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Experimental Modal Analysis for Aerial Centerline Fuel Tanks

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Abstract. External aerial fuel tanks are attached to the aircraft to extend their range and endurance. This experimental study presents a meticulous investigation into the dynamic characteristics of aerial fuel tanks A and B, employing resonance search tests and frequency sweep tests. The experimental setup, involving cyclic excitation and vibration analysis, aimed to predict and compare the tanks' natural frequencies, mode shapes, and structural damping. The acquired data revealed striking similarities in dynamic behavior, affirming that both tanks exhibit consistent responses to external forces. The structural damping values, mode shapes, and resonant frequencies closely aligned, indicating negligible variations in geometry, material, and production technology. The increase in natural frequencies with mode number reflects enhanced structural stiffness and responsiveness. The comprehensive analysis supports the conclusion that tank B is well-prepared for flight testing, showcasing its stability and reliability in dynamic conditions as tank A passed already the flight test.

Keywords. Aerial Fuel Tank, Experimental Modal Analysis, Resonance Search Test, Natural Frequencies, Structural Damping, Mode Shape, Spectral Analysis.

INTRODUCTION

Super-maneuvering aircraft incorporate external aerial fuel tanks to enhance their flight range (Roger et al., 1990). Nevertheless, the presence of these tanks, particularly when fully fueled, significantly compromises the aircraft's maneuverability (Crawford et al., 1990). Consequently, to mitigate this impact, the tanks are intentionally jettisoned before critical landings or when engaging in super-maneuvering missions (Johnston et al., 1965). Designed, qualified, and manufactured for either centerline or wing/pylon installation on such aircraft, both Tank A and Tank B are specifically positioned along the centerline of the aircraft fuselage on the lower pressure side (Roger et al., 1990) (Fig. 1).

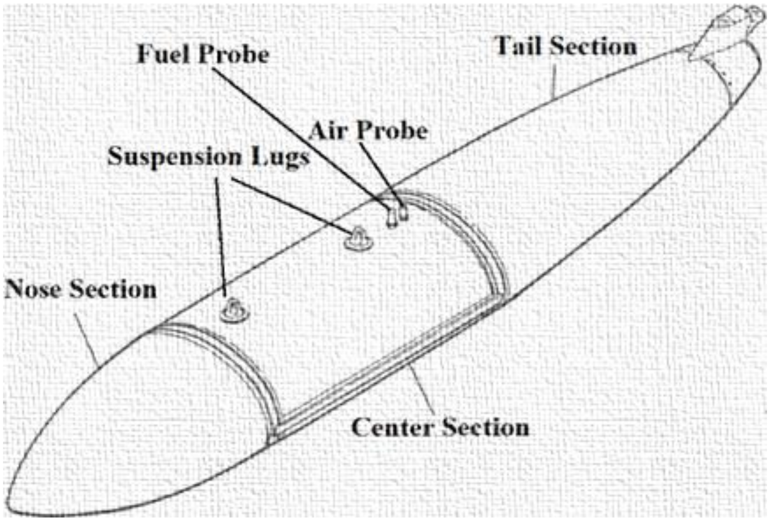

Fig. 1. External Centerline Fuel Tank of 1135-Liter capacity.

Advancements in aerospace technology demand a thorough understanding of the dynamic characteristics of structural components subjected to the rigors of flight. Experimental Modal Analysis (EMA) stands as a pivotal methodology, offering a comprehensive approach to investigate and quantify the vibrational behavior of structures. This study delves into the dynamic characteristics of aerial centerline fuel tanks A and B through the application of resonance search tests and frequency sweep tests, utilizing EMA as the primary investigative tool.

THEORETICAL FOUNDATION

EMA is rooted in the principles of structural dynamics, focusing on the inherent vibrational modes of structures under controlled excitations. Each mode corresponds to a specific pattern of deformation, and the analysis aims to unveil critical parameters such as natural frequencies, mode shapes, and structural damping. These parameters collectively define the dynamic response of structures, providing invaluable insights into their behavior under various loading conditions (Ewins, 2009; Harris, 1988).

Natural Frequencies and Mode Shapes

Natural frequencies represent the inherent rates at which a structure vibrates, and each frequency corresponds to a specific mode shape. As the mode number increases, the structure undergoes more complex vibrational patterns, revealing information about stiffness, flexibility, and overall structural integrity. Higher natural frequencies indicate a more rapid response to dynamic excitations, crucial for stability and control during flight.

Structural Damping

Structural damping is a key parameter in EMA, representing the rate at which a structure dissipates energy during vibrations. Consistent values of structural damping across different modes imply uniform energy dissipation, contributing to stable and controlled dynamic behavior. Similar damping characteristics between structures offer insights into their energy dissipation mechanisms and potential implications for real-world applications.

Methodological Framework

The experimental setup is a critical component of EMA, providing the means to induce controlled vibrations and capture accurate measurements. The study employs a sophisticated Data Acquisition System, including a Dual channel signal analyzer, Power amplifiers, Phase & amplitude controllers, Multiplexers, and various sensors such as accelerometers, force transducers, and vibration exciters. Calibration ensures the reliability of measurements, enabling a meticulous analysis of the tanks' responses to external forces.

RESONANCE SEARCH TESTS AND FREQUENCY SWEEP TESTS

Resonance search tests involve applying cyclic excitation to the structure across a specified frequency range. This method facilitates the identification of prominent frequencies and associated mode shapes. Frequency sweep tests extend this by exploring a broader range of frequencies, offering a more comprehensive understanding of the tanks' dynamic behavior. The results from these tests form the basis for the subsequent modal analyses (Ewins, 2009; Harris, 1988; Harris and Piersol, 2002).

Modal Analyses

Modal analysis is a technique used to determine the mode shapes corresponding to each natural frequency identifying how different parts of the structure move relative to each other under vibration conditions (Craig et al. 2006). Modal analyses involve the interpretation of acquired data to extract meaningful information about the structural behavior. Parameters such as mode shapes, natural frequencies, and structural damping values are derived, allowing for a detailed comparison between tanks A and B. The significance of the observed similarities or differences serves as a basis for drawing conclusions regarding their readiness for flight testing.

Objectives of the Study

This investigation aims to systematically explore and compare the dynamic characteristics of aerial fuel tanks A and B. By employing EMA methodologies, the study seeks to validate the structural stability, reliability, and readiness of these tanks for flight testing. The focus on resonance search tests and frequency sweep tests provides a nuanced understanding of their vibrational responses, essential for ensuring optimal performance in real-world flight scenarios.

In summary, this information establishes the theoretical underpinnings of EMA, emphasizing the importance of natural frequencies, mode shapes, and structural damping in characterizing structural dynamics. The methodological framework outlines the experimental setup and procedures, paving the way for a meticulous investigation into the dynamic behavior of aerial fuel tanks A and B.

Frequency sweep test or resonance search test investigate the dynamic characteristics (natural frequencies, modes shape, and structural damping) of aerial fuel tanks. The predicted dynamic characteristics of aerial fuel tanks on-ground are not changed during flight. In fact aerodynamic forces in flight are the same as on ground because they depend only on the geometry. This would encourage scientists to carry out the flight test without fear of appearance of any aeroelastic problems. A resonance search test, typically involves exciting the structure of the aerial fuel tank with a known force or input and measuring its response. The experimental setup and analysis for such tests can vary depending on the specific goals, the type of structure being tested, and the available equipment. The test is performed in a controlled environment to minimize external disturbances. A frequency sweep test is performed by gradually increasing the excitation frequency covering a range of frequencies that includes the expected natural frequencies of the investigated tank structure. Resonance frequencies of the tank are determined by varying the frequency of applied vibration slowly through the specified range at reduced test levels with amplitude sufficient to excite the tank.

The response of the structure has been predicted at each excitation frequency and capturing data until a sufficient range of frequencies is covered.

Fast Fourier Transform (FFT) is performed to convert the acquired signals from time-domain into frequency domain as;

$$X(f) = \int_{-\infty}^{\infty} x(t)\ e^{-j2\pi f t} dt \qquad (1)$$

where X(f) is the acquired signal in frequency domain, x(t) is the acquired signal in time-domain, f is the frequency, and j is the imaginary unit (Trampe Broch, 1984; Bendat and Piersol, 1980).

FFT decomposes the signal into its constituent frequency components, revealing the dominant frequencies present in the response. Fourier Transform is performed to identify the natural frequencies of the structure from the response data. Modal analysis techniques are performed to determine the mode shapes corresponding to each natural frequency. This involves identifying how different parts of the structure move relative to each other. The damping ratios are predicted from the response data to quantify the level of energy dissipation in the structure. Common methods include logarithmic decrement or half-power bandwidth analysis (Chopra,2011; Ewins, 2009; Harris, 1988).

Natural Frequency Extraction is achieved by the identification of the Peak Frequencies. After applying FFT to the time-domain response signal, peaks in the frequency domain represent the natural frequencies of the system.

Peaks in the frequency domain correspond to the vibrational modes of the structure, each peak represents a different mode or natural frequency (ωn) in radians per second, at which the structure resonances. The peak frequency (fpeak) corresponds to the natural frequency (ωn) is calculated as:

$$\omega n = 2\,\pi\, fpeak \qquad (2)$$

Damping ratio (ζ) is a measure of how fast the vibrations in a system decay after being excited and is related to the width of the peak in the frequency domain. The width of the peak at its half-power points (3 dB points) is used to determine the damping ratio.

- It is often expressed as the full width at half-maximum (FWHM) of the peak.

Damping ratio (ζ) is determined as:

$\zeta \ = \ 2 \, \omega n \, FWHM$ (3)

To identify Half-Maximum Points, the points on the frequency spectrum where the amplitude is equal to half of the peak amplitude, are located. These are the half-power points.
The FWHM is calculated by determining the frequency range between the half-power points.
The FWHM (Δf) is often calculated as the difference between the frequencies at the two half-power points:

$\Delta f \ = \ f2 - f1$ (4)

where f2 and f1 are the frequencies at the two half-power points.
Therefore, the damping ratio is predicted using the formula:

$\zeta \ = \ 2 \, \omega n \, \Delta f$ (5)

The structural damping of the structure is calculated as;

$\gamma \ = \ 2 \, \xi \, \omega n \ = \ 4 \, \omega n 2$ (6)

For example, if a system has a damping ratio (ξ) of 0.1 and a natural frequency (ωn) of 10 rad/s, you the structural damping is calculated as as follows:

$\gamma \ = \ 2 \times 0.1 \times 10 \ = \ 2 \, rad/s$ (7)

Keep in mind that structural damping is a simplification of the actual damping behavior in structures.
The Power Spectral Density "PSD" is determined to quantify the distribution of signal power across different frequencies. PSD provides information about the distribution of signal's energy across different frequencies.
Peaks in the frequency domain are identified corresponding to natural frequencies of the structure. Peaks in the PSD represent the modal frequencies/natural frequencies or resonances of a structure.
High values or sharp peaks in the PSD at specific frequencies indicate concentrated energy at those frequencies, while broader distribution suggests a spread of energy across those frequencies.
Amplitude and phase information of PSD are extracted from the peaks in the frequency domain to estimate mode shapes.
The power spectral density (PSD) is the square of the magnitude of the Fourier Transform X(f). It is often expressed in terms of power per unit frequency:

$Sxx(f) = | \ X(f) \ |^2$ (8)

This function Sxx(f) represents the power content of the signal at each frequency component. For a continuous-time signal x(t), the PSD, denoted by Sx(f), is the Fourier transform of the autocorrelation function Rx(τ):

$$Sx(f) = \int_{-\infty}^{\infty} Rx(\tau)\ e^{-j2\pi f\tau} d\tau \quad (9)$$

Rx(t) is the autocorrelation function, f is the frequency, j is the imaginary unit, and the integral is taken over all possible time lags τ.

Aautocorrelation function

$$Rx(t) = \int_{-\infty}^{\infty} x(t)\, x(t-\tau)\, dt \quad (10)$$

were, τ is the time lag (Ewins, 2009; Harris, 1988; Trampe Broch, 1988; Bendat and Piersol, 1980).

The units of PSD depend on the units of the original signal and is denoted as (g2/Hz) for vibration.

EXPERIMENTAL SETUP

Data Acquisition System

The data acquisition system consists of the following items;
(1 piece) Dual channel signal analyzer B&K 2034 (Modified)
(16 pieces) Power amplifier for shakers B&K 2707
(16 pieces) Phase & amplitude controllers B&K-WB0169
(1 piece) Multiplexer B&K 5795
(1 piece) Multiplexer B&K 5797
(1 piece) Control unit B&K 5794
(27 piece) Charge amplifiers B&K-WB0340 for signals from accelerometers/force-transducers
(1 piece) Group selector B&K 58201 Master
(1 piece) 20-Channel amplifier 5 B&K 541for signals from group selector to multiplexer 5795
(1 piece) Graphic printer/digital system controller
(16 pieces) Vibration Exciter B&K 4805/4814
(16 pieces) Force Transducer B&K 8200
(250 Pieces) Accelerometers of different types including B&K 4371
The experimental setup is shown in figures 2, 3 and 4.

Sensor Calibration and mounting on the tank structure

All sensors and the excitation system are calibrated to ensure accurate and reliable measurements. The test instruments are connected as shown in (Fig. 2, 3 and 4) and have been checked for proper functioning. An accelerometer is mounted on arbitrary chosen location on the front part of the tank “nose section”, while the excitation point is specifically chosen to lie far enough from the nodal lines of any mode as shown in (Fig. 2). A force transducer B&K 8200 is mounted between the axis arm of the shaker and the structure of the fuel tank at the rear part of the tank to apply a controlled known precise excitation force on the structure of the fuel tank to excite the structure to a sufficient level (Fig. 4).

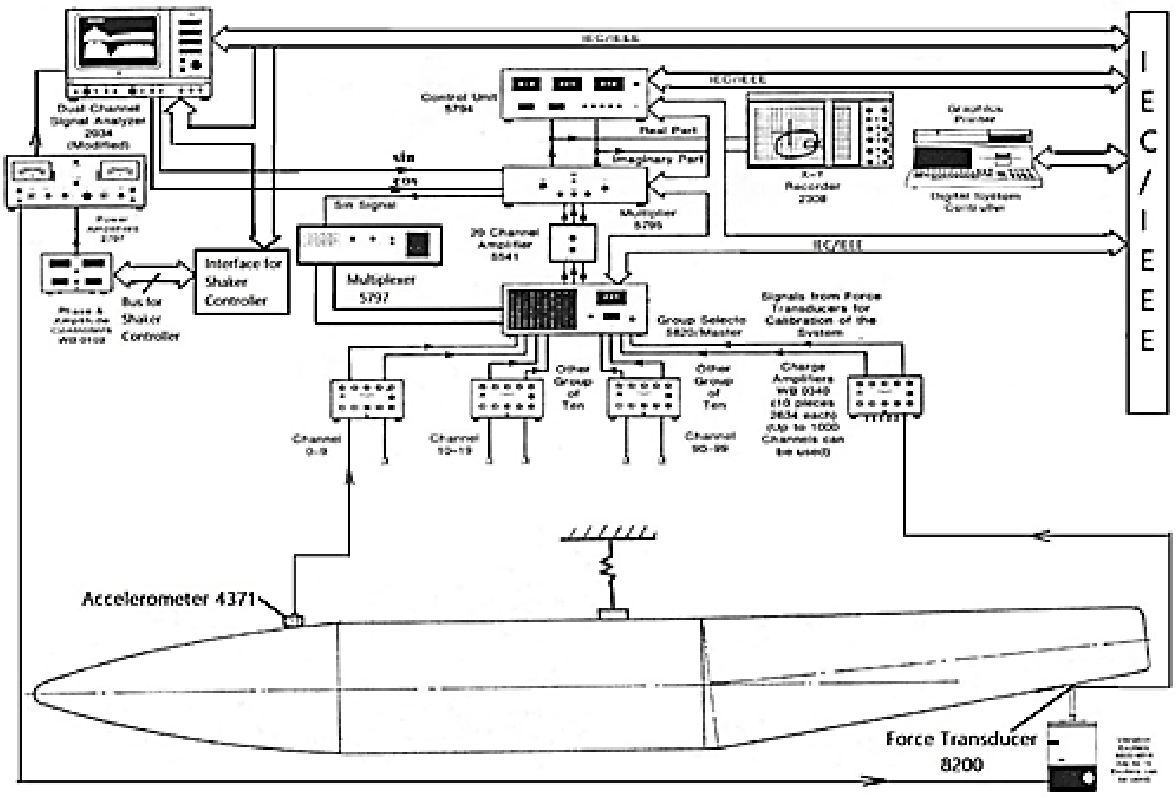

Fig. 2. Experimental setup for a dynamic test of external aerial fuel tank.

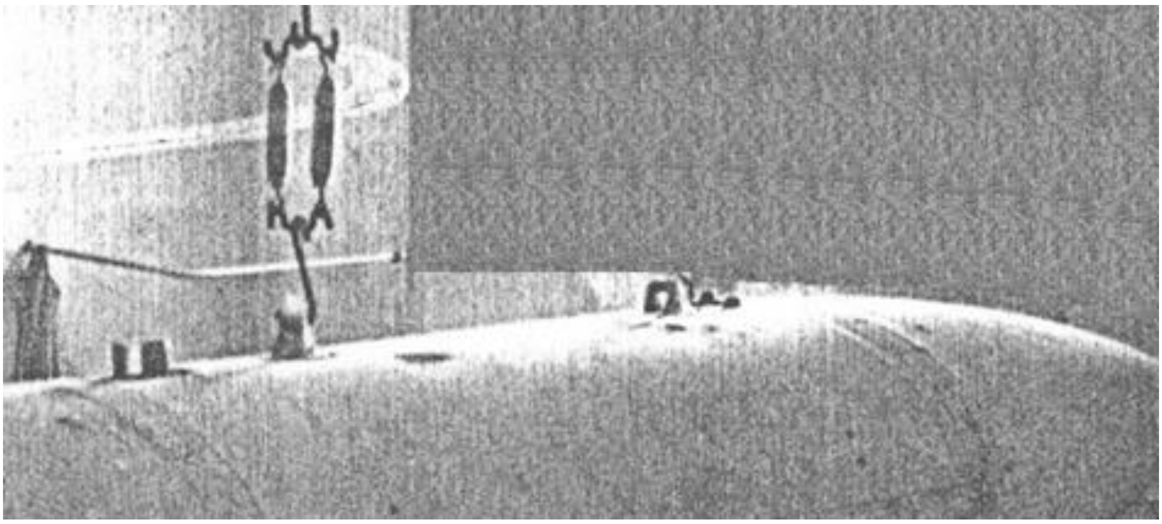

Fig.3. Suspension of the aerial fuel tank.

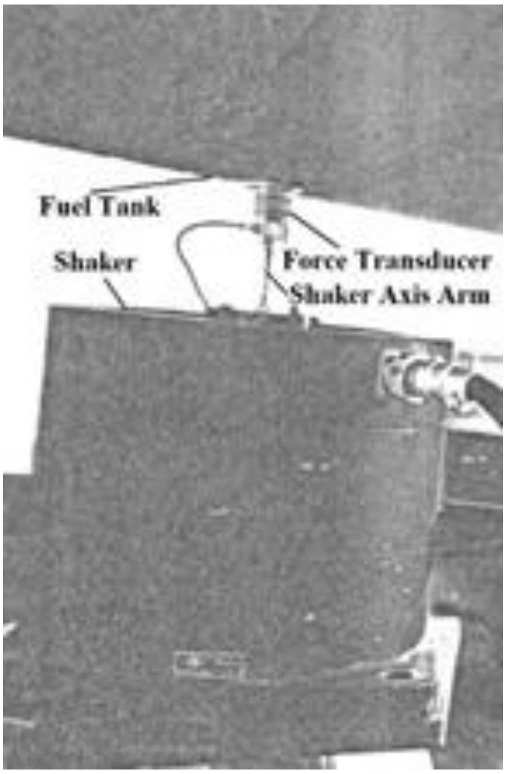

Fig.4. Supporting the shaker and Force Transducer to the Rear Structure of the Fuel Tank.

RESULTS AND DISCUSSION

The Resonance Search using frequency sweep test applies cyclic excitation on the rear part of the aerial fuel tank in the frequency range from 50 to 300 cycle per second "C.P.S." and from 80 to 150 C.P.S. for tank A as well as from 50 to 330 and from 80 to 150 C.P.S. for tank B. The acquired data predicts prominent frequencies of 108.5, 132.4 and 144.65 Hz for the 1st, 2nd and 3rd modes respectively for Tank A (Fig.5, 6) and 112.5, 133.9 and 146.85 Hz for the 1st, 2nd and 3rd modes respectively for Tank B (Fig.7, 8). The PSD values of both tanks lie in the range of 0.0287, 0.025 and 0.00858 g2/Hz related to the 1st, 2nd and 3rd modes respectively. The mode shape for the center of gravity line of both aerial fuel tanks A & B are shown in figure 9.

The main three natural frequencies with their three natural modes are considered in the analyses.

The mode shapes of both tanks are very similar despite slight differences in their natural frequencies. The structural damping γ of both tanks have very close values of;

1st mode, γ = 0.072

2nd mode, γ = 0.074

3rd mode, γ = 0.054

The resonance search test results for aerial fuel tanks A and B, reveals valuable information about their dynamic characteristics with the following physical interpretation;

- Similarity in Mode Shapes: The fact that the mode shapes of both tanks are very similar despite slight differences in natural frequencies suggests that the tanks exhibit comparable vibrational patterns. This similarity indicates a consistent structural response in terms of how different parts of the tanks move relative to each other during vibrations.

- Close Values of Structural Damping (γ): The structural damping values for the 1st, 2nd, and 3rd modes are very close for both tanks. This implies that both tanks dissipate energy at a similar rate when subjected to vibrations. The close γ values suggest a consistent level of energy dissipation, contributing to stable and controlled dynamic behavior. The close values of structural damping of both tanks suggests that;

(a) Both tanks exhibit similar levels of energy dissipation during vibrations.
(b) Could have several physical implications including Similar Energy Dissipation.
(c) Likely to exhibit comparable responses to dynamic loads, such as wind .
(d) Both fuel tank structures will respond similarly to external forces, leading to more predictable and consistent performance in terms of dynamic behavior.
(e) Simplifies the modeling process, and can lead to a more consistent design approach for both structures, similar design methodologies and considerations for mitigating dynamic effects can be applied.

- Prominent Frequencies and PSD Values: The prominent frequencies for both tanks are within a comparable range, and the Power Spectral Density (PSD) values lie within the range of 0.00858 across 0.025 to 0.0287 g^2/Hz. This indicates that both tanks exhibit consistent energy distribution across different frequencies. The resonant frequencies and PSD values are crucial for understanding how the tanks respond to external excitations.
- Minor Differences in Natural Frequencies: The slight differences in natural frequencies between both tanks (e.g., 108.5 vs. 112.5 Hz for the 1st mode) are likely attributable to variations in geometry, material, or manufacturing processes. However, these differences are relatively small, suggesting that the overall dynamic behavior of the tanks is similar.
- Structural Integrity and Predictable Performance: The data collectively suggests that both tanks possess similar structural integrity and are likely to exhibit predictable performance under dynamic conditions. The similarity in mode shapes, structural damping values, and resonant frequencies indicates a consistent response to vibrational stimuli.
- Readiness for Flight Testing: Given the negligible differences observed in the dynamic characteristics of the two tanks, especially considering their intended use in aerial conditions, the data supports the conclusion that both tanks are ready for flight testing. The consistent behavior across various modes enhances confidence in their performance during actual operational scenarios.

In summary, the physical interpretation of the data underscores the similarity in dynamic behavior between tanks A and B. The close values in mode shapes and structural damping, along with the minor differences in natural frequencies, collectively suggest that both tanks are well-suited for their intended applications, providing confidence in their stability and reliability during flight conditions.

Increasing the natural frequencies of both aerial fuel tank structures as the mode number increases generally implies a shift towards higher frequencies in the vibration response. The impact on the PSD reflects the distribution of energy at these higher frequencies, and this can have implications for the dynamic behavior and performance of the structure. Increasing the natural frequencies by increasing the mode number means that the structure tends to vibrate at higher frequencies by moving to higher modes. Higher natural frequencies imply that the structure responds more rapidly to dynamic excitations. The physical interpretation of increasing natural frequencies as the mode number increases in both aerial fuel tank structures can be understood through the following key points:

- Higher Mode, Higher Frequency: In structural dynamics, each mode corresponds to a specific vibrational pattern or shape of deformation. As the mode number increases, it signifies a higher order of vibration. Higher modes have higher natural frequencies, indicating that the structure vibrates at a faster rate or shorter period.
- Increased Structural Stiffness: An increase in natural frequencies with mode number often implies an increase in the structural stiffness of the system. Higher mode shapes involve more complex deformation patterns that demand a stiffer structure for their expression. The overall stiffness of the structure contributes to the speed at which it responds to dynamic excitations.
- Reduced Flexibility in Higher Modes: Higher modes typically involve more localized and complex deformation patterns, often indicating reduced flexibility in specific regions of the structure. The structure becomes less prone to large-scale deformations as mode numbers increase, leading to a more rigid response.
- Rapid Response to Dynamic Excitations: Higher natural frequencies indicate that the structure responds more rapidly to dynamic excitations. This is crucial for applications like aerial fuel tanks, where rapid response to external forces (such as wind gusts during flight) is essential for stability and control.
- Avoidance of Resonance at Lower Frequencies: As the natural frequencies increase with mode number, the structure is less likely to resonate with external forces operating at lower frequencies. This helps in avoiding undesirable resonance conditions that could lead to excessive vibrations or structural instability.
- Higher Frequencies Reflect Higher Energy States: In the context of structural dynamics, higher natural frequencies are associated with higher energy states in the system. The structure has more stored energy at higher frequencies, contributing to a more dynamic and responsive behavior.
- Improved Dynamic Performance: The increase in natural frequencies with mode number suggests that the aerial fuel tank structures are designed to have improved dynamic performance at higher modes. This is important for ensuring that the tanks can effectively withstand and respond to the dynamic loads experienced during flight.
- Mode Localization: Higher modes often involve more localized deformations, indicating specific areas of the structure that are primarily involved in the vibrational response. This information is valuable for understanding the distribution of dynamic forces within the structure.

In summary, the physical interpretation of increasing natural frequencies with mode number reflects a combination of increased structural stiffness, reduced flexibility, rapid response to dynamic excitations, avoidance of resonance at lower frequencies, and improved dynamic performance. These characteristics are vital for the structural integrity and reliable performance of aerial fuel tank structures, especially in the context of dynamic conditions experienced during flight.

The decrease in Power Spectral Density (PSD) values from 0.0287 to 0.00858 g^2/Hz as the natural frequencies increase from 112.5 across 133.9 to 146.85 Hz indicates a shift in energy distribution towards higher frequencies. This observation has several physical implications:

- Higher Natural Frequencies: An increase in natural frequencies implies that the structure is vibrating at higher rates or faster oscillations. In the context of the aerial fuel tanks, this could be due to increased stiffness or changes in the overall dynamic characteristics of the tanks.
- Rapid Structural Response: Higher natural frequencies indicate that the structure responds more rapidly to dynamic excitations. The structure tends to vibrate at higher frequencies, signifying a quicker reaction to external forces or disturbances.
- Concentration of Energy: The decrease in PSD values at higher natural frequencies suggests that the energy is becoming more concentrated at these frequencies. In other words, the structure is exhibiting a more focused or specific response in terms of vibrational modes.
- Damping Effect: The decrease in PSD values may also indicate effective damping mechanisms in the structure. As natural frequencies increase, the structure may dissipate energy more efficiently, resulting in a reduced amplitude of vibration and, consequently, lower PSD values.
- Structural Stability: A decrease in PSD values with increasing natural frequencies can be an indication of structural stability. The structure is effectively managing dynamic loads, and the energy is distributed in a way that minimizes potential resonances or undesired vibrations.
- Reduced Vibrational Excitation: Higher natural frequencies suggest that the structure is less susceptible to vibrational excitations at lower frequencies. This can be beneficial in terms of minimizing the impact of certain external forces or disturbances that operate at lower frequency ranges.

In summary, the observed decrease in PSD values with increasing natural frequencies reflects a structural response where energy becomes concentrated at higher frequencies. This behavior can be associated with increased stability, efficient energy dissipation, and a rapid structural response to dynamic loading conditions.

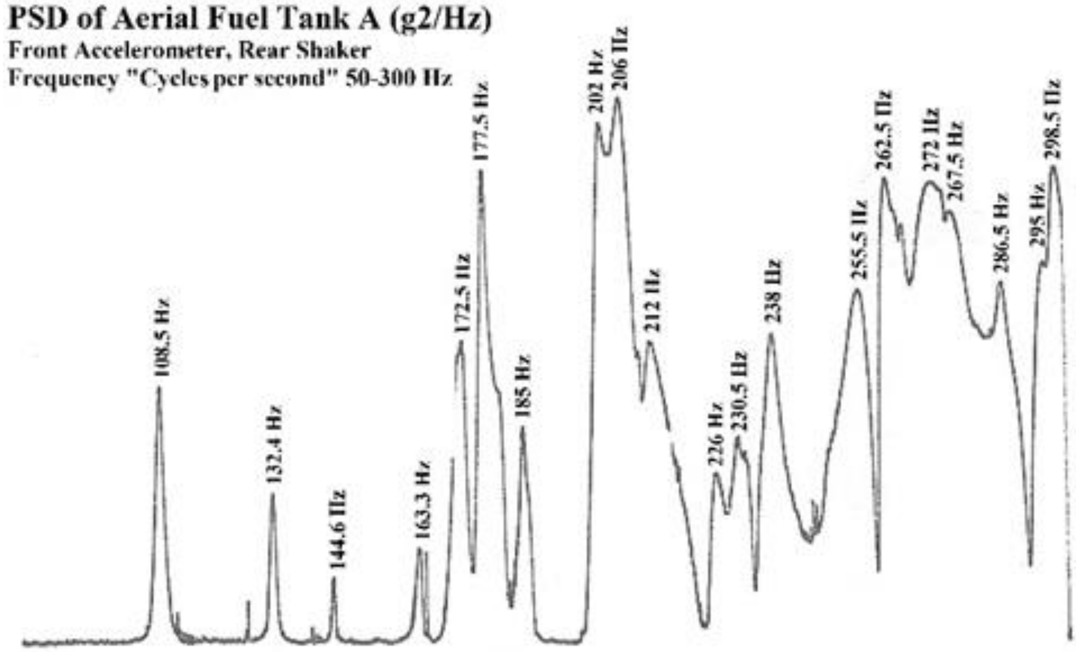

Fig.5. PSD of Tank A, Freq. 50-300 Hz.

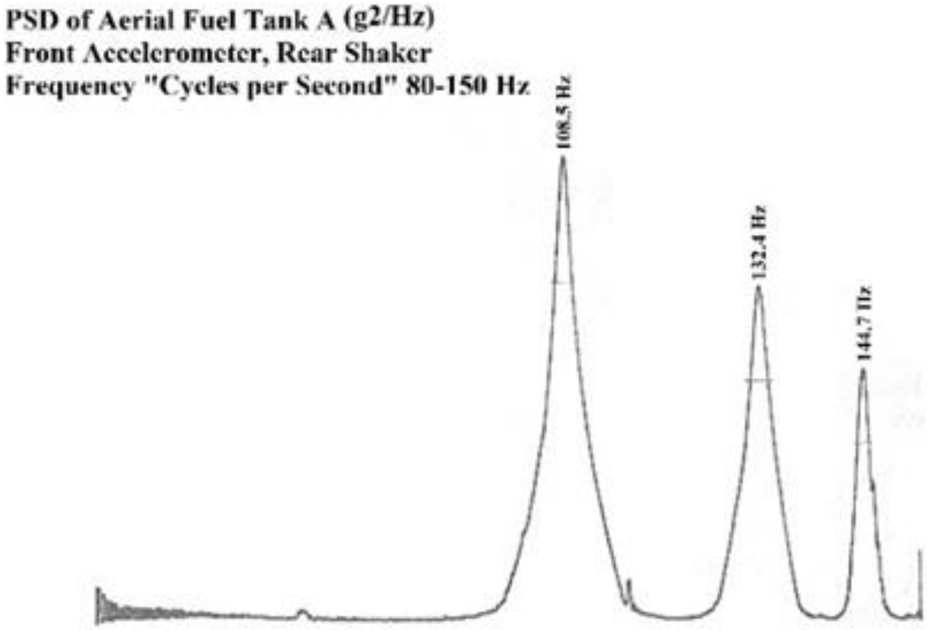

Fig.6. PSD of Tank A, Freq. 80-150 Hz.

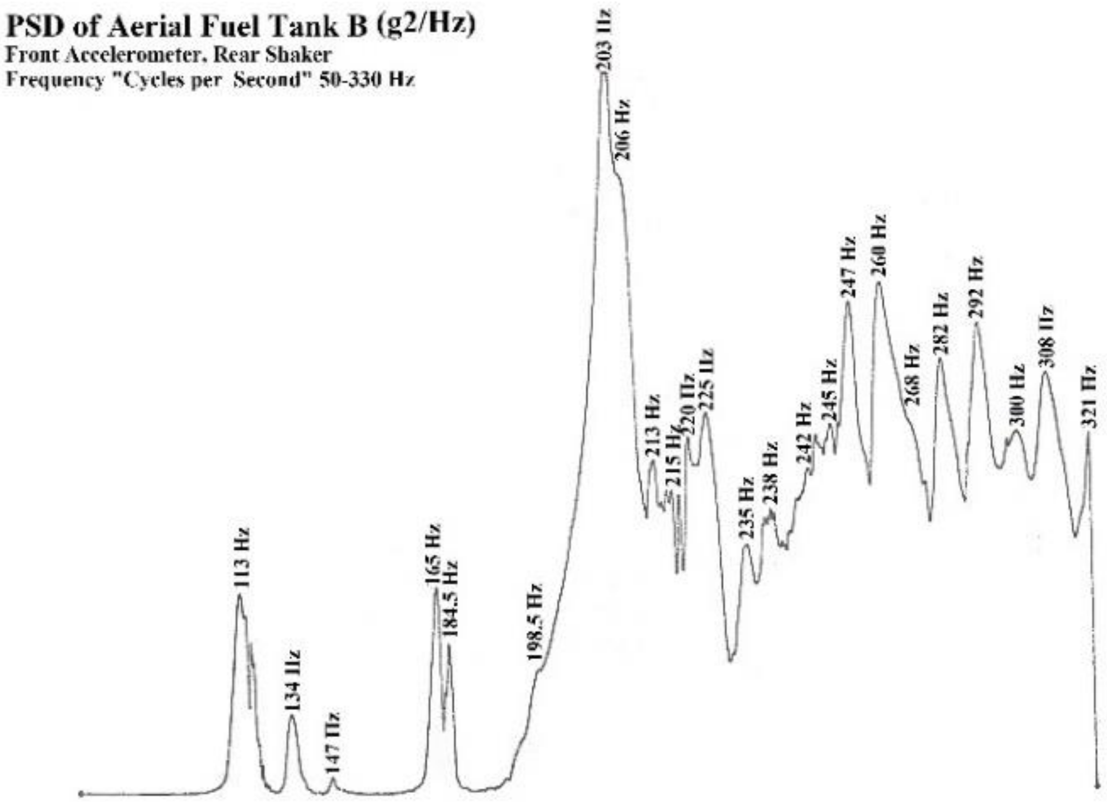

Fig.7. PSD of Tank A, Freq. 50-330 Hz.

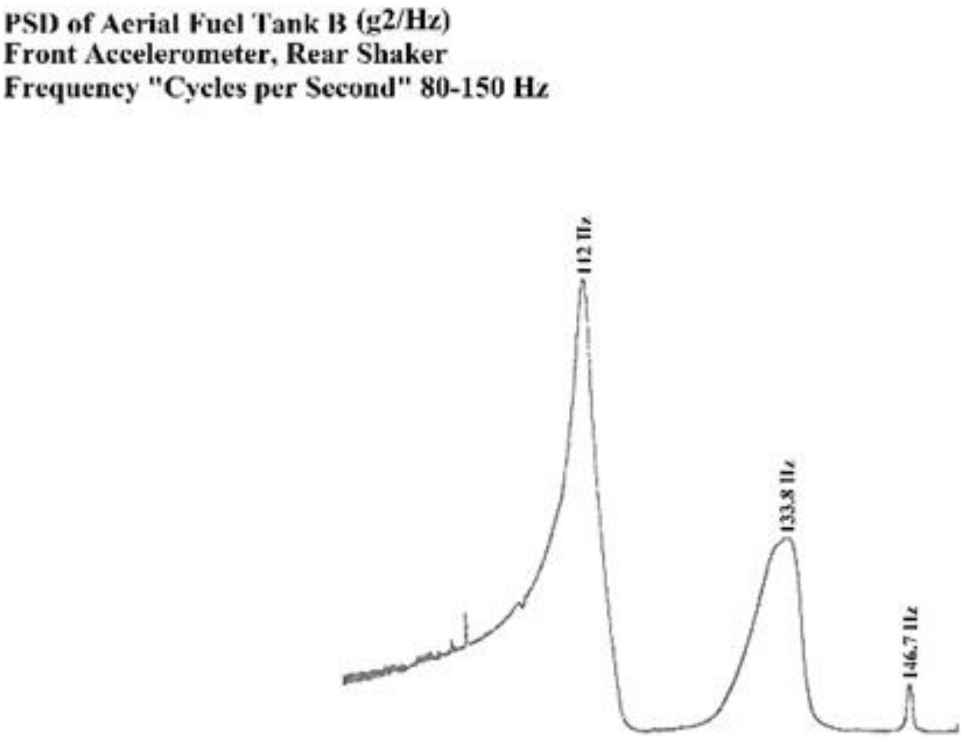

Fig.8. PSD of Tank A, Freq. 80-150.

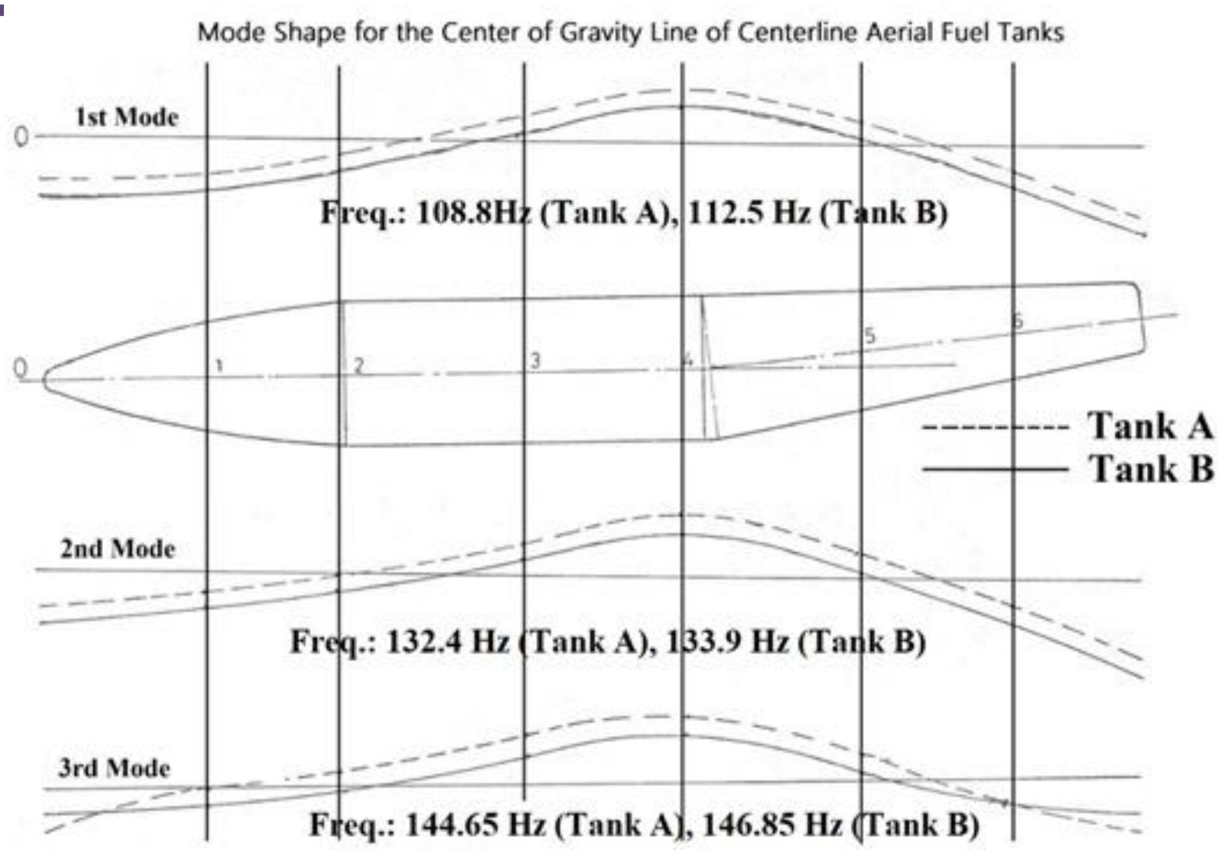

Fig.9. Mode Shape for the Center of Gravity Line of Aerial Fuel Tanks A & B.

CONCLUSION

This investigation delved into the dynamic characteristics of aerial fuel tanks A and B through resonance search tests or frequency sweep tests, and comprehensive modal analyses. The resonance search tests revealed prominent frequencies and Power Spectral Density (PSD) values, providing insights into the tanks' responses to cyclic excitation. The similarity in mode shapes, structural damping values, and natural frequencies despite minor differences suggests a consistent and reliable dynamic behavior for both tanks. Notably, the close correspondence in structural damping values implies similar energy dissipation, simplifying modeling processes and design considerations. The observed increase in natural frequencies with mode number indicates a well-designed and rapidly responsive structure. The structural readiness for flight testing is underscored by the negligible differences in dynamic characteristics between the two tanks. Overall, the data supports the conclusion that both tanks exhibit stability, reliability, and readiness for flight testing.

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