Journal of Research and Development 10[25]1-18: e21025118

Article

State of the art in mechanical vibration analysis for UAV´s

Estado del arte en el análisis de vibraciones mecánicas en Vehículos Aéreos no tripulados

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CONAHCYT classification:

Area: Engineering
Field: Engineering
Discipline: Mechanical Engineering
Subdiscipline: Structures

https://doi.org/10.35429/JRD.2024.10.25.1.18
Article History:
Received: January 20, 2024
Accepted: December 31, 2024

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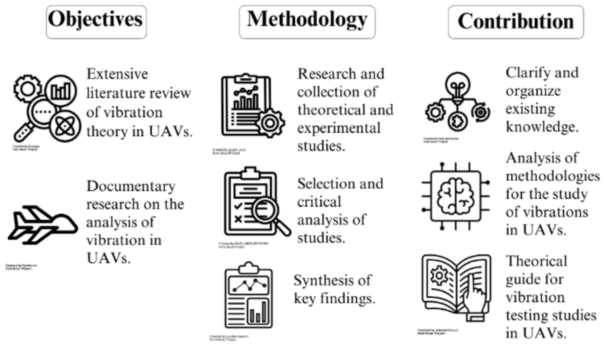
Abstract

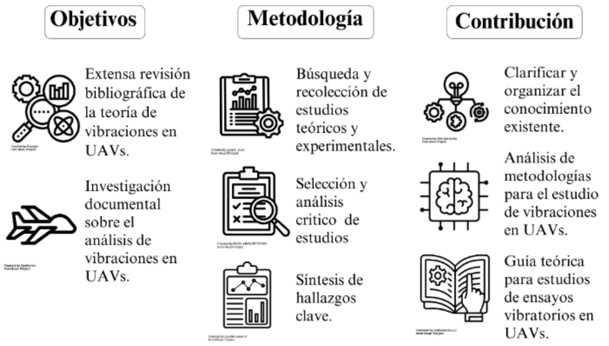
This article focuses on the study of the state of the art of theoretical and experimental investigations that carried out vibration analysis in an unmanned aerial vehicle (UAV). According to the review of literature, modal analysis is fundamental to determine the dynamic behaviour of the structure since it studies the nature of the vibrations and the behaviour of the UAV structure under different excitations. One unwanted vibration is flutter, which is a phenomenon that causes structural failure, performance degradation and in the worst case, partial or complete loss of the aircraft structure. The fundamental tool for the analysis of vibrations including flutter is the Fast Fourier Transform. As a result of the analysis of the studies reported in this work, some important points to be considered when implementing modal analysis in UAVs are listed.



Analysis, Modal, Flutter

Resumen

El presente artículo se enfoca en el estudio del estado del arte de investigaciones teóricas y experimentales que realizaron el análisis de vibraciones en un vehículo aéreo no tripulado (UAV). De acuerdo con la revisión bibliográfica el análisis modal es fundamental para determinar el comportamiento dinámico de la estructura ya que estudia la naturaleza de las vibraciones y el comportamiento de la estructura del UAV ante diversas excitaciones. Una vibración no deseada es el Flutter, el cual es un fenómeno que causa fallas estructurales, degradación del rendimiento y en el peor de los casos, perdida parcial o completa de la estructura de la aeronave. La herramienta fundamental para el análisis de las vibraciones incluyendo el flutter es la transformada rápida de Fourier. Como resultado del análisis de los estudios reportados en este trabajo se enlistan algunos puntos importantes que se deben considerar al implementar el análisis modal en UAV´s.



Análisis, modal, Flutter

Citation: Tejeda-del Cueto, María Elena, González-Cabrera, Sara Isabel, Vigueras-Zúñiga, Marco Osvaldo and Arroyo-Flores, Maria. [2024]. State of the art in mechanical vibration analysis for UAV´s. Journal of Research and Development. 10[25]-1-18: e21025118.

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Introduction

Unmanned aerial vehicles have become one of the most prominent areas of emerging industry. Currently, UAVs are used in sectors such as military operations, agriculture, mining, surveillance and monitoring, infrastructure inspection, film and photography, forest fire detection and firefighting operations (*Zhang et al.*, 2024).

Vibrations are unwanted movements that can arise in any component or mechanical system of UAVs. In these types of systems, they are caused by mechanical, aerodynamic sources and the natural forces of the vehicle (Abdulrahman Al-Mashhadani, 2019). In addition, vibrations have a significant impact on their service life, performance and safe operations. Therefore, understanding and controlling vibrations has become an essential area of study in this type of aircraft. To this end, vibration analysis is important as it considers the operational characteristics of the monitoring data which detects and diagnoses degradation in the vehicle structure (Bektash & Cour-Harbo, 2020).

In UAVs, instrumentation is fundamental because there is no pilot and the data obtained by the sensors are the only source of information that the operator on the ground has to know what is happening in the environment surrounding the aircraft (Rodas *et al*., 2013). Therefore, if the aircraft presents unwanted mechanical vibration during flight, this will hinder the accuracy of the on-board sensors, affecting the flight control system and thus presenting risks during the development of the vehicle's activity. To prevent UAV accidents, it is of vital importance to detect deviating data or behaviour patterns that do not match the behaviour of normal data. Determining the reasons for the occurrence of abnormal behaviour prevents major accidents and ensures the safe flight of the aircraft (Wang *et al*., 2023).

In recent decades, modal analysis has become a key tool in the analysis and solution of vibratory systems. Modal analysis is used to determine, improve and optimise the dynamic characteristics of a structure. Most of the practical application studies of modal analysis reported in the literature have been generated in the area of mechanical engineering, aeronautical engineering and automotive engineering.

In aeronautical engineering modal analysis in conjunction with aircraft structural dynamics has allowed modal tests to be performed on a wide variety of structures from a scale aircraft to an unmanned aerial vehicle (UAV).

There are two important events in the history of science that gave rise to modal analysis. The first was Newton's observation of the spectrum of sunlight, which confirmed the composition of colours and their components. The second was Fourier, who stated that an arbitrary periodic function with a finite time interval is represented by the sum of simple harmonic functions. With the analysis of Fourier series and spectra, a basis for the development of modal analysis was laid. In the 1980s, modal analysis was used in industry and methods for optimisation and application in structures started to be developed (Ewins, 2001).

In any type of aircraft it is possible to find a vibratory phenomenon called flutter. This vibration arises due to aerodynamic forces impinging on the structure that are located near or at the natural frequency of the structure, causing uncontrolled vibrations throughout the aircraft structure. This vibration is most commonly originated in the wings or tail of the aircraft and is therefore also referred to as flutter, because the aircraft simulates the movement of a bird's wings in flight.

The relevance of this state-of-the-art review lies in analysing recent research on UAV vibration analysis, identifying the most effective methodologies and tools, such as modal analysis and fast Fourier transform. This study is organised in four sections:

I. The first section deals with fundamental vibration theory and the analysis of vibration signals using the FFT.

II. The second section explores the theory of mechanical vibrations in UAVs, describing concepts of aeroelasticity, Flutter and studies focused on this topic.

III. The next section explores mechanical vibration analysis and disturbance detection methods. In addition, concepts of modal analysis, types of modal tests applicable to structures, necessary mechanisms and excitation techniques used in EMA are discussed, together with the measuring instruments used in vibration analysis, exemplified by studies that highlight the relevance of these tests.

IV. The last section presents the results of the analysis of the cited studies, listing key aspects to consider when performing vibration tests on UAVs.

Vibration theory

In the study by (Chu *et al*., 2024), they mention that vibration is an important aspect in the analysis of mechanical systems and is defined as the motion relative to a reference position caused by a random or periodic force.

Vibrations have several classifications, but the most common classification in the literature is:

- Free vibration.
- Forced vibration.

Free vibration

Free vibration occurs when the system oscillates under the action of the system's own forces, i.e. no external force forces force the structure to vibrate. The main contribution of free vibration to the fundamentals of vibration lies in demonstrating how the natural vibration of a system depends solely on the mass, stiffness and damping characteristics. These factors define the inherent vibrational behaviour of the system (Mobley, 2001). This type of vibration is subdivided into undamped free vibration and damped free vibration.

Undamped free vibration

In undamped free vibration the system oscillates at its natural frequency indefinitely around its equilibrium position and is described by equation 1.

$$\mathrm{m}\ddot{x} + kx = 0 \tag{1}$$

where $\ddot{x}$ is the acceleration of the system, x is the displacement, k is the elasticity or stiffness constant and m is the mass of the system.

Damped free vibration

In this type of vibration, the system oscillates as in undamped free vibration but its magnitude tends to zero due to energy dissipation and its motion is defined by equation 2.

$$\mathrm{m}\ddot{x} + c\dot{x} + kx = 0 \tag{2}$$

where $\ddot{x}$ is the acceleration of the system, x is the displacement, k is the elasticity or stiffness constant, m the mass of the system and c the damping coefficient.

Forced vibration

Forced vibration occurs when the system is excited by external excitation forces and is divided into undamped and damped forced vibration (Rajasekaran, 2009).

Undamped forced vibration

In this type of vibration the system will tend to vibrate following the excitation frequency of the external force and its motion is described by equation 3.

$$\mathrm{m}\ddot{x} + kx = F = F_0 sen\omega t \tag{3}$$

where $\ddot{x}$ is the acceleration of the system, x is the displacement, k is the elasticity or stiffness constant, m is the mass of the system and F is the disturbance force.

Forced damped vibration

In this vibration the system oscillates due to the disturbing force, but with energy dissipation due to the damping of the structure. It is defined by equation 4.

$$\mathrm{m}\ddot{x} + c\dot{x} + kx = F = F_0 sen\omega t \tag{4}$$

where $\ddot{x}$ is the acceleration of the system, x is the displacement, k is the elasticity or stiffness constant, m is the mass of the system, c is the damping coefficient and F is the disturbing force.

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Vibration signal analysis

In the analysis of signals, due to their complexity, it is necessary to convert them to simpler signals for easy interpretation. Therefore, the signal obtained from the time domain is converted into a frequency domain signal using the Fourier transform (FT) (Yan et al., 2022).

Fourier transform

The Fourier transform is a mathematical procedure of transforming a function from the time domain to the frequency domain, but without altering the information content. Equation 5 describes the Fourier transform of a time-domain function.

$$F(\omega) = \int_{-\infty}^{\infty} f(t) e^{-i\omega t} dt \tag{5}$$

On the other hand, the inverse Fourier transform is described by equation 6.

$$f(t) = \frac{1}{2\pi} \int_{-\infty}^{\infty} f(\omega) e^{i\omega t} d\omega \tag{6}$$

where $F(\omega)$ is the function in the frequency domain, f(t) is the function in the time domain, and $e^{i\omega t}$ is the complex conjugate.

Discrete Fourier Transform (DFT)

The discrete Fourier transform operates on sequences of complex numbers, which generates alternative representations in the frequency domain to extract features and perform operations on the data (Leitersdorf et al., 2023). The DFT is given by Equation 7:

$$X[k] = \sum_{n=0}^{N-1} x[n] e^{\frac{-j(2\pi)(k)(n)}{N}} \tag{7}$$

where N is the number of samples, n *is* the nth original sample and k *kth* DFT term.

Fast Fourier transform (FFT)

The fast Fourier transform is an indispensable signal processing tool and has been described as the most important numerical algorithm of our lifetime (Henry, 2022). The FFT takes vibration data in the time domain and transforms it into frequency spectrum components (Al-Haddad *et al.*, 2023).

With this algorithm, the FFT calculation is simplified by mathematical shortcuts for reduction of operations. Figure 1 shows how the transformation of a signal in the time domain to the frequency spectrum is performed.

Box 1

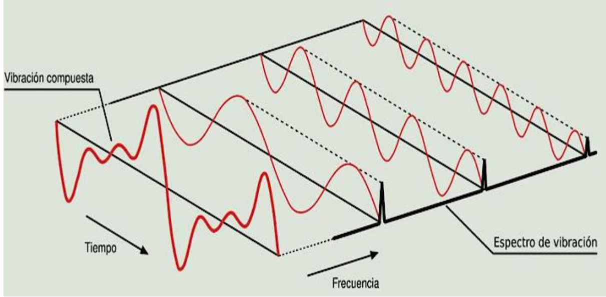

Figure 1

Transforming a signal from the time domain to the frequency domain.

Source: https://power-mi.com/es/content/estudio-de-las-vibraciones

Mechanical vibrations in an unmanned aerial vehicle

UAVs are susceptible to vibrational disturbances that affect their mechanical structure. These unwanted vibrations can cause failures, damage and reduce the flight performance of the aircraft, especially affecting the control instrumentation of the UAV (Beltran-Carbajal *et al.*, 2022).

According to (Ozkat, 2024), structural failures that occur during flight are essentially critical to the safety and efficiency of UAVs. It has been reported that 67% of UAV accidents are the result of mechanical system failures, of which 53% are related to propulsion system failures. These failures occur most frequently in mechanical components such as rotors, propellers and actuators, due to the stress they are exposed to during flight which causes them to wear out over time.

Aircraft vibration is defined by flutter, which is an unstable condition where aerodynamic forces excite the natural frequencies of the system structure. The critical causes of this vibration are aerodynamic factors, mechanical failures and external factors such as atmospheric turbulence (Agrawal *et al.*, 2021).

Aeroelasticity

Aeroelasticity is focused on aircraft structures. It is the science that studies the phenomena originated due to the interaction of elastic, inertial and aerodynamic forces (Čečrdle, 2015). This field of study is understood by means of the Collar's triangle presented in figure 2, where the three forces that generate the aerolastic problems are visualised.

Box 2

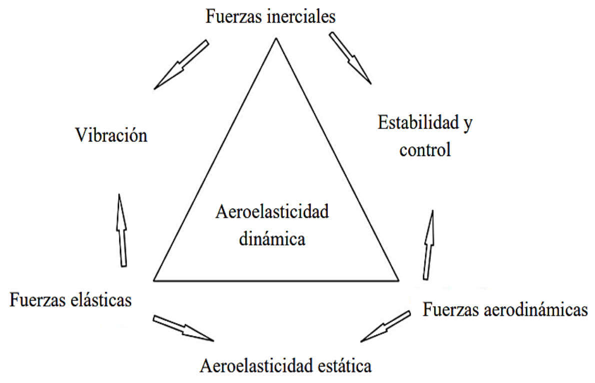

Figure 2
Triangle Necklace

Source: (Ansari & Novinzadeh, 2017)

Aeroelasticity is classified as static and dynamic. Static aeroelasticity considers the interaction of elastic and aerodynamic forces with the structure, and dynamic aeroelasticity involves the interaction of the three forces of Collar's aeroelastic triangle (Wright, 2001).

Flutter

In the study by (Abou-Kebeh *et al.*, 2021), they mention that aeroelastic flutter is a self-excited vibration where two different natural modes of the structure with different frequencies begin to change during flight as the dynamic pressure or velocity increases. When the frequencies are as close as possible there is an exchange of energy generating a harmony or coupling of the two frequencies, resulting in an increase in amplitude of the vibrations producing an unstable motion. This phenomenon is undesirable in aircraft because it causes degradation of aircraft performance, loss of control and partial or complete loss of the aircraft in a matter of seconds (Jonsson *et al.*, 2019).

Studies by (Čečrdle, 2015) and (Wright, 2001), classify Flutter as follows:

Torsion Flutter: In this type of flutter the wing or tail surface vibrates with bending/torsional deformations.

Stall Flutter: This type of flutter occurs with partial or complete separation of the flow around the airfoil during some part of the vibration cycle and is attributed to wing twist.

Propeller whirl flutter: This occurs when the rotational speed of the aircraft engine or propeller attached to the wing matches the natural frequency of the wing; this causes the wing to begin to vibrate to the point where the wing splits at the root.

Galloping Flutter: This type of flutter is caused by the formation of wake vortices in the wing structure, which cause oscillatory forces and produce a back and forth motion.

Studies on aeroelastic flutter rely on an accurate mathematical model and a numerical or analytical study to identify the flutter boundary: (Verstraete *et al.*, 2017) conducted research presenting a numerical simulation of dynamic aeroelastic instability in a biologically inspired reconfigurable wing model. They determined the stability and instability regions of the wing. They concluded that flutter decreases with increasing wing pitch angle.

Also in the study by (Venkatramani *et al.*, 2018), they performed wind tunnel experiments of an aerofoil system in the presence of fluctuating flows revealing flutter instability. They used an airfoil of NACA 0012 with a chord length of 100 mm and 500 mm wingspan with a maximum speed of 25 m/s in the wind tunnel. The results obtained concluded that having Flutter is an intermittency regime and, in addition, obtaining a set of measures such as entropy, Lempel-Ziv complexity and early warning flutter occurrence graphs measures.

A year later, (Lv et al., 2019), presented the design of a supercritical semi-wing for a transport aircraft, using composite materials. In the study, they developed four different wing tip models. The wing, named CHINT-1, was tested in a transonic wind tunnel, cantilever-mounted on a rigid fuselage, with Mach numbers ranging from 0.6 to 0.89.

In this research, the authors analysed the effect of the wing tips on the proposed design, demonstrating that the shape of the fin does not significantly influence the flutter speed. However, the fin weight considerably reduces the flutter speed, and the aerodynamic loads on the fin have a limited impact on the aeroelasticity of the wing.

On the other hand, in 2020 Amoozgar et al. presented an analysis to evaluate the aeroelastic instability of a wing with an initial out-of-plane curvature. The structural dynamics of the wing was modelled using the geometrically exact beam equations, while the aerodynamic loads were obtained through an incompressible unsteady aerodynamic model. The authors showed that the presence of initial curvature in the wing altered the dynamics, completely modifying the flutter speed and frequency. Furthermore, they concluded that, as the curvature value increases, the flutter speed first decreases and then increases abruptly. This sudden change in flutter speed and frequency is mainly due to an alteration in the vibrational modes influencing the phenomenon. They also confirmed that the length of the curved wing section has a significant impact on the speed, frequency of flutter and the location at which the change occurs.

In 2023, (Westin *et al*., 2023), conducted a study focused on characterising the dynamic behaviour of an aeroelastic system. This system consists of a wing with a high aspect ratio, a thin body at the tip and a NACA0012 airfoil. To understand the non-linear behaviour of this system, wind tunnel results are compared with computational simulations based on a geometric non-linear deformation-dependent methodology. In addition, two semi-empirical dynamic loss models are applied. The comparisons showed that the computational and experimental results agree well, obtaining dynamic behaviours similar to the 0-1 test. However, the results also revealed that the dynamic loss is not reduced in these models, indicating the need to apply more advanced methodologies to it.

Also in 2023 (Mertens *et al*., 2023), they presented a study where they performed an experimental analysis of the aeroelastic response of the Delft-Pazy wing under steady and periodic unsteady incoming flow conditions in a wind tunnel.

Two static tests were performed with different angles of attack, as well as two dynamic test cases with different gust frequencies. The measurements were post-processed to reconstruct the wing shape and the phase-averaged flow field using a unique measurement system. Aeroelastic loads acting on the wing were derived using physical models and validated against force balance measurements. Analysis of the aeroelastic response of the wing to the unsteady air inlet produced by a gust generator revealed that both the structural and aerodynamic response are significantly dependent on the frequency of the gust. The results of this study provide a detailed characterisation of the static and dynamic aeroelastic behaviour of a highly flexible wing and are useful for the validation of the implemented unsteady aerodynamic models.

The analysis of the studies presented and the theory investigated allows conclusions to be drawn for the theoretical evaluation of the flutter characteristics of an aircraft. Therefore, flutter analysis requires extensive calculations under wide parametric variations with respect to structural configurations, mass and aerodynamic states to fit the defined flight.

Mechanical vibration analysis

Vibration analysis is a non-destructive method used in engineering for early damage detection and structural integrity assessment. Damage to the structure causes changes in material properties which in turn alters the modal and mechanical properties of the structure (Kaewniam *et al*., 2022).

The identification of system parameters through vibration analysis and modal techniques has been of active and continuing interest. Therefore, vibration-based Structural Health Monitoring (SMH) aims to determine whether or not degradation exists according to the dynamic characteristics of the system to be monitored. This type of vibration-based technique is the most widely used due to its physical interpretation with reality (Limongelli *et al*., 2021).

On the other hand, in the study of (Zhang et al., 2021) they mention that there are some methods for the detection of disturbances in UAVs and they are classified into the following three categories:

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- **Analytical model-based method:** an accurate mathematical model of the expected behaviour of the system and the mode of operation of the UAV is used.

- **Knowledge-based method:** This method uses the established knowledge of expert systems in that area.

- **Signal processing based method:** In this method, the characteristics of the measurement signals are extracted using some tools such as the wavelet transform or spectral analysis using the fast Fourier transform.

According to (Larizza, 2010), the methodology applicable in the analysis can be subdivided into four main domains:

- **Time domain:** focuses on detecting the integral performance of the system.

- **Frequency domain:** The measured signal is decomposed into frequency components using the fast Fourier transform.

- **Joint (time/frequency) domain:** the response signals are related to the rotational speed of the devices.

- **Modal analysis:** studies the dynamic properties of structures under excitation.

Modal analysis

Modal analysis for vibration studies was developed as a tool for structural health monitoring and is defined as the process of determining the dynamic characteristics of a mechanical system in terms of natural frequencies, modal shapes and damping factors (Bolognini *et al.*, 2022). In Figure 3, the deformation modes of a system are shown.

Box 3

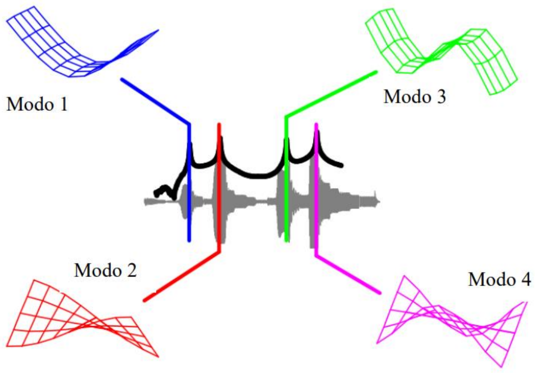

Figure 3

Deformation modes

Source: https://www.uml.edu/docs/s-vjan2001_modal_analysis_tcm18-189939.pdf

In the study conducted by (Reynders, 2012), he states that the process of modal analysis consists of three fundamental steps:

- **Data collection:** The data obtained by the excitation in the structure are collected by means of the data acquisition system and these are processed by means of specialised software.

- **System identification:** A mathematical model that reproduces the dynamic characteristics is obtained from the measured vibration data.

- **Obtaining modal parameters:** The modal parameters are determined from the modal decomposition and thus the modal forms or modes of vibration, the damping and the period of oscillation are obtained.

There are two types of modal analysis: experimental modal analysis (EMA) and operational modal analysis (OMA), whose main difference lies in the way in which the structure or system to be studied is excited, which in turn determines the specific application of each of these tests.

Operational Modal Analysis

Operational Modal Analysis (OMA), also known as output modal analysis, is used to identify the dynamic parameters of a structure under operating conditions, i.e. environmental forces or forces from cyclic loading are used for excitation.

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This method is used for large structures where no response to artificial excitations is obtained (Zahid *et al.*, 2020). A diagram illustrating the signals involved in the OMA is shown in Figure 4.

Box 4

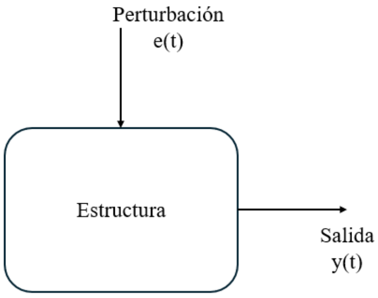

Figure 4
System with disturbance and output

Source: Own Elaboration

This type of analysis has the following advantages:

- Less time to perform the test.
- The normal operation of the structure is not interrupted.
- The measured response represents the actual operating conditions of the structure.
- The application of artificial loads is avoided.

An example of this analysis is the study conducted by (Coppotelli *et al.*, 2013), where they present the analysis of the Clarkson Golden Eagle UAV structure by means of experimental modal analysis and operational modal analysis. Focusing the study on the OMA, this was carried out with the engine running in taxiing and parking conditions. In the analysis, the frequencies obtained were higher compared to the EMA. This is due to the fact that the boundary conditions changed as the landing gear supported the vehicle and not elastic ropes as in EMA. The result obtained was the identification of the modal behaviour of the aircraft from the system's own performance.

Along the same line of comparison of OMA and EMA studies, (Zuñiga *et al.*, 2019), developed a methodology to characterise the aeroelastic behaviour of an unmanned aerial vehicle with high aspect ratio and structural flexibility. In the research, the OMA relied on enhanced frequency domain decomposition to process the operational vibration data, which allowed the identification of five vibration modes in the frequency range of 0 to 50 Hz. By comparing the results obtained from both vibration tests, there was a strong correspondence in the modal shapes and associated frequencies of the identified modes. Furthermore, the OMA confirms the flutter behaviour and mechanism observed in the aeroelastic analysis and the flutter mechanism detected through the EMA analysis, confirming the accuracy of both approaches in the structural evaluation of the UAV.

On the other hand, (Soal *et al.*, 2024) presented an OMA study for the identification of flutter in an unmanned vibration demonstrator during flight tests using operational modal analysis. The analysis is based on the natural dynamic responses of the aircraft during normal operating conditions. In addition, an online monitoring system was used to identify and track critical vibration modes using real-time OMA. The OMA system was able to robustly identify and track critical modes of vibration. The aeroelastic damping of the wing's symmetric torsional mode was monitored from 3.3% to 0.4%, indicating that the aircraft was on the edge of the stable flight envelope.

Research applying operational modal analysis (OMA) on UAV structures is relatively limited and has been less expected in the scientific literature compared to other methods, such as EMA. This is partly due to the fact that OMA has been most often implemented on large-scale structures, such as aircraft and helicopters, where its application is optimal. In these structures, OMA allows better capture of dynamic responses under real operational conditions, whereas in UAVs, its use is more restricted due to their smaller size and limitations in terms of installation of complex measurement equipment.

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As UAVs continue to evolve in size, capability and complexity, it is expected that interest in operational modal analysis will also increase allowing for improved structural validation under real-world conditions, which is key to improving the safety and operational performance of these aircraft.

The application of OMA on structures larger than UAVs has been investigated and applied by some authors. The most notable studies are:

In 2016, Neu *et al*., presented a study for the extraction of modal parameters from a large-scale transonic flow-excited wind tunnel wing model. The modal parameters are extracted from the dynamic measurements of the high Reynolds number aero-structural dynamics wind tunnel model. As a result, the surface pressure measurements revealed that the wind excitation was neither white noise nor stationary and, in addition, included strong, narrow-band transonic pressure waves. In the test, the wing model broke up slowly during the entire measurement period. Furthermore, they showed that the natural frequencies had dependence on the angle of attack (AOA), particularly at low frequencies, which they attributed to a structural geometrical nonlinearity. Modal shapes and damping coefficients showed no distinct AOA dependence.

A year later, (Rizo-Patron & Sirohi, 2017), presented a new procedure to perform an operational modal analysis on a scaled-down helicopter rotor blade with a diameter of 2 m. Using a pair of high-speed digital cameras, images were captured of the blade rotating at 900 RPM, with a sampling rate of 1000 frames per second. From these images, out-of-plane bending deformation of the blade was measured using the digital image correlation technique. The first three out-of-plane bending modes were identified at each rotational speed and the results were compared with an analytical finite element model of the blade. The obtained natural frequencies showed a deviation of 0.2% with respect to the analytical models and the maximum was 10%. In addition, the experimental modal shapes showed high agreement with the analytical predictions.

Also, Kocan in 2020**,** presented a study on the estimation of modal parameters on an aircraft wing during a full test flight under various environmental conditions and manoeuvres. He applied two modal identification techniques based solely on output data: frequency domain decomposition and stochastic subspace identification. The results showed that tests in static start-up and cruise conditions at low speed and high altitude are optimal for the OMA, exciting all vibration modes except torsional modes above 30 Hz.

In 2024 Al-Haddad et al. presented an innovative approach for UAV propeller failure diagnosis, taking advantage of non-traditional features. Recognising the limitations of standard UAV sensors, which have low sampling rate and restricted access, they designed a high-performance data acquisition system to achieve accurate fault location and classifications. This system includes an STM32H743IIT6 microcontroller equipped with passive components, enabling real-time data processing and efficient fault detection. The lightweight and compact design ensures that the system does not affect the UAV dynamics. It was tested on two UAVs, Parrot Bepop 2 and 3DR, capturing complex variations in data and highlighting slight operational discrepancies even under normal conditions. Furthermore, they concluded that, among the features extracted in the tests, the TKEO features were the most outstanding for their ability to improve the classification and predictive performance of the model.

Experimental Modal Analysis

Experimental modal analysis (EMA) comprises a series of experimentally based procedures (Kranjc *et al*., 2016). The excitation frequency is measured along with the responses of the structure to this excitation. These signals are often used to estimate response functions (RFR), from which modal parameters are identified (Berthold *et al*., 2024). Three main mechanisms are necessary to perform EMA (Silva, 2001):

- **Excitation mechanism:** This is the system that provides the motion or input force to the structure being analysed. The choice of this system depends on some factors such as the input excitation, accessibility and the physical properties of the structure.

Tejeda-del Cueto, María Elena, González-Cabrera, Sara Isabel, Vigueras-Zúñiga, Marco Osvaldo and Arroyo-Flores, Maria. [2024]. State of the art in mechanical vibration analysis for UAV´s. Journal of Research and Development. 10[25]-1-18: e21025118. https://doi.org/10.35429/JRD.2024.10.25.1.18

- **Sensing mechanism:** This mechanism is constituted by sensing devices known as transducers, which generate electrical signals that are proportional to the physical parameters to be measured.

- **Data acquisition and processing mechanism:** The purpose of this mechanism is to measure the signals developed by the sensing mechanism and to determine the magnitudes and phases of the excitation forces and their responses.

Figure 5 shows the basic configuration of the measurement mechanism for an experimental modal analysis.

Box 5

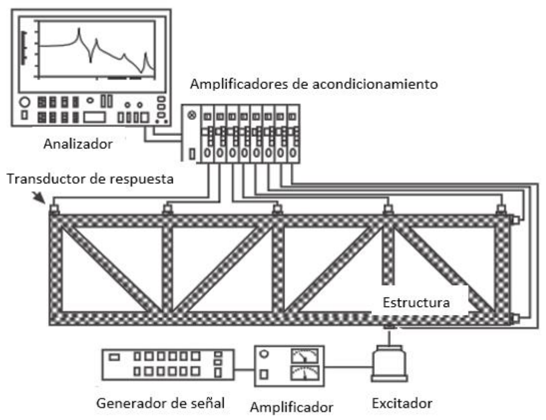

Figure 5
Configuration of mechanisms for an EMA

Source: (Silva, 2001)

The application of EMA has been found in a variety of research:

(Simsiriwong & Sullivan, 2012), conducted a study showing a vibration test performed on the wings of a UAV using 16 accelerometers. The modal characteristics are obtained from the whole aircraft in a free configuration and these are compared with the vibration characteristics obtained on a single wing using a shake table approach. The results obtained with the shaking table approach produced higher magnitude signals with less noise compared to the data obtained from the full aircraft configuration and the differences are attributed to the stiffness and the fact that the wings are limited to excitation in only one direction due to restricted motion.

On the other hand (Lemler & Semke, 2013), developed a research where they present an experimental structural analysis for a small UAV. The data analysis was performed in Moodal VIEW software. The structure is suspended on elastic ropes in order to comply with the free-free boundary condition and the loads with which it usually works were also considered. The result obtained were the bending and torsional modes of the wings. Also, (Olejnik *et al*., 2021) presented an analysis for the structure of the UAV Aereal target drone Jet-2. This structure was fitted with equivalent masses corresponding to the weight at which the UAV commonly operates. This system was suspended by two flexible ropes and for data acquisition accelerometers were used on both wings at asymmetrical points. The result was the tuning of 27 vibration modes of the UAV. In 2023 Herrmann *et al*. presented a study for the identification of a nonlinear system of a slightly flexible 25 kg fixed-wing UAV using a computational aerodynamics model and a linear structural dynamics representation. To determine the structural modes of the aircraft, a ground vibration test and a modal-experimental analysis were performed. This test resulted in seven structural modes and a small measurement uncertainty, demonstrating that the computational model provides a suitable basis for real-time simulation.

Excitation techniques

There are several excitation techniques for experimental modal analysis, but the most common ones reported in the literature are described in the following sections.

Impact excitation

This excitation technique is the best known in modal analysis and is performed using a hammer-type exciter. The procedure consists of a user striking several times and averaging the impulse and dynamics of the resulting structure to minimise measurement errors (Farshidi *et al*., 2010). The magnitude of the impact is determined by the mass of the hammer head, the speed with which it moves when striking the structure and the stiffness of the contact surface. In figure 6, the configuration for performing an impact test is shown. In this picture it can be seen that the impulse signal and response are measured in order to obtain the modal parameters of the structure.

Box 6

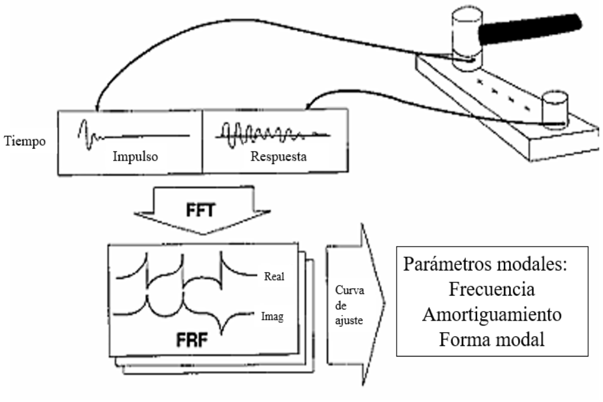

Figure 6
Impact test configuration

Source: https://issuu.com/vibranttechnology/docs/experimental_modal_analysis

In the research of (Xu & Zhu, 2013), they mention that this analysis has some drawbacks associated with the excitation by means of an impact hammer, which are:

- Some tests must be repeated several times at different excitation locations to understand the dynamic characteristics of the structure.
- A contact excitation force may damage a fragile structure.
- The input frequency may be too low to fully excite the high frequency modes of the structure under test.

Bonded exciters

Bonded exciters are devices that are used in EMA analysis to generate controlled excitations on a structure and study its dynamic responses. The most common types used in modal testing are described below.

Electromagnetic exciter

Also known as electrodynamic shaker, in this type of exciter a magnetic force is applied to the structure to be excited without any direct physical contact. It has certain disadvantages such as difficulty in moving it, force variation and the need for transducer force for calibration dynamics (Lee, 1991).

Electrodynamic exciter

The electrodynamic exciter is an essential tool for durability and vibration reproduction testing of mechanical products. It is widely used in the field of machinery, vehicles and aerospace structures (Zuo *et al.*, 2020).

Electrohydraulic exciter

This exciter has the ability to apply a static and dynamic load at the same time. It allows the excitation of large structures, but one of its drawbacks is that they are limited in the operating frequency range (Silva, 2001).

Figure 7 shows the connection configuration of an electrodynamic shaker and the elements needed to perform an EMA test.

Box 7

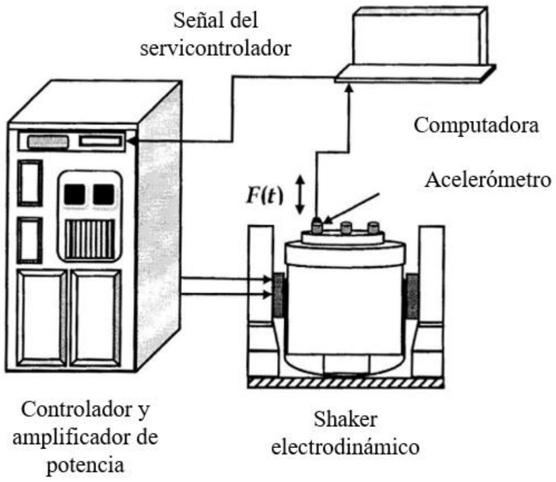

Figure 7
Electrodynamic shaker configuration

Source: (Chakraborty & Ratna, 2020)

Measuring instruments in vibration analysis

Microelectromechanical systems (MEMS) sensors are commonly used in real-time vibration analysis

These sensors are microstructures with mechanical and electrical elements that are suitable for unmanned aircraft due to their light weight (Ghazali & Rahiman, 2022).

Some measuring instruments commonly used in vibration analysis are described in the following lines.

Tejeda-del Cueto, María Elena, González-Cabrera, Sara Isabel, Vigueras-Zúñiga, Marco Osvaldo and Arroyo-Flores, Maria. [2024]. State of the art in mechanical vibration analysis for UAV´s. Journal of Research and Development. 10[25]-1-18: e21025118. https://doi.org/10.35429/JRD.2024.10.25.1.18

Accelerometer

Accelerometers are components that are used in various fields of application because of their unique characteristics: low cost, small size, low power consumption small size, low power consumption, high performance and low weight (Ahmed *et al*., 2023).

According to (Niu *et al*., 2018), accelerometers based on the principle of operation are divided into:

Piezoresistive accelerometer: This accelerometer uses a substrate instead of a piezoelectric crystal. Its detection process is based on the fact that the mass inside the accelerometer is under the force of inertia generating a variation of resistance in the substrate. Figure 8 shows the elements that make up a piezoresistive accelerometer.

Box 8

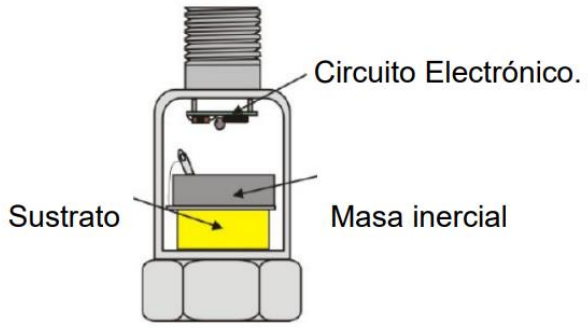

Figure 8
Piezoresistive accelerometer

Source: https://www.ingmecafenix.com/automatizacion/sensores/acelerometro/

Piezoelectric accelerometer: This type of sensor uses the piezoelectric effect to detect the change in acceleration. The operation is similar to the piezoresistive but with the difference that it uses a piezoelectric element. This instrument has a wide working frequency range, good linearity and high robustness. Figure 9 shows the parts that make up a piezoelectric accelerometer.

Box 9

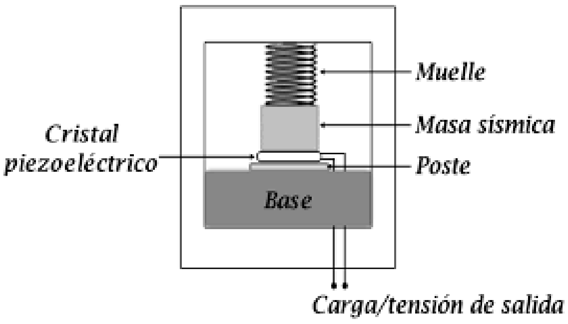

Figure 9
Piezoelectric accelerometer

Source: http://www.ptolomeo.unam.mx:8080/xmlui/bitstream/handle/132.248.52.100/299/A5.pdf?sequence=5&isAllowed=y

Capacitive accelerometer: This accelerometer uses the change in capacitance to detect the change in acceleration. When the acceleration changes, the capacitance between the sensitive structure and the clamping mechanism also changes, and the peripheral circuit tests the amount of change by obtaining the true acceleration of the object. Its main advantages are low power consumption, high measurement accuracy and good linearity. Figure 10 shows the configuration of the elements that make up a capacitive accelerometer.

Box 10

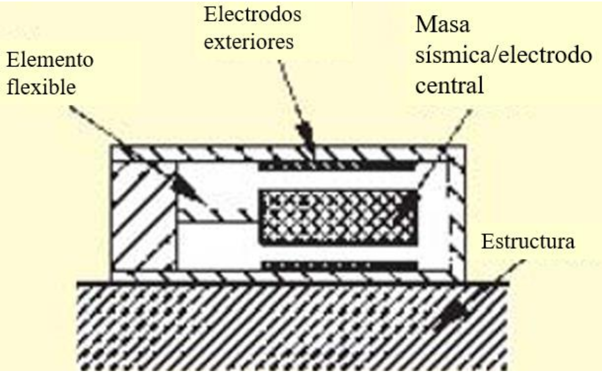

Figure 10
Capacitive accelerometer

Source: https://repositorioaberto.up.pt/bitstream/10216/67103/2/56957.pdf

Strain gauge

The strain gauge is a resistor whose electrical resistance varies proportionally to the variation of its length (Button, 2015).

The principle of operation is based on the piezoresistive effect of metals and semiconductors where their resistivity varies depending on the deformation to which they are subjected, the material they are made of and the design. In addition, it generates measurements of three types (Alzate *et al*., 2007):

- Static: This is carried out when the structure is subjected to fixed loads.
- Dynamic: When the structure is in vibration or presents impact actions.
- Mixed: Where the structure is subjected to fast acting loads.

Figure 11 shows a strain gauge and the elements that make it up.

Box 11

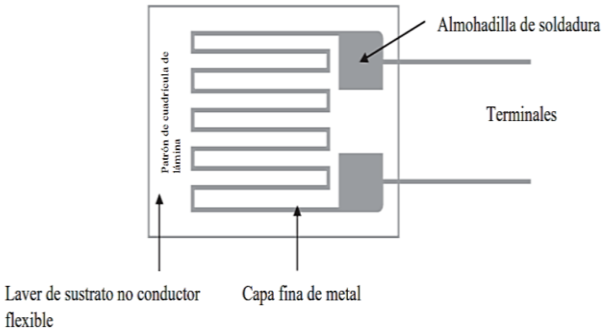

Figure 11

Strain gauge.

Source: (Button, 2015)

The reading is made when the deformation of the surface of the system under study is transmitted to the body of the sensor. This deformation will produce in the gauge a variation in its electrical resistance (Rodriguez *et al*., 2016).

Results

Important considerations for ground vibration analysis of UAVs

Through the analysis of the literature reviewed in this study, the following important points were obtained that should be considered when performing vibration testing on structures, specifically UAVs:

I. In order to perform an experimental ground vibration analysis on UAVs, it is important to suspend them using flexible ropes. This is in order to guarantee the boundary or free flight condition during the test. The free flight condition implies that the engine is not running and only the aerodynamic characteristics of the aircraft design are considered. By suspending the UAV, this isolates the structure from external influences and allows the vibrations generated to be representative or similar to those that would occur during flight.

II. The masses with which the UAV usually operates must be considered, by means of equivalent or substitute masses which simulate the weight with which the vehicle works.

III. The sensors or measuring instruments to be used in the test must be placed in key or asymmetrical points such as the wings, fuselage and control surface.

IV. Keeping electrical connectors and wiring safe from airflow and human interaction is critical to ensure reliable and stable data acquisition. This contributes to the accuracy and consistency of the results obtained, as airflow can cause interference or noise leading to inconsistent sensor readings. Keeping connectors and wiring out of reach of human interaction reduces the possibility of accidental disconnections.

V. Each vibration analysis on UAV structures is unique due to its particular design, therefore, it is crucial to determine the type of vibration test to be performed and the appropriate form of excitation for the system.

VI. In the case of performing a vibration analysis with the engine running, the boundary conditions are different, which implies working in real and dynamic conditions that become more complex due to active vibrations, transient changes and interaction with air.

VII. For data processing, the FFT algorithm is an essential tool in the vibration analysis of a UAV structure. It provides frequency spectrum plots allowing the analysis and interpretation of the data, facilitating the identification of key vibrational characteristics and helping to understand the dynamic behaviour of the structure.

Conclusions

Vibration analysis on UAVs is essential to ensure their structural integrity, operational efficiency and longevity. This analysis helps to identify and mitigate potential problems caused by vibration, which can affect system performance and reliability.

Moreover, modal analysis, both experimental and operational, is a fundamental tool in vibration analysis and engineering. It helps to identify the natural frequencies and modal shapes of structures, which is critical to understand their dynamic behaviour and response to excitations.

In addition, in order to perform a good modal analysis, it is necessary to have a wide and clear knowledge in the three main areas, since without this knowledge, the analysis will be complicated to develop, and the proposed objectives or results will not be obtained, and time will be wasted.

The difference between an EMA and an OMA analysis lies in the type of forces applied during the assessment. In EMA, artificial forces generated by means of exciters are applied to analyse the structure. In contrast, in OMA, the natural operating and/or environmental conditions of the structure are used. In addition, it should be noted that modal analysis, whether operational or experimental, can vary in complexity depending on the structure to be studied and the methodology to be used. The complexity of the analysis will be determined by the nature of the structure and the methods applied.

Various excitation techniques, such as impact hammers and electrodynamic exciters, are used to induce vibrations in structures for analysis. The choice of technique depends on the specific requirements of the analysis to be performed, such as the frequency range and the nature of the structure to be tested.

Flutter is a phenomenon where the aircraft structure, especially the wings, enters into resonance which causes an exponential increase in vibration leading to structural failure of the UAV. Furthermore, it is a complex phenomenon to obtain due to the extensive and complex calculations under structural parametric variations.

Declarations

Conflict of interest

The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection and analysis of the submitted studies; in the writing of the manuscript; or in the decision to publish the research.

Authors' contribution

Tejeda-del Cueto, María Elena: Contributed to the writing, structure, editing of the original draft and administration of the project.

González-Cabrera, Sara Isabel: Contributed to the project idea, research and data analysis.

Vigueras-Zúñiga, Marco Osvaldo: Contributed to the structure and editing of the draft.

Arroyo-Flores, María: Contributed to the drafting and research of project studies.

Availability of data and materials

This article is a literature review of published experimental data.

Funding

The research was funded by the Master in Applied Engineering of the Universidad Veracruzana.

Acknowledgements

González-Cabrera would like to thank the Consejo Nacional de Humanidades, Ciencias y Tecnologías for the scholarship granted during his master's studies.

Abbreviations

UAV	Unmanned aerial vehicle
DFT	Discrete Fourier Transform
FFT	Fast Fourier Transform
SMH	Structural Health Monitoring
EMA	Experimental modal analysis
OMA	Operational modal analysis
MEMS	Sensors for microelectromechanical systems

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