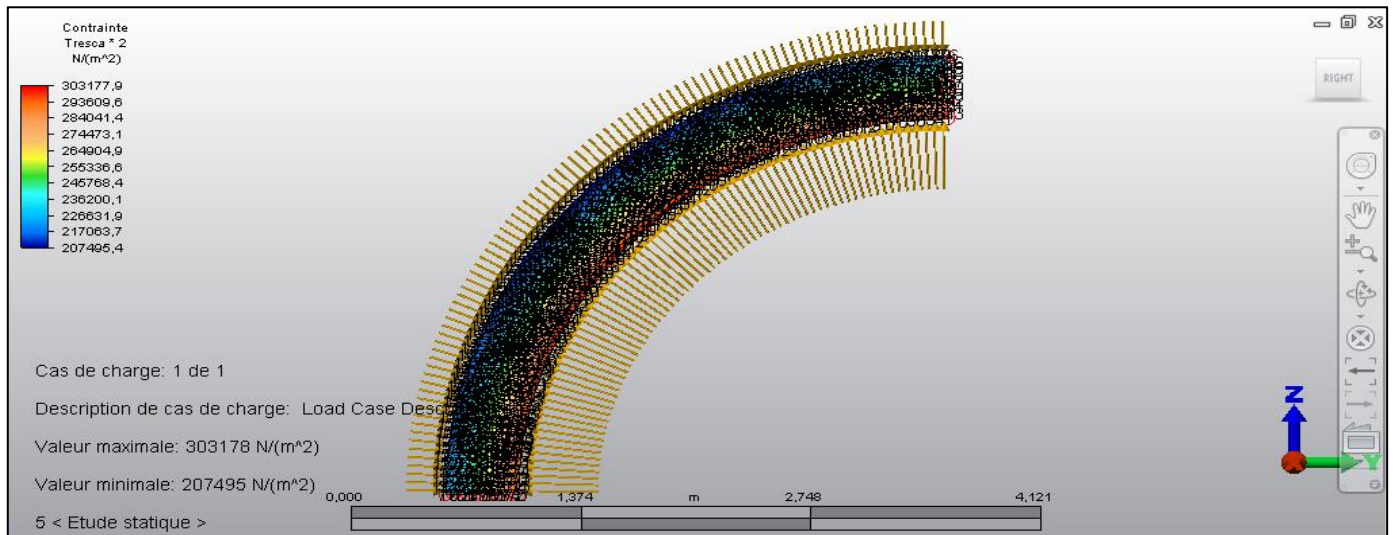


Fig 8 Tresca Stress Distribution of the Fuselage Section Under Pressure Loading.

The displacement field exhibits a relatively uniform deformation distribution over the fuselage section. The maximum displacement was estimated at approximately:

$$u_{max} \approx 8.6 \times 10^{-6} \text{ m}$$

This very small displacement amplitude indicates a relatively high global stiffness of the structure under the considered pressure loading conditions.

The corresponding Tresca stress distribution reveals localized stress concentrations near geometrical transition regions and structural boundaries. The maximum stress value was estimated at approximately:

$$\sigma_{max} \approx 3.0 \times 10^5 \text{ Pa}$$

This stress level remains significantly below the yield strength of conventional aerospace aluminum alloys, indicating that the structure remains within the elastic regime under the considered loading conditions.

However, the obtained stress levels remain relatively low compared with realistic fuselage pressurization conditions encountered during aircraft operation. This discrepancy is mainly related to the simplified pressure loading assumptions and the reduced axisymmetric representation adopted in the present study.

Despite these limitations, the results demonstrate the capability of the proposed finite element model to reproduce the general mechanical behavior of thin cylindrical aerospace structures subjected to combined vibratory and pressure loading conditions.

IV. CONCLUSIONS

This study presented a numerical investigation of the dynamic behavior of an aircraft fuselage structure using a hybrid finite element and spectral analysis approach. A simplified axisymmetric model representative of the fuselage

of the Airbus A330-300 was developed using Autodesk Simulation Mechanical 2015 under a two-dimensional plane strain formulation.

The modal analysis enabled the identification of the principal dynamic characteristics of the structure, including the natural frequencies and associated mode shapes. The obtained results revealed a clear distinction between low-frequency global deformation modes and higher-frequency localized vibration modes. The progressive increase in modal density observed at higher frequencies is consistent with the expected behavior of thin-walled cylindrical aerospace structures.

To overcome the limitations of the finite element software regarding direct PSD-based random vibration analysis, the modal results were exported to MATLAB for spectral reconstruction of the stochastic response. The obtained response spectrum exhibited resonance peaks corresponding to the identified natural frequencies, confirming the dominant contribution of modal resonance phenomena to the global dynamic behavior.

The estimated RMS displacement remained relatively low under the considered excitation conditions, suggesting moderate vibration levels for the simplified loading configuration adopted in this study. Nevertheless, the obtained results remain strongly dependent on the simplified excitation spectrum and modeling assumptions.

Several limitations must therefore be acknowledged. The axisymmetric representation does not allow accurate reproduction of non-axisymmetric deformation mechanisms and local structural discontinuities encountered in real fuselage configurations. Furthermore, the absence of experimentally validated turbulence spectra, realistic damping characterization, and fluid–structure interaction effects limits the predictive capability of the present model.

Despite these limitations, the proposed hybrid methodology provides a computationally efficient framework

for preliminary dynamic assessment of aerospace fuselage structures subjected to stochastic excitation. Future work should focus on the integration of realistic turbulence models, three-dimensional structural representations, and fatigue-oriented dynamic stress analysis in order to improve the physical representativeness of the numerical predictions.

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