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Effect of Material Property Variation on Mode Shapes and Natural Frequencies: A Comparative Analysis of CFRP and Al 7075-T6

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ABSTRACT

This study examines the effects of changing Young's modulus on mode shapes and natural frequencies in an airplane model, with an emphasis on Carbon fiber reinforced polymer (CFRP) for airplane fuselage and Aluminum alloy 7075-T6 (Al 7075-T6) for airplane wings. The study examines the effects of changed Young's Modulus while maintaining other parameters constant using NX Nastran simulation. Taguchi analysis is used to find the best material configurations for increasing Signal-to-Noise Ratios (SNRs) in a variety of aerodynamic modes. The study uses one-way Analysis of Variance (ANOVA) to statistically assess Young's Modulus's impact on mode values. The results show that Young's Modulus modifications cause different differences in mode shapes and natural frequencies. Notably, Mode 2 is highly responsive to Young's Modulus changes in both materials, emphasizing its importance in design optimization. These findings highlight the possibility of precisely influencing dynamic behavior through tailored material selection, providing valuable insights for aerospace design. Such insights are important for optimizing mode shapes and frequencies, which will ultimately improve aircraft performance and reliability.

Keywords : Modal Analysis, Natural Frequency, Young's Modulus, Taguchi & ANOVA, NX Nastran

1 INTRODUCTION

THE pursuit of improving aircraft performance and reliability through modifications and upgradations in material and its specification has long driven the field of aerospace engineering. A bad material selection could lead to dissatisfaction among both producers and customers. Furthermore, it may cause an assembly to fail and products to perform poorly, reducing efficiency and production and harming the organization's brand [1]. A thorough understanding of the dynamic behavior of aircraft structures, including the study of mode shapes and natural frequencies, is critical for achieving these goals [2], [3]. Natural frequencies, the frequencies at which these patterns occur, and mode shapes, the spatial patterns of structural deformation, play critical roles in determining the structural integrity, stability, and overall performance of aerospace systems [4]. However, the presence of wing vibrations affects turbulence measurements greatly, especially in the frequency range near the wing's natural resonance frequencies [5].

Numerous researchers have performed free vibration analyses by modifying the fundamental structures of engineering models and designs. Nikhil A. Khadse and Prof. S. R. Zaweri conducted a modal analysis of aircraft wings, revealing that the natural frequencies obtained through numerical and theoretical approaches exhibited similarity [6]. Kakumani Sureka and R Satya Meher created a digital model of an A300 aircraft wing, including different materials for the spars and ribs [7]. Hrushikesh N et al. performed a harmonic analysis of wing for identifying crack [8]. Meral Bayraktar and Ali Demirtaş used a cantilever beam as a model to compute theoretical natural frequencies for various modes, then performed a numerical analysis on the same model to confirm the theoretical findings [9]. However, vibration analyses based on varying material properties were still a research gap in aerospace material advancement.

The fuselage, serving as the aircraft's central body, plays a pivotal role in integrating all the aircraft's components. Its long, tubular structure, often hollow, is purposefully designed to maintain a lightweight profile. The choice of material specification for the fuselage is of paramount importance, as it directly impacts the aircraft's overall weight, structural integrity, and performance [10]. Tailored materials, such as lightweight and durable composites or alloys, are often chosen to strike a balance between strength and weight, depending on the aircraft's intended purpose. Likewise, the wings of an aircraft are critical components that significantly influence its aerodynamic performance. The wing design, including its shape and material specification, is tailored to the aircraft's mission profile. The choice of wing materials directly affects factors such as lift, fuel efficiency, and structural stability [10], [11]. Advanced materials like composite materials and aluminum alloys are commonly employed to optimize the wing's strength-to-weight ratio, allowing for greater maneuverability and fuel economy.

This study seeks to illuminate a key feature of aircraft engineering: the effect of material quality variation on mode shapes and natural frequencies. We concentrate our research on two separate materials often used in the aerospace industry: Carbon Fiber Reinforced Polymer (CFRP) and Aluminum Alloy 7075-T6 (Al 7075-T6). These materials have distinctive mechanical properties, most notably variances in Young's Modulus, which is an important predictor of stiffness [12]. This study tries to explore the subtle relationship between material qualities and the dynamic characteristics of aircraft structures by altering Young's Modulus while holding other parameters constant. In order to achieve this goal, advanced engineering analysis techniques such as Finite element simulation [13], Taguchi analysis for optimizing Signal-to-Noise Ratios (SNRs) across different aerodynamic modes [14], and one-way ANOVA [15] to statistically evaluate the influence of Young's Modulus on mode values were found to be most suitable. Modal tests and analysis are effective tools for obtaining information about the damping, stiffness, natural frequencies, and mode shapes inherent in the structure's dynamic response [16]. The findings of this extensive study demonstrate distinct differences in mode shapes and natural frequencies caused by changes in Young's Modulus, providing valuable insights for aircraft design and engineering.

2 METHODOLOGY:

The methodology section provides an in-depth look at the research approach and techniques used to investigate the effect of varying Young's Modulus on mode shapes and natural frequencies in an aircraft model.

Several key assumptions are made to establish a foundational framework for the research:

1. The airplane model has a rigid body. This means that the aircraft model's deformations are minor and can be ignored.
2. Throughout the aircraft model, the material properties remain constant. This means that the material properties of the aircraft model do not differ from one location to the next.
3. The boundary conditions are predetermined. This means that the aircraft model cannot move or deform at its edges.

The study focuses on two materials: Carbon fiber reinforced plastic (CFRP) for the fuselage and aluminum 7075-T6 for the wings. This particular arrangement is best suited for supersonic airplane models with cruise speed up to 2.0 Mach [17]. The material properties relevant to this study are discussed in Table 1.

Table 1: Material Properties for CFRP and Al 7075-T6

Material Property	CFRP (Carbon Fiber Reinforced Polymer)	Al 7075-T6 (Aluminum Alloy)
Young's Modulus (E)	145 GPa	71 GPa
Shear Modulus (G)	60.42 GPa	26.92 GPa
Poisson's Ratio (ν)	0.2	0.33
Mass Density	1600 kg/m³	2800 kg/m³

These materials and their specific properties form the basis for subsequent simulations and analyses, and they are best suited for airplane models [12].

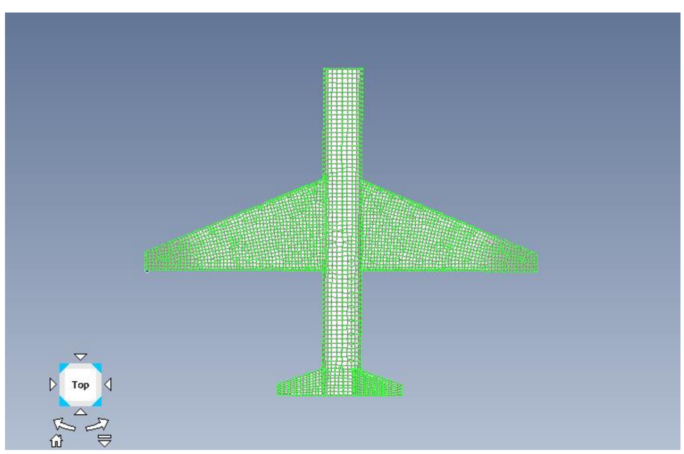

Figure 1: Airplane model to be simulated in Nastran

The numerical simulations are carried out using Siemens FEMAP with NX Nastran v12.0.0 simulation software. NX Nastran is a well-known and reliable finite element analysis tool that is widely used in aerospace engineering for structural and dynamic analyses [18]. Because the primary goal of this research is to investigate the effect of varying Young's Modulus (E), a systematic variation of Young's Modulus is used to achieve this for both CFRP and Al 7075-T6 materials. For each material, the Young's Modulus values listed in Table 2 are taken into account.

Table 2: Series of values of Young's Modulus

CFRP (Carbon Fiber Reinforced Polymer)	Al 7075-T6 (Aluminum Alloy)
140000000000	66000000000
145000000000	71000000000
150000000000	76000000000

A meshing process is used to discretize the aircraft model for analysis. The meshing scheme in this simulation employs linear, triangular, and quadrilateral elements, totaling 4725 linear elements, 176 triangular elements, and 4549 quadrilateral elements. Choosing right mesh type and size is crucial for achieving precise desired results [19], [20].

Taguchi analysis is used to investigate the effect of different material properties on mode shapes and natural frequencies. Experiments for different combinations of Young's Modulus values for CFRP and Al 7075-T6 are carried out using a Taguchi L9 array. Table 3 shows mode frequencies in relevance of Taguchi L9 array combinations.

Table 3: Taguchi L9 array

CFRP (Factor 1)	Al 7075-T6 (Factor 2)	Mode 1	Mode 2	Mode 3	Mode 4	Mode 5
140000000000	66000000000	2.78E-07	3.94E-07	4.87E-07	6.21E-07	6.74E-07
145000000000	71000000000	2.37E-07	2.92E-07	5.16E-07	5.21E-07	7.45E-07
150000000000	76000000000	2.82E-07	3.22E-07	4.70E-07	5.52E-07	8.95E-07
140000000000	71000000000	2.35E-07	2.78E-07	4.86E-07	5.28E-07	7.00E-07
145000000000	76000000000	9.48E-08	3.45E-07	7.00E-07	9.36E-07	1.06E-06
150000000000	66000000000	5.02E-08	2.56E-07	6.15E-07	6.69E-07	1.24E-06
140000000000	76000000000	1.46E-07	3.56E-07	4.58E-07	6.20E-07	7.74E-07
145000000000	66000000000	3.36E-07	3.95E-07	4.27E-07	5.14E-07	1.61E-06
150000000000	71000000000	5.91E-08	2.30E-07	5.88E-07	6.14E-07	8.94E-07

One-way Analysis of Variance (ANOVA) is used to determine the impact of Young's Modulus variations on mode values. ANOVA aids in statistically evaluating Young's Modulus' influence on mode shapes and natural frequencies, providing quantitative insights into the variations observed.

The simulation and statistical analysis results are thoroughly examined and discussed in order to highlight the distinct variations in mode shapes and natural frequencies caused by changes in Young's Modulus. This discussion serves as the foundation for reaching conclusions and gaining insights into the potential of tailored material selection to influence dynamic behavior in aerospace design.

3 RESULTS

The findings of our study, which focused on the effect of varying Young's Modulus on mode shapes and natural frequencies in an aircraft model made of CFRP and Al 7075-T6 materials, are explained numerically.

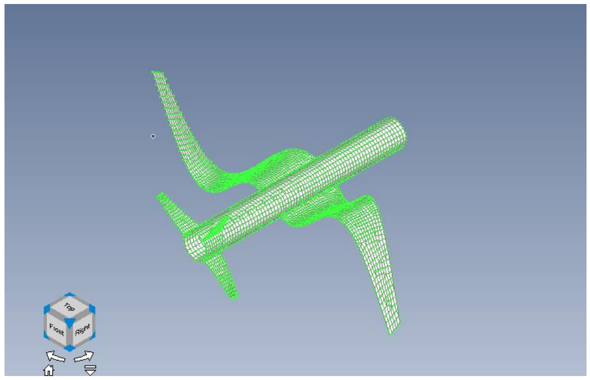

Figure 2(a): Model deformation subjected to its natural frequency (isometric view)

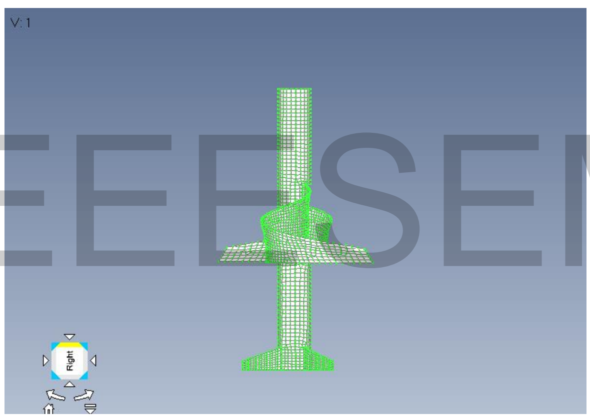

Figure 2(b): Model deformation subjected to its natural frequency (side view)

The Taguchi analysis results are summarized in Table 4. Taguchi analysis aids in determining the best SNR levels for CFRP (Factor 1) and Al 7075-T6 (Factor 2) for each mode. The SNR values represent the best combinations of Young's Modulus values for these materials, resulting in improved mode characteristics.

Table 4: SNR Values for both materials

Mode	Best SNR Level for CFRP	Best SNR Level for Al 7075-T6
Mode 1	Level 1	Level 2
Mode 2	Level 2	Level 2
Mode 3	Level 1	Level 1
Mode 4	Level 1	Level 1
Mode 5	Level 1	Level 2

Table 4 shows notable trends in the best SNR levels for both CFRP and Al 7075-T6 across the five distinct modes examined in our study. These trends shed light on how material selection and specific Young's Modulus values can influence the dynamic

behavior of the aircraft model, providing valuable insights into the sensitivity of each mode to variations in Young's Modulus. For example, in Mode 2, both CFRP and Al 7075-T6 have the highest SNR levels, indicating that this mode is most responsive to higher Young's Modulus values for both materials. In Mode 3, however, the optimal SNR levels for CFRP and Al 7075-T6 are both at Level 1, indicating that lower Young's Modulus values are more appropriate for this mode.
Table 5 shows the results of a one-way Analysis of Variance (ANOVA) for CFRP (Factor 1) to determine the impact of Young's Modulus variation on each mode. For each mode, the table includes the F-Value, P-Value, and percentage of variance explained (R-sq).

Table 5: ANOVA values for CFRP

Mode	F-Value	P-Value	R-sq (%)
Mode 1	0.68	0.541	18.53 %
Mode 2	1.94	0.224	39.31 %
Mode 3	0.68	0.541	18.51 %
Mode 4	0.16	0.853	5.15 %
Mode 5	1.81	0.242	37.67 %

Analyzing the overall trends, we discover that variations in Young's Modulus in CFRP have varying effects across modes. CFRP's Young's Modulus, for example, appears to have a more pronounced effect in Modes 2 and 5, with higher F-Values and moderate to low P-Values. This suggests that changes in CFRP's Young's Modulus contribute significantly to the variance in these modes, accounting for 39.31% and 37.67% of the variance, respectively.
Modes 1, 3, and 4, on the other hand, have lower F-Values and higher P-Values, implying that Young's Modulus variations in CFRP have a minor influence on these modes, explaining 18.53%, 18.51%, and 5.15% of the variance, respectively. These findings suggest that for some modes, other factors or material properties may be more important in determining their behavior.
Table 6 shows the results of a one-way ANOVA performed on Al 7075-T6 (Factor 2) to assess the effect of Young's Modulus variation on each mode. For each mode, it includes the F-Value, P-Value, and the percentage of variance explained (R-sq).

Table 6: ANOVA Values for Al 7075-T6

Mode	F-Value	P-Value	R-sq (%)
Mode 1	0.15	0.865	4.70 %
Mode 2	2.39	0.172	44.36 %
Mode 3	0.08	0.922	2.68 %
Mode 4	1.02	0.416	25.33 %
Mode 5	1.43	0.310	32.35 %

Mode 1 has a low F-Value of 0.15 and a high P-Value of 0.865, accounting for only 4.70% of the observed variance. This implies that changes in Young's Modulus for Al 7075-T6 have little effect on Mode 1. Mode 2, on the other hand, exhibits a significant response, as evidenced by a high F-Value of 2.39 and a relatively low P-Value of 0.172, explaining a significant portion (44.36%) of the variance. As a result, Mode 2 is highly sensitive to changes in Young's Modulus for Al 7075-T6, emphasizing its importance in design optimization. Modes 3 and 4 have low F-values (0.08 and 1.02, respectively) and high P-values (0.922 and 0.416, respectively) to Young's Modulus variations. Only a small portion of the observed variances are explained by these variations (2.68% for Mode 3 and 25.33% for Mode 4). Mode 5 has moderate sensitivity, with an F-Value of 1.43 and a P-Value of 0.310, explaining a significant portion of the variance (32.35%). As a result, when designing with Al 7075-T6, Mode 5 requires careful consideration because variations in Young's Modulus can moderately influence its behavior. These behaviors are illustrated in Figure 4.

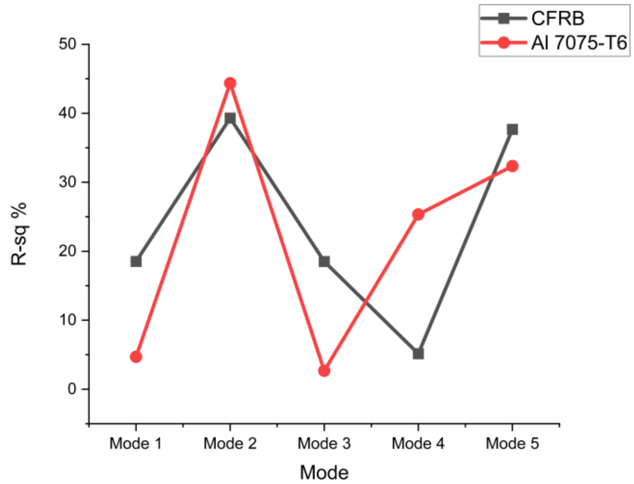

Figure 3: Coefficient of determinations for CFRB and Al 7075-T6 at different frequency modes

4 Conclusion

The effect of varying Young's Modulus on mode shapes and natural frequencies in an aircraft model made of Carbon Fiber Reinforced Polymer (CFRP) and Aluminum Alloy 7075-T6 (Al 7075-T6) was investigated. Several key findings and insights emerged from our comprehensive analysis using advanced engineering techniques:

1. Different modes in the aircraft model were sensitive to changes in Young's Modulus to varying degrees. Some modes were highly responsive to material variations, while others were relatively insensitive.
2. We identified optimal combinations of Young's Modulus values for CFRP and Al 7075-T6 using Taguchi analysis, resulting in improved mode characteristics. This data is useful for material selection in aerospace design.
3. Mode 2 was found to be highly sensitive to changes in Young's Modulus for both CFRP and Al 7075-T6, implying that it plays an important role in design optimization. Our findings show that tailored material selection has the potential to precisely influence dynamic behavior in aerospace structures. This opens the door to improving aircraft performance and reliability by optimizing mode shapes and natural frequencies.

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