Chapter 15

On Vibration Analysis and Health and Usage Monitoring Systems (HUMS) of Dynamic Components of Helicopters

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On Vibration Analysis and Health and Usage Monitoring Systems (HUMS) of Dynamic Components of Helicopters

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Abstract

This chapter presents a compilation of the research work done by the authors and collaborators on the topics of vibration analysis and Health and Usage Monitoring Systems (HUMS) of dynamic components of helicopters, comprising: i) an introduction to helicopter vibration; ii) a discussion and details of vibration analysis techniques for helicopter rotors and dynamic components, from the point of view of the operational user and the technical maintenance of the helicopter; iii) a discussion and details on vibration-based Health and Usage Monitoring Systems (HUMS) philosophy in the predictive maintenance of helicopters, from the point of view of history and evolution of the market; architecture; benefits, disadvantages, limitations; certification challenges; and application perspectives; and iv) a discussion on vibration-based HUMS of dynamic components of helicopters, focused on results and discussions done during the Offset Program of Transfer of Technology in HUMS of the helicopter EC-725, a program involving AIRBUS HELICOPTERS, HELIBRAS, UNIFEI, and ITA. The latter includes, in particular: 1) some discussion and details of the M'ARMS system; 2) its evolution towards the MOD45 indicator; 3) a case study of electrical/signal errors in the vibration acquisition system (accelerometers, cables, etc) with a proposed error indicator; and 4) a finite element modeling of a typical coupling between two sections of a tail drive shaft.

Keywords: helicopter rotor vibration; vibration analysis; HUMS – Health and Usage Monitoring Systems, helicopter dynamic components

1. Vibration analysis and HUMS in dynamic components: chapter outline and introduction to helicopter vibration

This chapter concentrates on a discussion of vibration analysis techniques and the use of a framework of Health and Usage Monitoring Systems (HUMS) for helicopter dynamic components.

Some helicopter vibration reduction techniques focused on balancing and tracking the helicopter rotors are discussed in a separate chapter, concentrated on model-based parameter identification for balancing and tracking a helicopter's main rotor using once-per-revolution vibration data.

1.1 Section content

Subsection 1.2 presents an introduction to helicopter vibration.

Section 2 presents a discussion and details of vibration analysis techniques for helicopter rotors and dynamic components, from the point of view of the operational user and the technical maintenance of the helicopter.

Section 3 presents a discussion and details on vibration-based Health and Usage Monitoring Systems (HUMS) philosophy in the predictive maintenance of helicopters, from the point of view of history and evolution of the market; architecture; benefits, disadvantages, limitations; certification challenges; and application perspectives.

Section 4 presents a discussion on vibration-based HUMS of dynamic components of helicopters, focused on results and discussions done during the Offset Program of Transfer of Technology in HUMS, a program involving AIRBUS HELICOPTERS, HELIBRAS, UNIFEI, and ITA.

Section 5 presents some concluding remarks.

1.2 Introduction to helicopter vibration

This section is based on class notes materials for the courses “Foundations of Helicopter and Rotary Wing Engineering”, ITA [1], and “Flight Test Course - vibration theory”, PEV, DCTA (Gomes & Cruz, 2008).

All helicopters shake due to rotary sources, such as the rotors, transmission gears, engines, and several other dynamic components. The main causes of the vibration can be understood by remembering some basic concepts about oscillatory movements.

A body must satisfy two conditions to oscillate: it must be able to store potential energy (which means an elastic behavior) and it must be able to have kinetic energy (which means to have mass and velocity). Therefore, oscillation represents the continuous exchange of kinetic and potential energy.

A motion that repeats itself after an equal interval of time T, called the period of the oscillation, is called periodic motion, and the reciprocal $f = {}^{1}\!/_{T}$ is known as the frequency. The simplest form of periodic motion is the harmonic motion, which can be obtained, for example, by the movement of a mass coupled to spring without the action of external forces, acting in a vacuum, as shown in Figure 1.

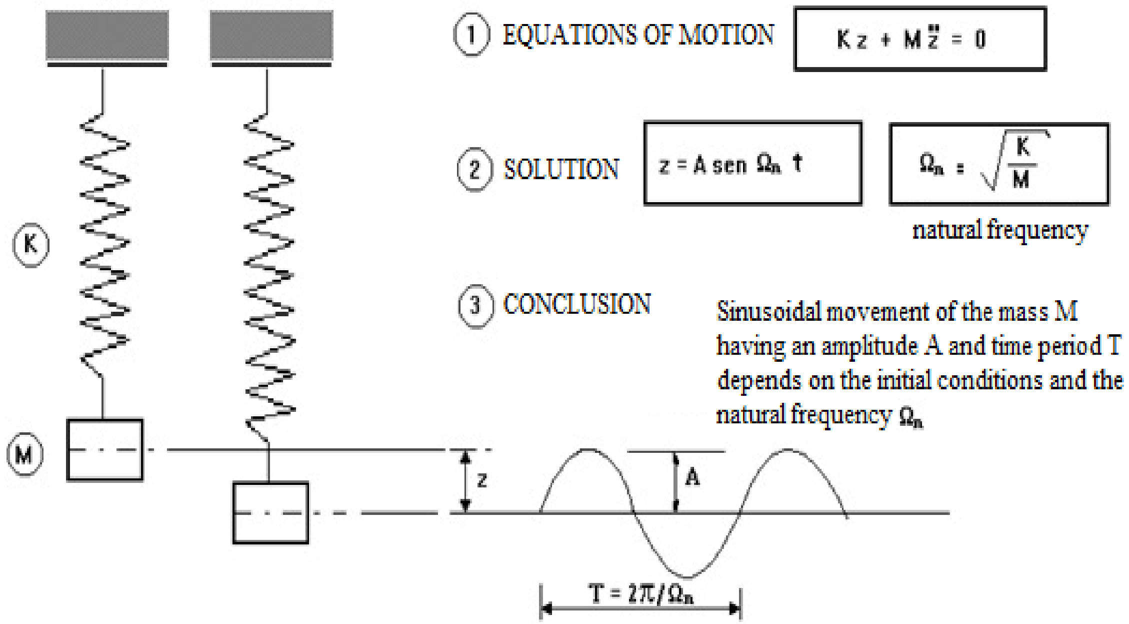


Figure 1: Free Vibration (Adapted from [2])

In this simplified system, the spring has negligible weight concerning the mass *M* and has a stiffness constant *K*. Disregarding the damping of the air, this mass-spring system is conservative and, therefore, the total energy of the system is constant and can be determined by the sum of kinetic energy E_c and potential energy E_p.

When the mass M is displaced from the equilibrium position and then released, sinusoidal oscillations will occur around the equilibrium position of the system according to the equation $z = A \sin \Omega_n t$, where Ω_n is the natural frequency of the spring-mass system in rad/s ($\Omega = 2\pi f$), A is the amplitude of motion and f is the frequency in Hz. Also, if the total energy of the system is constant, the energy equation can be applied between two instants of sinusoidal motion. Thus, if 1 is the static equilibrium position with maximum kinetic energy and 2 is the maximum mass displacement and, therefore, the maximum potential energy, we have, equating both terms, that:

$$\frac{1}{2}KA^2 = \frac{1}{2}MV_{máx}^2 = \frac{1}{2}M(\Omega_n A)^2 \Rightarrow \Omega_n = \sqrt{\frac{K}{M}} \quad (1)$$

Equation (1) allows us to obtain the natural frequency of the system as a function of its stiffness and mass. However, helicopter vibrations originated from periodic external forces. The system presented in Figure 2 represents an example of harmonically excited vibration, where the upper end of the spring is connected to a base of an eccentric shaft that excites the system with an amplitude X and a frequency Ω.

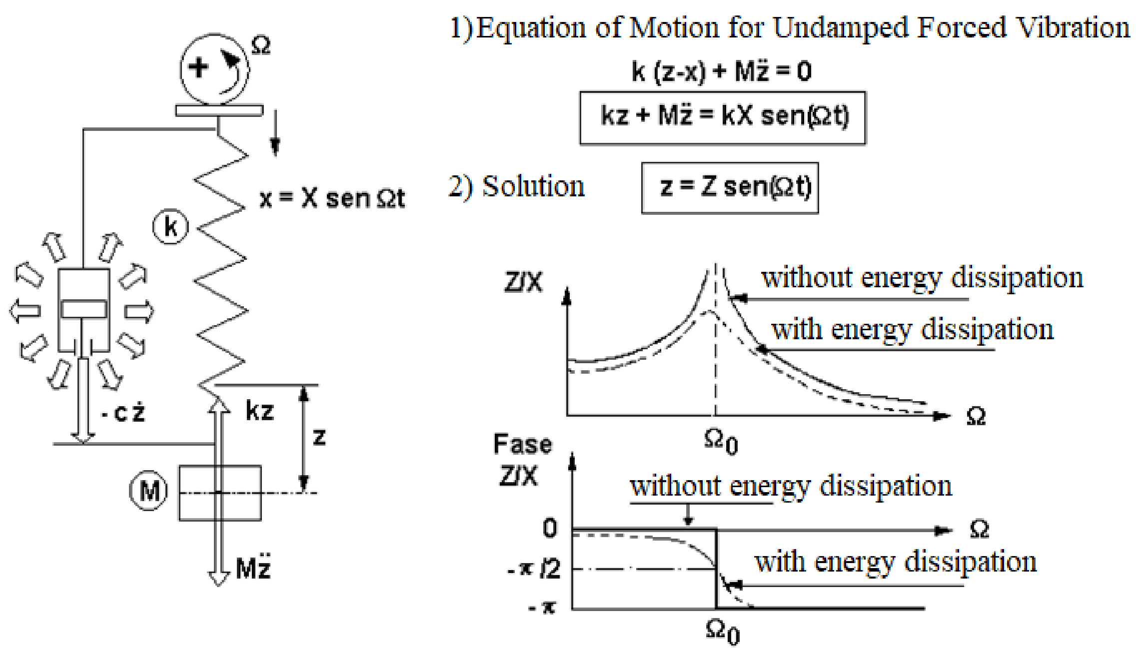


Figure 2: Harmonically excited vibration for damped and undamped systems (Adapted from [2])

If the rotor speed of that axis is slow, the mass M follows the movement of the base. This means that the mass oscillates with the frequency forced by the eccentric, and both are in phase. If the rotor speed increases, the amplitude passes, in the case of an undamped system, to infinity at the natural frequency of the system. This is the so-called resonant frequency, where there is still a phase inversion. Continuing to increase the speed, the amplitude tends to zero as the excitation frequency approaches infinity, while the mass oscillates in phase opposition regarding oscillatory excitation force.

Introducing viscous damping into the mass-spring system of Figure 2 considerably modifies the response. Its effect is basically to dissipate the energy of the system and, consequently, reduce the oscillation amplitude. This is the basic principle of a helicopter vibration damper. Some examples of vibration dampers are the landing gear dampers and the main rotor lead-lag dampers. Their main functions are to dissipate energy to avoid a catastrophic phenomenon known as ground resonance, an auto-excited instability that occurs when the frequency of the blade lead-lag regressive mode coalesces with a frequency of a fuselage mode on the ground.

Other devices used by helicopter manufacturers to reduce the amplitude of oscillation are vibration isolators and vibration absorbers. Ref. [3] presents a comprehensive analysis of both kinds of vibration controls. Regarding the vibration absorbers, they consist of another mass-spring system attached to the original mass that needs to reduce its vibration amplitude. Therefore, they constitute a two-degree-of-freedom system as shown in Figure 3.

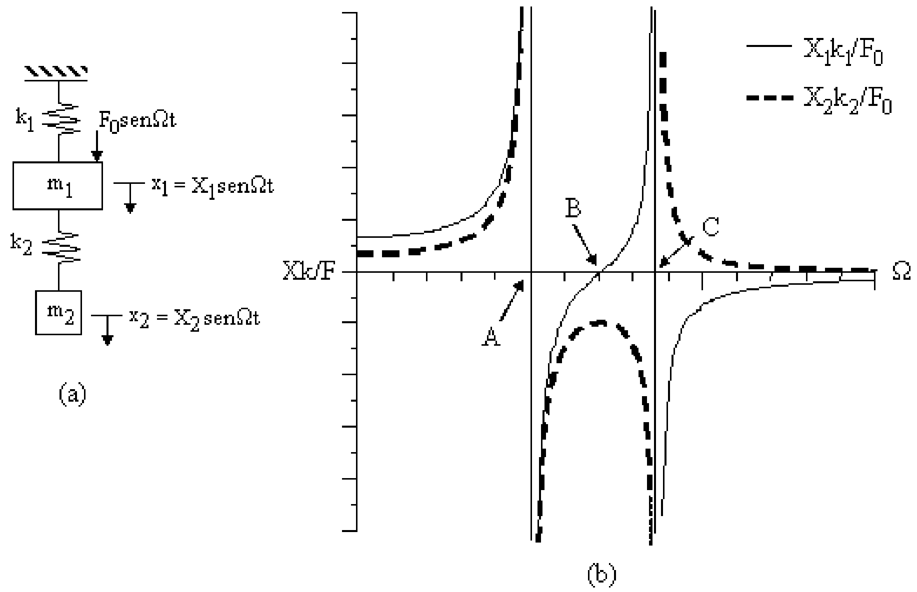


Figure 3: Two-degree-of-freedom system (Adapted from [2])

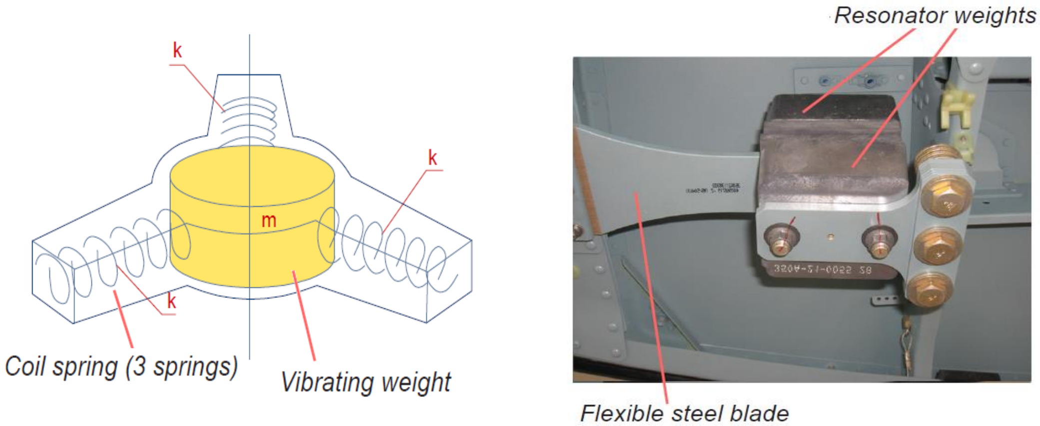
This type of system has two normal vibration modes: the first mode corresponds to the main mass and the attached absorber mass movement in phase; while the second one consists of a movement of both masses in opposite phases. Each mode has its natural frequency. If there is no external harmonic force acting over the two-degree-of-freedom system, the resulting motion, after an initial excitation, will be the superposition of both normal modes of vibration. However, if there is an external harmonic force acting over the system, the resulting forced harmonic vibration frequency will be the same as the applied external force.

A helicopter vibration absorber has k_2 and m_2 tuned to match the frequency of the external force to be absorbed, which will be the frequency bΩ, where b is the number of blades and Ω is the main rotor speed.

As shown at point B in Figure 3, the attached absorber mass will vibrate at the same frequency bΩ but in the opposite phase of the external harmonic force. Consequently, the movement of the main mass m_1 is reduced to zero. It should also be noted from Figure 3 that:

a) for the interval $0 < \Omega < \Omega_A$, m_1 and m_2 move in phase with the external harmonic force, once both amplitudes vibrations are positive. For frequencies close to 0, both movements of the bodies are slightly different, depending on the stiffness and mass parameters; however, for $\Omega \approx \Omega_A$, the maximum amplitudes of both masses tend to infinity. Therefore, Ω_A corresponds to the natural frequency of the 1st normal mode of vibration related to the in-phase motion of the masses;
b) for the interval $\Omega_A < \Omega < \Omega_C$, m_1, and m_2 initially move in phase but in opposite phase with regarding the external harmonic force since both maximum amplitudes are negative. Increasing Ω, it will be observed that the bodies start moving in opposite phases from $\Omega \approx \Omega_B$; and
c) for the interval $\Omega_C < \Omega < \infty$, m_1 and m_2 move symmetrically out of phase, so that m_2 and m_1 are, respectively, in-phase and in opposite phase with the external harmonic force. For $\Omega \approx \Omega_C$, the maximum amplitudes of both masses tend to infinity, and then Ω_C corresponds to the natural frequency of the 2^{nd} normal mode of vibration related to opposite phase motions of the masses.

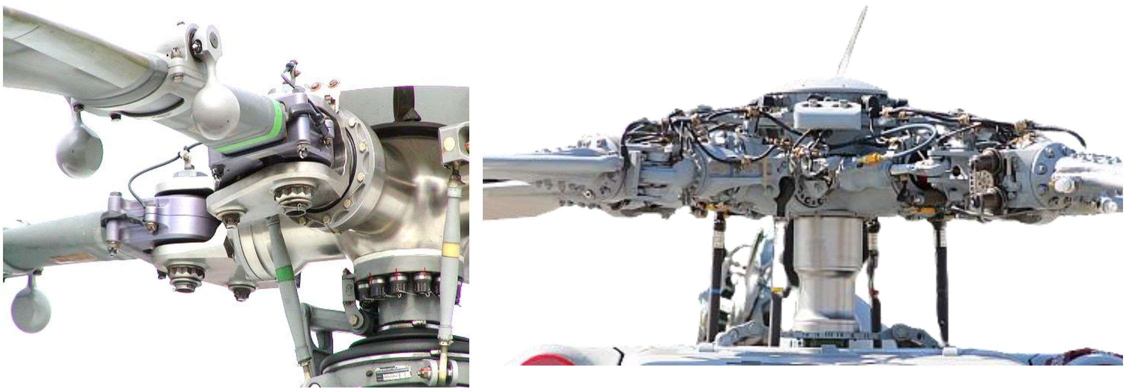
There are several examples of helicopter vibration absorbers. Some of them, such as the cabin resonators and the main rotor vibrator absorber of the Squirrel AS350 helicopter (Figure 4) utilize a physical spring so that it is tuned to one frequency and is effective only over a narrow band of frequencies. Considering the nominal rotor speed of 390 rpm, the bΩ frequency tuned is 19.5 Hz. Changing rotor speed, the effectiveness of this device is reduced significantly.



(a) Vibrator absorber (b) Cabin Resonator

Figure 4: Vibration Absorbers of the Squirrel AS350
[adapted from (EUROCOPTER, 2010)]

Other helicopter vibration absorbers such as the centrifugal pendulums of the BK-177 and the bifilar weights of the UH-60 “Black Hawk” (Figure 5) replace the physical spring with a centrifugal spring. So, using the centrifugal force, the main gain of those absorbers is that they are automatically tuned to bΩ, considering any rotor speed.



(a) Kawasaki / Eurocopter BK117 centrifugal pendulums [adapted from (JGSDF Camp Akeno Airshow, 2002)] (b) Black Hawk bifilar absorber (Photo and editing: B. Mattos)

Figure 5: Examples of helicopter vibration absorbers

Vibration absorbers need to be tuned to match the frequency bΩ of the helicopter's main rotor. It is important to pay attention that lower frequency values mean higher vibration amplitudes, so the main rotor is the main source of helicopter vibration, and much lower frequencies vibration must be reduced.

Considering that the external harmonic forces acting on the blade are cyclic, their effects can be decomposed into the sum of sines and cosines harmonically related, in other words, their forces correspond to frequencies multiples of the rotor speed (1Ω, 2Ω, 3Ω, and successively), in a Fourier series. For the case of the helicopter main rotor, the forced vibrations on the blades are in frequencies multiples of the fundamental frequency Ω (mainly 1Ω). This characteristic requires special attention during blade design, once each blade has many flapping, lead-lag, and torsion elastic modes, as shown in Figure 6. The position of those natural frequencies concerning the harmonic excitation determines the increase or attenuation of the forces applied to the main rotor blades.

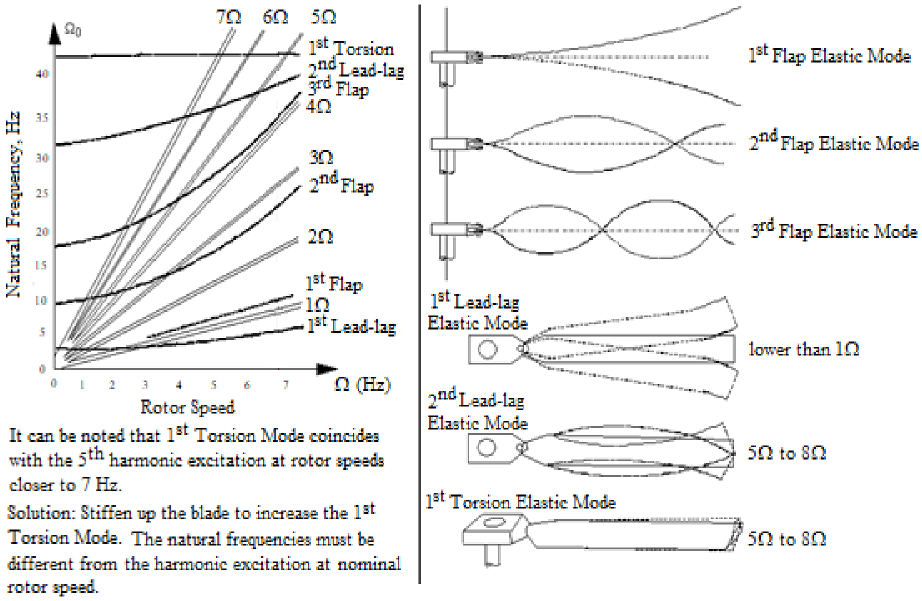


Figure 6: Main Blade Elastic Modes (Adapted from [1])

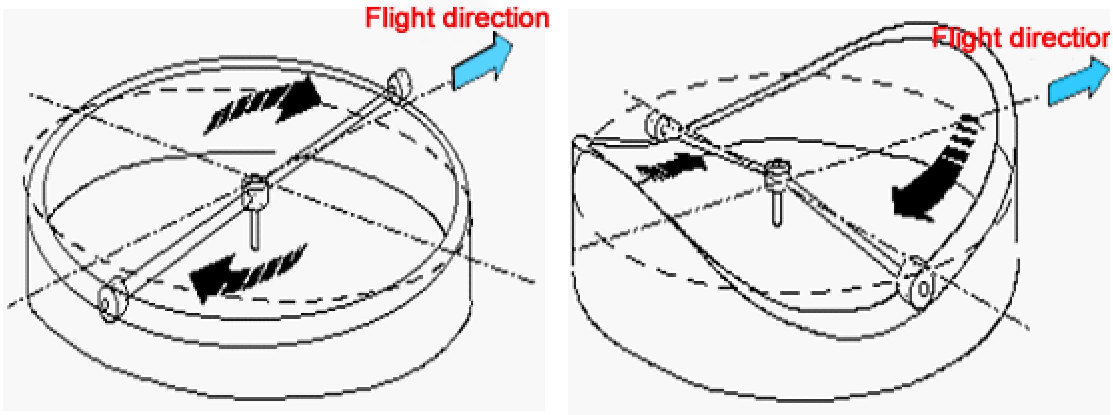
Furthermore, it should be observed that the aeroelastic coupling of the rotor blades can also cause some instabilities, such as flap/lead-lag instability, pitch/lead-lag instability, flutter, and stall flutter at high blade angles of attack, which also provokes the increased of the vibration levels and the blade loads.

For that reason, the natural frequencies of elastic modes must be separated from each other and also from the harmonic excitation frequencies of the blades at the nominal rotor speed.

This is a design criterion, therefore, if necessary, the manufacturer adds mass or changes the stiffness of the blades to move their natural frequencies away from the excitation harmonics, at least, according to [4], up to typically 4Ω or 5Ω for single-rotor helicopters and up to 6Ω or 8Ω for tandem helicopters.

Such efforts acting on the blades are transmitted to the main rotor hub that works like a filter exciting the fuselage vertically and horizontally at frequencies multiples of the number of the blades, nbΩ, where n is an integer number.

Ref. [5] presents such mathematical deduction for both vertical and horizontal forces transmitted to the fuselage. However, some simplified models can also be used to explain how the main rotor hub acts example for the 1Ω and 2Ω flap excitation as shown in Figure 7.



(a) 1st Harmonic Excitation – Flap 1Ω (b) 2nd Harmonic Excitation – Flap 2Ω

Figure 7: Graphical Representation of Flap Excitation (Adapted from [2])

For the 1Ω in flapping, there is a complete oscillation in one rotation of the rotor (Figure 7a). it means there is a maximum vertical displacement at $\psi_P = 180^o$, a minimum at $\psi_P = 0^o$, and zeros at $\psi_P = 90^o$ and 270^o, where ψ_P is the blade azimuth position, counted from the position furthest from the flight direction (FD indicated in Figure 7).

As shown in Figure 7a, the two-blade rotor will have one of its blades on a crest and the other one, diametrically opposite, in a depression.

Therefore, the main rotor hub displacement will be zero, in the vertical direction, as long as the trajectory of the blades is the same. For that reason, a two-blade rotor doesn't transmit vertical vibration at 1Ω frequency to the fuselage, if its blades are correctly tracked.

For the 2Ω in flapping motion, there are two complete oscillations in one rotation of the rotor (Figure 7b). This means that there are maximum vertical displacements at $\psi_P = 0^o$ and 180^o, minimum at $\psi_P = 90^o$ and 270^o, and zeros at $\psi_P = 45^o$, 135^o, 225^o, and 315^o.

One can conclude that the two-blade rotor will always present vertical displacements that add up.

Therefore, a two-blade rotor will transmit vertical vibration at 2Ω frequency to the fuselage, even if the rotor is perfectly tracked. That is a non-correctable vibration, thus the structure will be excited along the vertical axis at frequencies nbΩ (mainly bΩ).

Another important helicopter vibration feature is related to the horizontal vibration, which is similar to the movement of a sieve. In this case, the structure will be excited along the longitudinal and lateral axes with frequencies (n + 1)Ω and (n - 1)Ω, provided that (n + 1) and (n – 1) are multiples of the number of the blades.

Thus, for a two-blade rotor (b = 2), a horizontal force at 3Ω frequency (n = 3) will transmit forces at 2Ω (m = 1) and 4Ω (m = 2) to the fuselage.

For a three-blade rotor (b = 3), *m* will not be an integer and, therefore, a horizontal force at 3Ω frequency will not transmit forces to the fuselage.

Table 1 presents the oscillatory forces that are transmitted to the fuselage as well their harmonic excitation frequencies as a function of the number of blades.

Table 1: Main Rotor Vibration Transmitted to the Fuselage

	HARMONIC EXCITATION FREQUENCIES ON THE BLADES	MAIN ROTOR VIBRATION FREQUENCIES TRANSMITTED TO THE FUSELAGE		
		***b* = 2**	***b* = 3**	***b* = 4**
VERTICAL EFFORTS AT FLAP HINGE	1Ω	-	-	-
	2Ω	2Ω	-	-
	3Ω	-	3Ω	-
	4Ω	4Ω	-	4Ω
	5Ω	-	-	-
HORIZONTAL EFFORTS AT LEAD-LAG HINGE	1Ω	2Ω	-	-
	2Ω	-	3Ω	-
	3Ω	2Ω and 4Ω	-	4Ω
	4Ω	-	3Ω	-
	5Ω	4Ω and 6Ω	6Ω	4Ω

This table is only valid if the rotor blades are at the same trajectory and perfectly balanced. Otherwise, vibration amplitudes at frequencies of 1Ω, 2Ω, and 3Ω, successively, will appear in the fuselage. That vibration can be reduced utilizing balancing and tracking of the main rotor. This table answers the question about absorbers tuning to match the frequency bΩ. While frequencies different from nbΩ are correctable by balancing and tracking, multiple frequencies of the number of blades are uncorrectable. For that reason, those frequencies, and especially bΩ, are the focus of helicopter manufacturers to reduce the vibration level in the fuselage.

Indeed, the vibration at a particular point of the helicopter depends on the fuselage's response to the efforts transmitted by the main rotor hub at frequencies multiple of the number of blades. Many helicopter manufacturers and research centers made use of software to obtain modal shapes and their respective frequencies to calculate the fuselage response. Some of them have already been published, such as the NASTRAN (NASA Structural Analysis). An example is shown in Figure 8 for the AS 330.

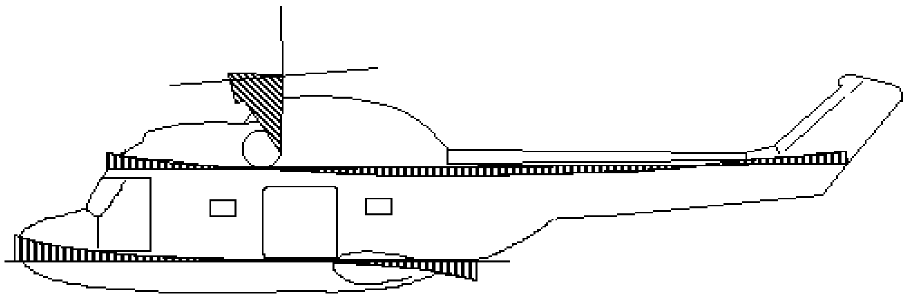


Figure 8: Typical AS 330 dynamic response, longitudinally excited by the rotor hub (4Ω = 17,4 Hz) (Adapted from [2])

This sort of analysis allows designing the structure in such a way that the nodal points (zero amplitude vibration points) are positioned along the fuselage where it's desirable to have the lowest vibration level. This can be done utilizing mass and rigidity adjustments, as well as using vibration absorbers as previously discussed.

Unfortunately, such fuselage regions can change a lot due to different loadings and determined flight conditions. For that reason, flight tests under certain specified conditions are required to confirm the accuracy of the computer model and to certify the helicopter according to paragraph 251 (Vibration) of 14 CFR Part 27 [6] and Part 29 [7], which requires that the helicopter not to be subjected to excessive vibration in all approved flight envelope.

2. Vibration analysis techniques for helicopter rotors and dynamic components

This section is based on the article of Jorge & Torres Filho [8], first presented at "XI Simpósio de Segurança de Aviação da MB", SIPAERM, 1989, Rio de Janeiro, RJ, Brazil.

2.1 Vibration in dynamic components: causes and effects

The study of the causes and effects of vibrations in dynamic components has become a continuous task for manufacturers of aircraft, helicopters, engines, transmission gears, and dynamic components in general, to implement techniques for minimizing the effects of these vibrations, either by suppression, absorption, reduction, isolation, or active/passive control of vibrations, or a combination of these techniques. As a result of this study, several maintenance techniques have been developed, to be employed by the aircraft user, which can be divided into two groups: reduction of the vibration levels and analysis of vibrations.

The vibration reduction techniques available for helicopter users are concentrated, in the first step, in the correction of the trajectory traveled by the blade tips (adjustment of the blade "track") of the main and tail rotors, and/or in the correction of any imbalance present in these rotors, as well as any imbalance present in some specific dynamic components of the aircraft, such as gearboxes, main and tail rotor drive shafts, oil cooler fans, etc.

In a subsequent step, the user should concentrate his efforts on the vibration analysis, which consists in obtaining the aircraft vibration signature, i.e., the survey of the values of vibration amplitude versus frequency, carried out in pre-established locations and flight conditions, utilizing accelerometers and analyzers that directly respond the frequency domain. The records of vibration signatures, duly filed, will form a vibration database of each model aircraft, which will be used as a starting point for the assessment of the vibration levels of a particular aircraft at a certain time of its useful life, allowing the detection, location, and identification of problems or defects, even when they are still incipient. Thus, vibration analysis would become an important predictive maintenance tool, to monitor the wear and fatigue of components, to obtain a reduction in maintenance costs.

The statement of the problem, at the user level, in these two steps, is detailed below. In addition to vibration reduction and analysis techniques, some details of the equipment used for these purposes are described, as well as some prospects for the future.

2.2 Objectives of the vibration Reduction

The vibration reduction has the objectives:

a) Reduce the probability of failures in structural components during their useful life, which considers a certain magnitude of cyclic loads, acting on them. Because there is a direct relationship between the vibration level of the structure and the cyclic loads acting, a high level of vibration shows that the structural components of the helicopter are being subjected to efforts beyond its design envelope and, consequently, present a high probability of in-service fatigue failures;

b) Minimize the effects of tiredness and fatigue on the crew. Prolonged and repeated exposure to vibrations of different frequencies, amplitudes, and directions can cause various types of aggressions that essentially consist of headaches, tinnitus, general malaise, feeling of drowsiness, general weakness, irritability, a reduction in willingness to work, concentration deficit, slower reflexes, a psychic depression as well as fatigue of the eyes and ears. These disturbances, depending on their intensity and persistence, can decisively contribute to helicopter accidents.

   From a mechanical point of view, the human body is a complex structure with viscoelastic tissue supplemented by bone tissue. The human body can be considered as a system composed of masses, springs, and dampers. Thus, each region or organ of the body will have a resonant frequency, at which that region or organ will shift or deform more than the other parts of the body, being, therefore, more sensitive to external or excitatory vibrations at that frequency. The resonant frequencies of the human body vary in the following ranges:

   - 4 to 8 Hz - chest (internal) and abdomen
   - 11 to 15 Hz - spine and joints
   - 11 to 25 Hz – skull
   - 40 to 60 Hz - rib cage (rib and muscles)

   Frequencies between 15 and 30 Hz cause a reduction in visual acuity when the crewmember's gaze is fixed on an immobile object at infinity. This reduction is even more pronounced if the object is fixed but close to the pilot, such as an indicator on the instrument panel.

   On the other hand, vibrations transmitted to the pilot through his feet (by the pedals) and the seat, at frequencies between 8 and 15 Hz, combined with the vices of position or posture that the pilot assumes to control the aircraft, can bring spinal trauma, such as injuries to intervertebral discs or herniated discs, for example.

   By way of illustration, helicopter main rotors typically rotate between 3 and 7 Hz, depending on the aircraft, and the main vibrations perceived in the structure vary between 3 and 22 Hz, while tail rotors and other accessories rotate at higher frequencies.

c) Improved weapon firing accuracy. Limitations in the use of weaponry can also occur, as the vibrations may make the helicopter an inefficient weapons platform, both from the point of view of directional stability of the machine guns and rockets, as well as from the fact that vibrations in the auxiliary weapons equipment, such as the gun shooting sights, or the guided missile tracking sights can make their use impractical; and

d) Reduce breakdowns in helicopter avionics and electromechanical items. Such breakdowns are caused by friction between internal components or by their fatigue. As a rule of thumb, an estimate of 50% of helicopter breakdowns may be due to problems related to fuselage vibrations.

2.3 Causes of vibration in helicopter rotors and other dynamic components

The most common causes for the occurrence of vibration can be categorized into two groups, depending on the possibility of the operator acting to eliminate or minimize the efforts that caused the vibration:

a) Unavoidable causes:

- the variable aerodynamic forces resulting from the cyclic movement of the blades, necessary to allow translational flight. It is found that such forces predominantly induce vibrations at the multiple frequencies of the aircraft's main rotor rotation times the number of blades, that is, for a 4-blade helicopter with a main rotor rotation speed of 340 RPM (5.7 Hz), the cyclical variation of the pitch of this rotor blades will cause efforts that will induce vibrations in the frequencies of 22.8 Hz, 45.6 Hz, 91.2 Hz, etc., in the aircraft. These efforts increase with the aircraft's translational speed;
- centrifugal forces resulting from the variation in the position of the CG of the rotor set, resulting from the flapping motion of the blades, are necessary to maintain translational flight. The resulting vibration occurs in the plane of the rotor, at the rotation frequency of the main rotor; and
- aerodynamic forces arise from the airflow from the rotors, acting on the helicopter fuselage, or from turbulence and gusts on the aircraft.

b) Avoidable causes

- unbalance of rotating parts and rotors: unbalance always exists, to a greater or lesser degree, in any set or rotating part and is characterized by vibration that occurs once per rotation as shown in Figure 9.

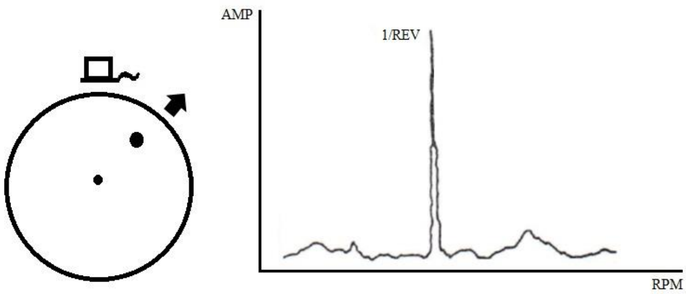


Figure 9: Unbalance of rotating parts and rotors (Adapted from [8])

Imbalance occurs when the center of mass of the rotating body is different from, or farther from, the center of rotation of that body. If the center of mass and the center of rotation are equal, the system is said to be balanced. As the center of rotation cannot be moved, the solution is to move the center of mass, adding weights in opposition to the inertia force produced by the imbalance, which is of the form given by Equation (2):

$$F = M.\, r.\, W^2 \tag{2}$$

where:

F = Force produced by unbalance
M = Mass of the set
r = Radius (radial position of the center of mass)
W = Angular Velocity

Vibration at the frequency of once per revolution is not always due to unbalance but could be indicative of another problem (such as mechanical backlash). The characteristics of unbalance are:

- the vibration occurs at the frequency of once per revolution;
- the phase is stable. For example, if we are trying to balance a tail rotor that exceeds established vibration limits and the phase indication is not stable, this could be an indication of mechanical clearances rather than unbalance; and
- the amplitude of vibration increases with increasing rotational speed.

I. Misalignments of couplings and bearings

Vibration in an axis due to misalignment is usually intense at a frequency of twice the rotational speed, and the highest levels are in the longitudinal direction of that axis. Misalignment can be of two types:

1. Pre-stress in a bent shaft or improperly bedded bearing; and
2. Deviation of axis centerlines.

Flexible couplings increase the ability to tolerate misalignment, however, they are not the solution to more serious alignment problems.

The longitudinal vibration phase measured at one end of a bi-supported shaft will be 180 degrees out of phase with that measured at the other end of that shaft, provided that the shaft is operating below its natural frequency, as shown in Figure 10.

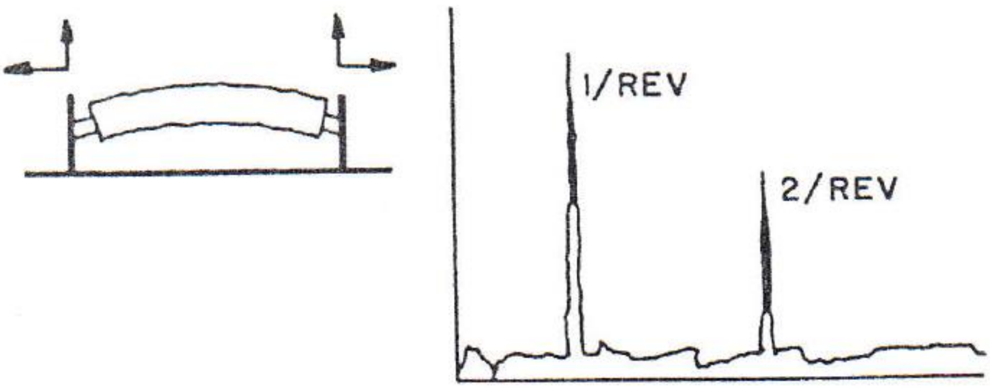


Figure 10: Misalignment of a shaft (Adapted from [8])

This relationship can be used to differentiate misalignment from unbalance, which produces in-phase longitudinal vibration at both ends of the shaft.

This test cannot be used in vertical or lateral directions, as the phase of unbalance varies with its type. It is interesting to note that:

a) Machine dynamics affect phase readings, so the phase difference of vibration in the vertical direction may not be exactly 180 degrees, but may vary between 150 and 200 degrees; and
b) The orientation of the transducers that will capture the vibration is important. These transducers must be placed in the same direction, at both ends of the shaft. If this is not possible, they can be placed pointing one to each side, remembering that now the phase difference between them will be 0 degrees.

I. Worn, eccentric, or damaged gears.

One of the frequencies associated with gear problems is the so-called "gear mesh", which is equal to the number of teeth times the speed of rotation of the gear. High vibration rates at the gear mesh frequency are common and therefore must be compared with average values taken as a reference to detect the existence of a possible problem. Figure 11 shows a typical spectrum of gear mesh.

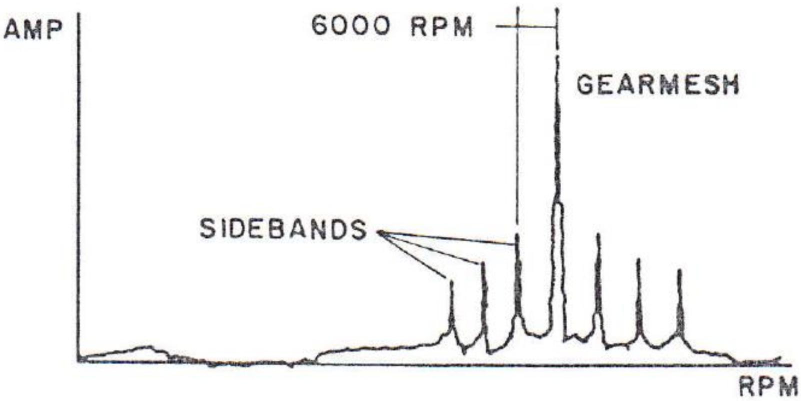


Figure 11: Gearmesh typical spectrum (Adapted from [8])

Sidebands around the gear mesh frequency are usually caused by small eccentricities or backlash in the gears. High levels of vibration at the rotation speeds of the sidebands are a good indicator that there is a problem with the gear. Identifying problems in gears, and examining vibration spectra is a difficult task, as it depends on the resolution of the analyzing equipment used, therefore, this problem identification technique must be used in conjunction with oil analysis, swarf detectors, and monitoring of the temperature of the gear oil.

II. Looseness in the fixing of components, or mechanical clearances.

Mechanical clearances almost always result in a large number of harmonics in the vibration spectrum. The harmonics (1, 2, 3, etc times the fundamental rotational speed) that characterize the backlash are the result of impulses and truncation (limitation) of the component's response. Figure 12 shows the typical vibration caused by a backlash, both in the time domain (Amplitude versus Time) and the spectrum in the frequency domain (Amplitude versus Frequency).

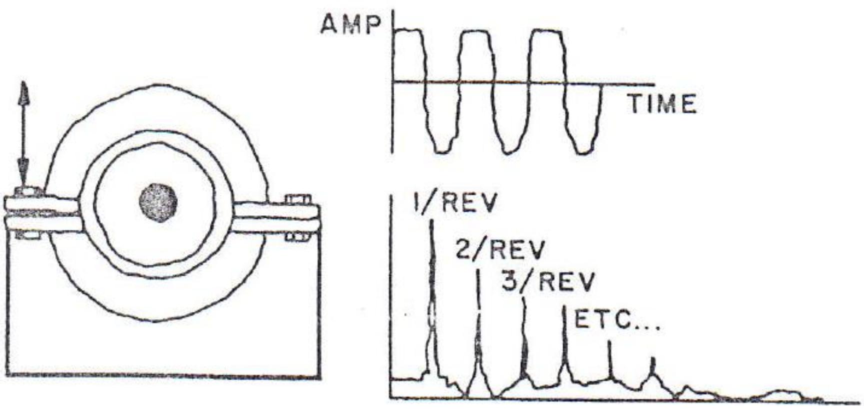


Figure 12: Mechanical backlash vibration (Adapted from [8])

The truncation of the top of the sine wave seen in the time domain is what causes harmonics to appear in the vibration spectrum.

Warped shafts present a situation where the backlash does not result in many harmonics because the truncation is dampened by the warping and the resulting vibration is essentially one time per revolution.

III. Other causes such as:

1. defective shock absorbers;
2. damaged housing bearings;
3. little lubrication in rotating elements; and
4. displacement of panels.

Balancing dynamic components

The procedures may vary according to the aircraft involved and are provided for in the maintenance manuals for each system, set, or accessory of interest. Thus, for a particular aircraft, the manufacturer may have considered it important to perform the task of balancing the main gearbox oil cooling system fan shaft, while for another aircraft, the balancing of the transmission shaft for the tail rotor may have been considered more important.

It is important to keep in mind that not all shaft problems are due to unbalance. So, if, for example, we add balancing masses and the vibration level does not drop, the shaft may be misaligned or warped, and adding mass will not correct this problem, putting even more stress on the bearings on that shaft. The best solution will be to correct this misalignment, and even replace the shaft, if appropriate.

The clearance in certain components of the aircraft can change the rigidity of the structure, bringing the frequencies of the dynamic loads acting on the structure closer to the natural frequencies of the fuselage. As an example of this situation, one can verify that, in the case of the WG-13 Lynx helicopter, the excessive clearance of the upper mast bearing in its seat in the main gearbox causes an increase in the amplitude of the vibration at the fundamental frequency of the main rotor.

2.4 Vibration analysis in dynamic components of helicopters

Vibration analysis objectives

1. Detect defects in mechanical components (slacks, wear of bearings, gears, misalignments, lack of lubrication) before catastrophic damage to the assembly occurs;
2. Detect structural problems in the aircraft (cracks, loosening of screws and rivets) before catastrophic failures occur;
3. Assist in the diagnosis of breakdowns in mechanical components, indicating the subcomponents of abnormal behavior;
4. Allow maximum utilization of components subject to wear and fatigue, removing them for overhaul only when there is evidence of failure (predictive maintenance), rather than at scheduled time intervals (preventive maintenance).
5. Plan repairs or replacement of components, consequently increasing the quality of repairs, reducing operating costs, and allowing an ordering, in time, of the needs for replacement parts.

Theoretical foundations of vibration analysis

It can be shown that a periodic motion can be represented by a summation of sinusoidal functions, which in turn, represented in the form Amplitude X Frequency, constitute the frequency spectrum of that movement. Figure 13 illustrates a periodic motion, plotted in the time domain and the frequency domain.

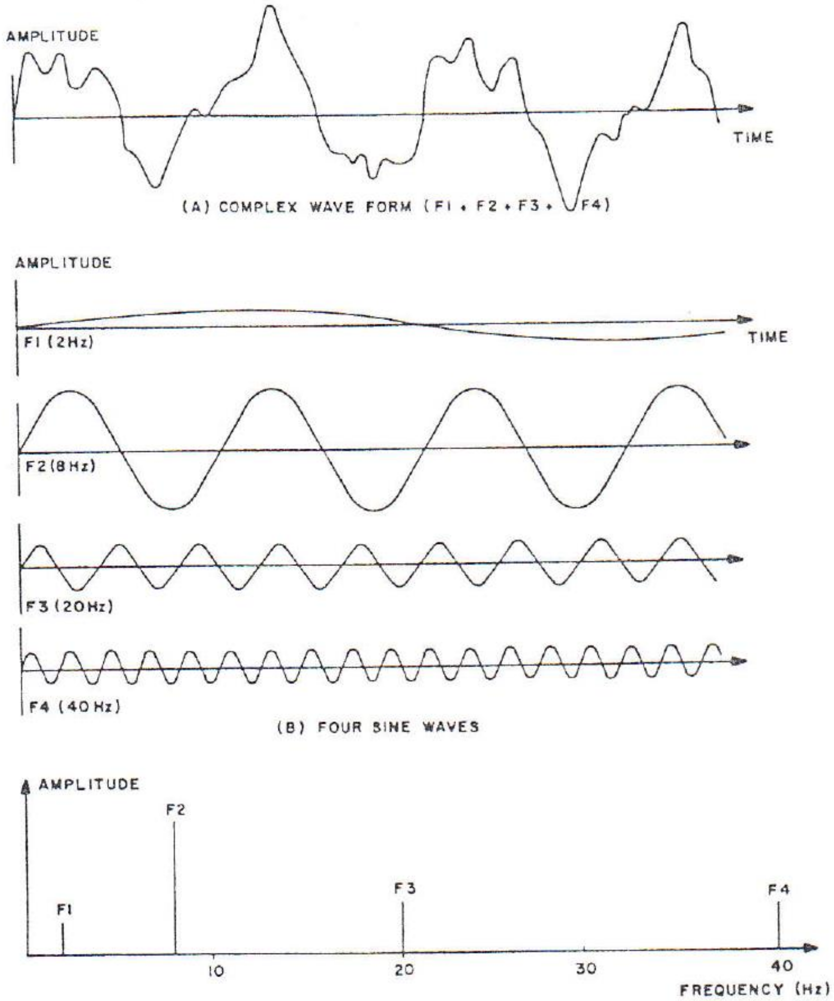


Figure 13: Periodic Motion (time domain and frequency domain) (Adapted from [8])

One must note that forced vibrations occur at the frequency of the external forces causing them, and consequently, a large amplitude of vibration at a certain frequency of the spectrum can be related to the possible causing force. Therefore, the tracking or monitoring of the frequency spectrum of components allows the detection of the beginning of anomalies in components and the determination of their origin.

In the case of helicopters, some manufacturers provide a frequency order sheet that allows locating the possible cause of any discrepancy in the frequency spectrum, obtained by sensing specific points on the helicopter's fuselage.

The transmission of vibrations along the structure of the aircraft is a function of the distribution of mass and stiffness along with the structure. Vibration spectra different than expected or high amplitudes at a certain frequency without an apparent reason can mean changes in structure characteristics, such as loose rivets and screws, cracks, etc.

A practical example of vibration analysis for a helicopter

Figure 14 shows a vibration signature card, obtained with the "Scientific Atlanta model 2521" analyzer for an SH3-A helicopter, where the vibration amplitude at 8099 BPM is very high.

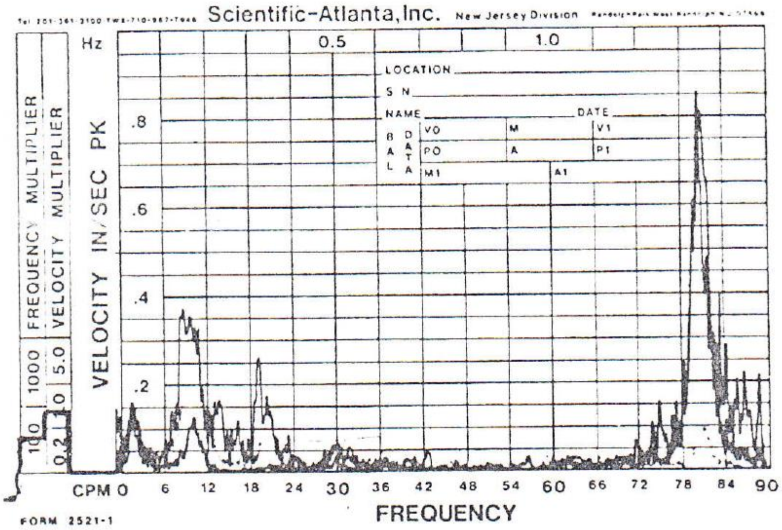


Figure 14: Vibration signature of a helicopter on the ground, with a problem at 8099 rpm (Adapted from [8])

The research of possible causes was done with the help of the "H-3 Troubleshooting Chart". We had, among others: "Generator Adapter broken/deteriorated".

After some research, it was found that the number 2 generator adapter was cracked, a problem that had not yet been discovered during normal aircraft maintenance. After replacing this adapter, the spectrum was as shown in Figure 15, where one can see that the vibration at 8099 RPM was drastically reduced. As it is a high frequency for the sensitivity of the human body, the problem was only detected with the help of the analyzer, not being felt by the crew when in flight.

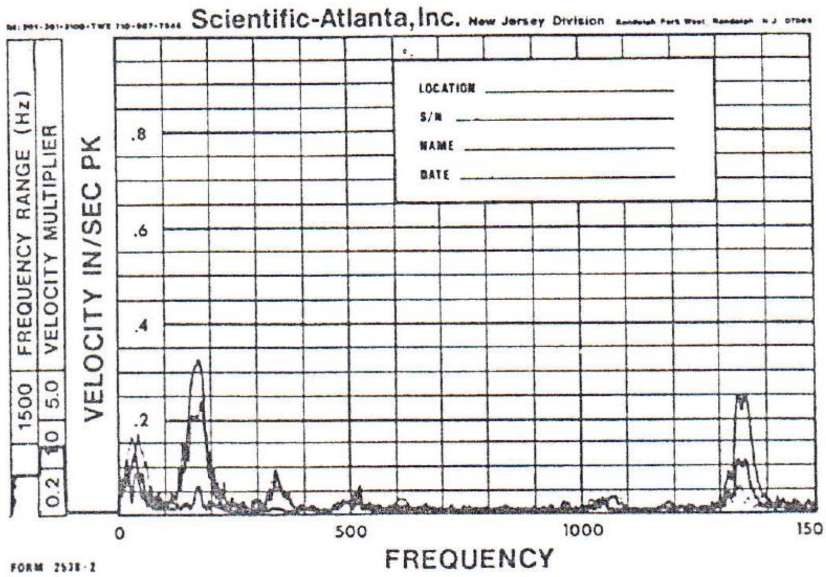


Figure 15: Vibration signature of the helicopter, after changing the generator adaptor (Adapted from [8])

Outline of a vibration analysis program for a helicopter fleet

a) The program consists of all aircraft having their vibration signatures registered and archived for the formation of a vibration database, to have data to compare the vibration signature of an aircraft at a certain time of its useful life (for example aircraft with 500 hours flown; aircraft after overhaul; aircraft after SDLM (Standard depot-level maintenance); aircraft after major structural repair or after an accident, etc) with:

- the vibration average of the different aircraft of the same model, to verify how this aircraft behaves concerning all the others;
- the same aircraft at a previous time, to investigate the possible degradation of the vibration state of the aircraft with use.

b) Aircraft vibration signature records must be obtained:

- only after having been eliminated, or minimized, as far as possible, avoidable vibrations once-per-revolution of the main and tail rotors, by the use of vibration reduction techniques;
- for the flight conditions foreseen for the aircraft, trying to keep the flight parameters as constant as possible;
- with the accelerometers fixed in the positions provided for in the aircraft manuals; and
- usually at pre-established periods or after major maintenance inspections, overhauls, major structural repairs, accidents, etc.

c) After obtaining the cards with the aircraft vibration signature, a data reduction is performed, which consists in obtaining average values of vibration amplitudes, to be used as a source of future comparison. These values are calculated using statistical sampling criteria for each type or model of aircraft, for each flight condition, for each of the frequencies, predicted to be the most significant in terms of vibration problems in the aircraft, and for each of the directions of interest (vertical, lateral, and longitudinal).

For each flight of an aircraft of a particular model, each vibration amplitude value will be compared with the average value existing in the corresponding table, and the evaluation of the results will be made by pre-established criteria, reaching conclusions about the maintenance actions that must be undertaken or not.

Thus, if the vibration amplitude value, at a particular frequency, is considered:

- Good, it means that there is no action to be undertaken;
- Regular, means that the vibration level at that frequency is already in the "Marginal" range, and some maintenance must be programmed (in any equipment which could be somehow related to this vibration frequency) as soon as possible, and greater attention must be paid to secondary indications (as, for example, visual inspection of the equipment involved, analysis of lubricating oil or hydraulic fluid, when applicable, to try to detect particles or debris, etc); and
- High, means that, before the next flight of the aircraft, maintenance troubleshooting must be carried out, according to the appropriate manual for each aircraft.

d) As the vibration of the aircraft is an eminently random phenomenon, one must redouble the attention when finding a vibration value, only, in "High", because this value can just be the result of a single event of turbulence that was registered by the accelerometer, not being, therefore, a vibration of the aircraft itself.

The following guidelines should be followed, as far as possible, to have more solidly based conclusions:

- if the vibration is "High" at a certain frequency in a given flight condition, check if it is also "High" or "Marginal" at the same frequency in other flight conditions; if it is, the need for troubleshooting is consolidated; if not, it could be a problem of turbulence or any other effect that has masked the measurement, generating the need for a better evaluation;
- whenever there are doubts about the intensity of vibration obtained, or if the result obtained indicates the need for replacement or repair of a large component, a new vibration analysis should be carried out to collect more data and be able to obtain more accurate and reliable results; and
- in parallel with the vibration analysis, one should seek to collect as much data as possible, as well as information that may be useful, such as the "life" in hours of the components involved, their last replacement, relevant maintenance information, information on contamination of lubricating oil, hydraulic fluid, etc., when applicable.

e) The evaluation of the results can also be done, in parallel, by comparison with the maximum vibration foreseen in existing international standards on the subject. Thus, as long as there are no average results calculated for a certain model of aircraft, or these average results are not judged sufficiently reliable, or if another criterion for evaluating their vibrations is desired, we can adopt internationally disseminated evaluation criteria. These criteria can be qualitative, such as the "Cooper Harper" scale, or quantitative, such as, for example, those described in the following standards:

- MIL-H-8501A, General Requirements for helicopter flying and ground handling qualities;
- MIL-STDTD-810D, environmental test methods, and engineering guidelines;
- AvP 970, Design Requirements for Aircraft for the RAF and RN, volume 3: rotorcraft design requirements; and
- DEF STAN 00-970, volume 2, chapter 501, vibration and internal noise.

Some remarks on vibration analysis in dynamic components of helicopters

The problem of vibrations in helicopters is considerably more complex than what exists in airplanes, as the helicopter experiences cyclic a variation of aerodynamic loads that cause strong vibrations in the structure, and which currently can only be mitigated by the use of heavy vibration absorbers, insulators, dampers along the fuselage or dynamic decoupling between rotor and fuselage (and also some active systems, currently in the prototype phase or with limited application).

However, until a type of aircraft is obtained that allows translational and hovering flights to be carried out more efficiently (such as V-22 Osprey) this is one of the prices that one has to pay for the use of the helicopter in his entire flight envelope, which is unique.

The existing vibrations in the fuselage of helicopters entail a higher maintenance cost, reduce crew performance, and may even compromise flight safety by the possibility of causing fatigue failures in structural components. It remains for operators to know the causes of the phenomenon and, using existing equipment, reduce the vibration levels of their helicopters to the lowest possible value. Vibration analysis techniques, however, appear as a possible way out of the problems of high maintenance costs and reduced flight safety, as they may allow monitoring the operating conditions of all helicopter components, allowing the installation of reliable programs of predictive maintenance.

Future perspectives: the HUMS for dynamic components of helicopters

The scope of the computer-based HUMS for dynamic components of helicopters typically may include vibration analysis, balancing, and rotor tracking equipment, equipped with computer-based expert systems (artificial intelligence).

Such equipment must present the capacity to be operated by personnel without knowledge of vibrations, to provide the best possible correction of balance and track of rotors, and to analyze vibration spectra, indicating eventual problems and their causes.

In terms of helicopter design, the equipment installed on board may include active systems to nullify vibrations considered "unavoidable". These systems act, through the blades, on the excitation forces, generating a new set of aerodynamic forces that, added to the existing one, cancels the structural vibrations at certain points of the helicopter.

HUMS systems enable continuous monitoring of vibrations, allowing the almost unlimited use of components subject to wear and fatigue, with the assurance that any start of a defect will be detected, and the component will be replaced promptly before catastrophic failure occurs in the assembly. These HUMS systems may also help to reduce or even eliminate the need for periodic replacement or removal of components for overhaul.

The available HUMS equipment can be coupled to onboard computers, as well as to central computer stations on the ground (transmitting their vibration information either online and/or offline), for monitoring and continuous analysis of the information collected. Thus, the comparison with established limits can be done on board or offline, by land-based computers, which can analyze the records obtained in flight.

3 Vibration-based Health and Usage Monitoring Systems (HUMS) philosophy in the predictive maintenance of helicopters

This section is based on the article of González & Donizeti [9], first presented at "XII SIGE - Simpósio de Aplicações Operacionais em Áreas de Defesa", 2010, São José dos Campos, SP, Brazil. XII SIGE, 2010, and on excerpts from the master's thesis [10], for the Post Graduate Program in Mechanical & Aeronautical Engineering at ITA, São José dos Campos, Brazil, 2012.

3.1 Introduction

HUMS (Health and Usage Monitoring Systems) were initially developed for large-size helicopters, such as the one used in offshore activity, being one of the types of condition monitoring systems, commonly called Health Monitoring Systems (HMS), that also consider helicopter employment parameters. Aligned to the philosophy of predictive maintenance, the HUMS actions propose to guarantee continued airworthiness and reduce operating costs through diagnostics forecasting (early diagnosis) and fault prognosis that increase reliability, from the treatment of data collected by algorithms dedicated to increasingly expanded functions and integrated into other subsystems. This collected data for the prediction of failures comes from vibration sensors, such as accelerometers, permanently installed in the fuselage and/or in dynamic components and/or in engines, with different vibration levels corresponding to various helicopter operating conditions. The research effort is also justified by the potential of HUMS to improve flight safety through their proposal to guarantee the replacement of components always before their failures.

This section aims to present an introduction to predictive maintenance for helicopters and a brief qualitative summary of these HUMS systems, segmented into history and evolution of the market; architecture; benefits, disadvantages, limitations; certification challenges; and application perspectives.

The condition monitoring systems, or HMS, were initially developed to improve safety on commercial airplanes. Currently, in this sector, the analysis of information collected by some operating companies that belong to the quality assurance program of their flight operations – FOQA (Flight Operational Quality Assurance), from which potentially dangerous trends in operation and use of components can be identified, even allowing to point out the need for training.

Efforts to develop a particular type of HMS, also considering usage parameters such as the count of operating cycles/time and flight data records (FDR) and exceeding recommended limits (torques and speeds), focused on rotary-wing aircraft, lead to the condition monitoring systems known as HUMS (Health and Usage Monitoring Systems). In this case, in addition to following the degradation of dynamic components (engines and power systems; landing gear; gearboxes and transmission shafts; structural cells) and to the rotor tuning (rotor balance and blade tracking), there are also the benefits of the registration of the performance and the indication of exceeding operational limits, which may significantly compromise the life expectancy of a component. For this purpose, the HUMS relies on a variety of sensors (mainly accelerometers for vibration data collection) by integrating a so-called data acquisition system, which can even include both voice and flight data recorder functions (CVR and FDR).

This data can be processed simultaneously with the flight (on board the aircraft or at a ground station via data cards, provided they are properly interpreted, modify (anticipate/postpone) the required maintenance schedule as well as the crew's operational actions even before the next landing.

Complete systems such as HUMS are expected to perform acquisition, analysis, communication, and storage of data from sensors permanently monitoring critical items and, therefore, are expected to be essential to flight safety, aiming to limit the risk of human and/or material damage to an acceptable level, as defined from Risk Assessment strategies.

In this context, one must note many rotating and critical systems acting on helicopters, a peculiarity whose effects are classified as catastrophic events in the category of the severity of defects (aircraft and human lives). Thus, the vibration magnitude monitoring technology for the detection of associated faults arises from the demand for early diagnostics and effective predictions. And so the HUMS has expanded its acceptance as a strategy aligned with the effectiveness of the maintenance philosophy and, nowadays, has been used as a complementary method to ensure continued airworthiness, defined as guaranteeing the certified level of safety throughout the life cycle of operation of the product (aircraft and/or its systems), as stated in aeronautical regulations, such as, for example, the RBAC 01 from ANAC [11].

3.2 An introduction to predictive maintenance for helicopters

From the point of view of safety and continued airworthiness, aeronautical maintenance is known as an activity of inspection, review, repair, cleaning, conservation, or replacement of parts of an aircraft and its components [11].

Helicopter operating costs are extremely high mainly due to maintenance (24%) and insurance (29%) costs, given the relevant civil and legal liabilities, as well as the perceived levels of danger associated with society [12]. So, as for maintenance costs, they are around a quarter of the total cost of operation [13].

There are compelling prospects for reducing both the consolidation of predictive maintenance and its results in aviation safety and reliability.

Each efficient maintenance program implies the adoption of elements of three types of philosophy that reflect the acquired technological capacity: corrective maintenance; preventive maintenance and predictive maintenance.

Corrective Maintenance is the oldest and most common until the 1950s. It is a reactive fault management technique, expensive because it usually involves major repairs and inopportune times. It emerged when the performance data deficiency of the components involved was mastered. On the surface, the idea of being less costly is conveyed, but the costs increase due to production losses (loss of profits) and the resulting secondary damage, in addition to excessive time to remedy the problem; however, it is useful when sudden failure does not threaten production, such as a drinking fountain, for example. It applies to items classified in the manual as Condition Monitoring – replacement is recommended only in case of discrepancies. Also, the fail-safe design concept allows for corrective, effective, and timely maintenance to be carried out at more favorable times and conditions, such as in major overhauls, allowing much greater tolerances for cracks, a clear practical advantage in areas that are commonly difficult to access.

Preventive Maintenance establishes the second generation. It is based on the predictability of operational behavior, acquired from experimental and statistical observations, and imposed by restrictions on certification specifications that are more suited to the risk peculiarities of the aeronautical activity. For the first time, these conditions were created for proactive maintenance and anticipating failures. In the general context, it includes all maintenance management programs triggered by time, such as operating hours and/or cycles of the items (counted by landing, engine shutdown, etc.), in which they are removed. There may be situations in which they are still usable at the moment of replacement, and there may be also some cases, undesirable ones, in which they may be replaced only after they fail. They are discarded via recording “scrap” or mutilation to avoid unintentional reapplication based on manufacturers' performance projections. It is a highly conservative position, with the disadvantage of wasting time and material by replacing an item with an appreciable useful life when one could act more frequently than necessary. For a machine that could still operate satisfactorily for a longer time, stopping it just for a check does not seem reasonable. It is worth reflecting that opening/closing increases the probability of introducing human factor errors. On the other hand, one should not wait for a breakdown to be corrected, and, therefore, the best solution is to intervene at the ideal moment.

Predictive Maintenance is based on measurements (which must be representative and consistent) of the actual conditions of the equipment on a continuous and periodic basis, according to the criticality level of the item. But some measurements are unfeasible, and imprecise, while some components have a low replacement cost, such as replacing the lubricating oil, for example. In this case, vibration is a vital parameter to define the dynamic conditions of rotating machines. The Predictive Maintenance Philosophy was first born in the analysis of lubricating oil implemented by American Naval Aviation in the 1950s. From there it spread, establishing itself as the third generation from the 1960s onwards, bringing new paradigms to the maintenance logistics function.

The industry continues to evolve in technology, motivated by the relentless search for financial results associated with operational efficiency, which depends on safety and availability. In this sense, as it allows for a better understanding of the dynamics of the phenomena involved, mastery of manufacturing processes, as well as the ability to measure and process evidence of performance, this methodology for having the aircraft at hand has advanced (from the Latin “manutention”: the action of holding in the hand): the philosophy based on the condition. As techniques have become more sensitive, failure predictions give way to condition changes, keeping failure at bay.

Predictive Maintenance is positioned as a philosophy that, unlike the reactive doctrine of Corrective Maintenance, is proactive to unpredictable failures to increase the reliability and safety of operation. Based on component condition and integrity, rather than time/life cycle, it identifies the tendency to future failure according to some deviation from the standard of thermal, acoustic, and vibratory quantities (mainly in helicopters), which reveal the known behavior of the system. One can mention the following issues:

- oil spectrometric analysis;
- ferrography (as part of Tribology - investigation of friction wear);
- analysis of particles in hydraulic fluid;
- thermographic analysis;
- noise analysis;
- and vibration analysis (the most important parameter in the case of helicopters).

It is the philosophy most associated with computational resources – it is based on the trend graph (curve) and spectral analysis (if an increase beyond the tolerable is detected). The experience accumulated in the database facilitates the association of each frequency for the diagnosis of each type of failure.

Trends of the fourth generation of these quality tools have recently emerged, characterized by the application of continuous monitoring systems associated with systems for supervising failures. These systems are equipped with signal analysis algorithms (Fast Fourier Transform – FFT, and/or Wavelet, and/or Hilbert), and/or artificial intelligence techniques (Artificial Neural Networks – ANN and/or neuro-fuzzy systems, among others), to provide the diagnosis and prognosis of incipient failures. In search for higher reliability, there is Reliability Centered Maintenance - RCM, which has become popular for its methodologies such as FMEA (Failure Mode and Effect Analysis), FTA (Fault Tree Analysis), and Probabilistic Risk Analysis - PRA. For Root Cause Failure Analysis, see [14].

3.3 Historical developments and market evolution of HUMS

The nature of the aircraft maintenance tasks being performed reflects the technological capacity acquired through time. In the early days of aviation, reactive maintenance prevailed, due to the lack of performance data of the components involved. In this case, no maintenance action was necessary, until a failure occurred, featuring a low level of safety and high costs, both direct (major repairs) and indirect (unavailability). Considering the peculiarities of the risk in an aeronautical activity, the specifications of the related certification processes became more restrictive over time, leading to advances in manufacturing processes that create more reliable items. The predictability of their behavior, acquired from the experimental observations and operating statistics, created conditions for proactive maintenance procedures, anticipating failures. The first one, based on time/operation cycles, was established under a preventive philosophy.

In this situation, each component is replaced according to previous appointments, according to its design concept being fail-safe, Safe Life, or Damage Tolerance. Thus, for decades, high-cost components were removed and discarded, based on manufacturers' performance projections. Several times, this removal could have happened well before the component was unusable and sometimes this removal may have happened only after the failure of the component. In the relentless pursuit of efficiency of operation (and, obviously, on the financial results associated with it), dependent on safety and availability, the industry continued to evolve in technology. With a better understanding of the dynamics of the phenomena involved, a mastery of the manufacturing processes, as well as with the ability to measure and process evidence of performance, progress has been made in yet another methodology of “having the aircraft at hand”: the philosophy based on condition monitoring. In this case, aircraft components and systems are monitored to project when their failure is likely, under pre-established criteria of risk analysis. Therefore, ideally, the components are used for the entirety of their useful life, and without the need for premature replacement, reducing operating costs and keeping the preponderant advantage of always being replaced before the failures, potentially increasing the aircraft safety and reliability.

Furthermore, the HUMS gained prominence in the transition between the traditional preventive maintenance philosophy and the new condition-based philosophy. The HUMS had its first certified flight in 1991, aboard a transport helicopter in support of offshore activities in the United Kingdom (North Sea). Commissioned by the British Civil Aviation Authority (CAA), an investment was made in the development of systems that could provide the early detection of defects and, as far as possible, the ability to predict/manage a window of safe fleet operation. Later, the American civil aviation authority - FAA (Federal Aviation Administration) issued the airworthiness requirements for normal category helicopters AC-27-1B [15] and transport category helicopters AC-29-2C [16], as a guideline for the certification of HUMS installation.

To inhibit possible compromising distractions of the pilots from the flight situation awareness, there is a tendency, in the operations, in waiving the cockpit performance trend notification - essential data only to the evaluation at the monitoring center, on the ground.

The acceptance of the HUMS is growing, and the US Military continues to develop HUMS capabilities for more accurate diagnoses and prognoses. For example, it is worth mentioning the HUMS are already standard and fully operational on the helicopters Sikorsky S-92 and S-76 C+, and on the Airbus Helicopters H-135; also, the system is offered as an option on the AgustaWestland AW-139, among others. More details on HUMS Technology can be found in [17].

The HUMS is also operational on the Brazilian Armed Forces Airbus Helicopters H-225M aircraft, which are equipped also with CVR/FDR in the system. The Brazilian offshore market already has advanced systems technologies such as the HOMP (Helicopters Operation Monitoring Program), a system that monitors each flight in detail, standardizes operations, and identifies in advance any quality problem. These systems are associated with the HUMS, having been recently added to the S-92 and S-76 C++ aircraft, for example. In parallel, many other operators are adapting their helicopter fleets to this new equipment.

The list of major HUMS manufacturers includes Smiths Industries of the United Kingdom, which acquired SHL - responsible for the research that culminated in the pioneer flight; and the American Goodrich, a large and traditional supplier of this type of systems to the global civil and military market.

This market has new entrants from the area of structures, whose strategic planning focuses on expanding the number of customers through the development of low-cost similar systems. More information on HUMS for Light Commercial Helicopters can be found in [18].

For example, Smiths HUMS systems are installed in: Canadian Armed Forces (Bell 412); Airbus Helicopters H-225; Sikorsky S-61 and S-76; Safran Arriel engine; AgustaWestland EH-101; and Bell-Agusta 609 tiltrotor. Several units of this HUMS are in service and accumulating flight hours aboard the Boeing HC Mk II Royal British Air Force Chinooks, which continuously monitor the tracking and balancing of the rotors, thus dispensing extra flight tests and the use of specific balancing and tracking equipment on board.

Goodrich, in turn, is the supplier of the first HUMS incorporated on the Sikorsky S-92, and their mastery of diagnostics covers from failures in gears and bearings of gearboxes transmission to infiltration of water between the layers of composite blades. Their products are already in the 3rd and 4th generations. The company has demonstrated its ability to balance the Chinook's tandem main rotors without the use of a specific infrared detection device for tracking.

The algorithm built in their Integrated Mechanical Diagnostic HUMS (IMD-HUMS) can determine more accurate solutions to adjust rotating systems by making more detailed calculations related to the vibrations detected by the accelerometers in the helicopter cabin. In other words, a better use was made of the data usually collected by the HUMS. The trackerless concept by Goodrich presents faster results, eliminates repetitive and costly test flights, and has been proven on other IMD-HUMS equipped aircraft such as Sikorsky CH-53, H-60 BlackHawk, and MH-60R SeaHawk; and Bell AH-1 Cobra and UH-1.

A vibration monitoring equipment (HVM) is equipped in Bell 412 and 212 series, and Agusta A109 and A119 helicopters are supplied by IAC and Altair Avionics, which has been acquired by the Canadian engine manufacturer Pratt & Whitney aeronautics. The Altair SmartCycle+ system, with multiple channels, monitors the use of engines from the gas generator and turbine parameters such as torque, speed, and temperature; in addition to vibration levels and other HUMS parameters such as main rotor speed, outside airspeed, and temperature, and also altitude.

3.4 HUMS description and architecture

Briefly, the basic architecture of an HMS can be described as formed by sensors that transform the variables of interest of each aircraft into electrical signals, which are then processed and compared, using computational algorithms, with a historical database (reference) of the variable in question, and presented to an operator on board, or to a central monitoring system on the ground, to assess the current state of the component and its probability of failure, as shown in Figure 16.

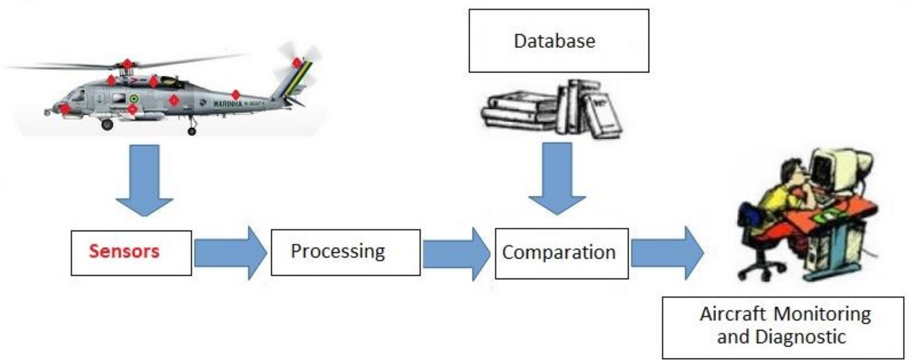


Figure 16: Simplified diagram of a Health Monitoring System (HMS) (adapted from [9])

Figure 17 shows a typical vibration spectrum, which is characteristic of each helicopter and acts as its fingerprint at a particular time or flight condition, to be added to the helicopter vibratory database. When analyzing this database, for each frequency band, any significant variations in the vibration at a particular frequency may be related to discrepancies of a corresponding dynamic component (rotating parts of engines, rotors, gearboxes, transmission shafts, etc.) or even a fixed element (such as fuselage stabilizers, etc.).

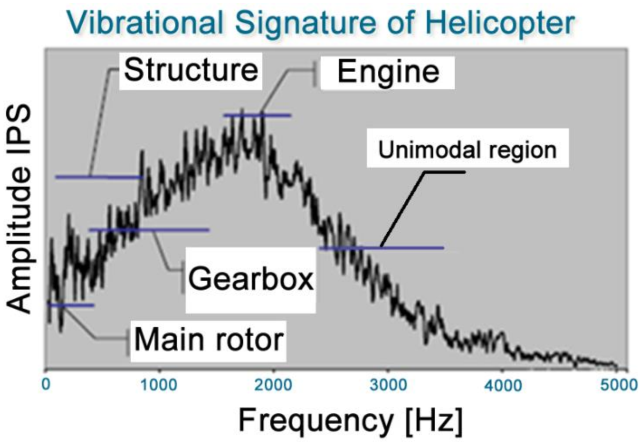


Figure 17: Vibration spectrum (signature) of a helicopter (Adapted from [9])

The sensors are essential to track aircraft conditions and can be primarily of magnetic, temperature, or inertial types. The inertial-type sensors include the accelerometers, which are responsible for collecting the oscillations of the fuselage in response to the external excitations, as seen in Figure 17. Some of these elements are built of quartz or ceramic, and HUMS use them under strict requirements of performance and reliability.

Most accelerometers need to be airtight to ensure efficient insulation in environments with high humidity and contaminants. Bandwidth, or frequency response, is the most important parameter in accelerometer selection. No accurate data is acquired if the bandwidth of the accelerometer does not include the frequency of the motion, vibration, or shock you are willing to measure. The sensitivity of an accelerometer defines at what rate the sensor converts mechanical energy into an electric signal (the output), and this will define the acceleration measurement range of the accelerometer. Sensitivity is usually expressed as mV/g (millivolts or per g) or pC/g (picocoulombs per g), where g is the acceleration due to gravity. The frequency response specification shows the maximum deviation of sensitivity over a frequency range. Great sensitivity and wide frequency response is a desirable feature for accelerometers, to ensure signal identification without significant sampling errors. As an example, high-quality accelerometers may present sensitivity in the order of 25 mV/g at 20,000 Hz (+15%).

Vibration-based damage detection techniques are associated with the combined condition and use monitoring (HUMS) or, more recently, condition management and prognosis (Prognostic and Health Management - PHM) systems. In a little more detail, in HUMS the monitoring of the mechanical or functional condition of a component or system aims, especially, to detect or possibly diagnose incipient degradations that could lead to a failure.

Condition management, on the other hand, describes the process of dealing with the information obtained from monitoring and prognosis to establish the real-time situation of the item and possibly, as desired, propose methods to extend the life of the item or limit its operation. The term "monitoring usage" means determining the lifetime consumption of critical components and systems according to operating records (cycles and hours) and loading history [12]. The generation of alerts is a differential of the HUMS and it boils down to establishing thresholds for each vibration condition and generating alerts as changes in the values in the trend reach them. In many cases, these thresholds need to be inferred from operational observation of HUMS in service, since there is no previous experience for helicopter manufacturers to issue their recommendations.

Threshold levels are not effective when applied to fleets due to the indication variations between components and aircraft. Therefore, these levels have been raised individually by automatic techniques that register those that were previously classified as statistically significant, through reasonableness tests and other processes [19]. Trends emerge from research suggesting that the performance of diagnostics can be improved by advances in the signal processing process and by advances in sensors [12]. To illustrate some performance statistics, information from the Civil Aviation Authority of the United Kingdom indicates that 69% of the increasing threats registered to continued airworthiness (mostly problems of balance and tracking in the rotor) were successful in detecting the failure, 17% had their evidence, but they did not carry out the alert, and only 14% of the cases the failures were not detected.

Provided that the results presented by the HUMS are properly interpreted under a risk analysis framework associated with the severity of the failure, the aim is to:

- guarantee the continued airworthiness of the aircraft - defined as the guarantee of the certified level of safety during the entire operational life cycle of the product [11];
- increase flight safety by increasing the situational awareness of the crew and supporting their operational decision-making; and
- reduce operating costs through Reliability Centered Maintenance (RCM) – which offers to track (anticipating/postponing) the best intervention opportunity (increasing availability); and to offer savings in the reduction of maintenance flights to adjust the main rotor, consumable material (sealants, sealing rings, lubricants, cleaning items, etc.), man-hours and the optimization of logistical support for spare parts.

HUMS must provide the precise status of the current use of critical components such that statistical models can be used to estimate the point in time when parts must be replaced, as well as indicate the presence of incipient damage that could lead to failure before the end of his cherished life in the safe-life philosophy. As for PHM systems, in general terms, it can be said that their prognosis is the prediction of the remaining life of this component or system. This requires propagation models of detected defects as a better approximation than monitoring usage [12].

The ultimate objective of HUMS and PHM is to allow predictive maintenance of the helicopter, that is, according to the philosophy that dictates that interventions should only occur associated with a predicted failure. However, for this, robust, reliable, and accurate HUMS or PHMs are necessary, which are not yet available in the current state of the art [12]. Meanwhile, manufacturers adopt it, at least, as a backup to primary conservative maintenance measures, according to safety factors and design redundancies, and frequently scheduled replacements in a safe-life context, complemented by damage tolerance techniques (fail-safe).

HUMS developers maintain a growing database of current vibration information inherent to the diagnostic function of HUMS associated with more than thirty faults detected and evidenced by vibration monitoring that can be related to maintenance actions. This information is used in the assistance service to different operators operating in different environments.

Brian D. Larder [19] categorizes the failures into classic and new in the diagnostic process, when he summarizes ten examples among more than twenty classes that make up this data in the HUMS library. The first ones refer to those that are the result of a known failure mechanism or that the associated indicators are a constant focus of attention, based on theoretical knowledge or bench tests. The failures of the so-called new category are those that do not allow for anticipation by the HUMS, nor are there any established indicators to recognize its effects. These can only be pointed out through lessons learned. The necessary experience can be maximized by combining information from the HUMS supplier, its operators, and the aircraft manufacturer [19].

3.5 HUMS advantages and benefits

Statistical information documented in the North Sea by the CAA indicates a high success rate in detecting failures, some of which could have turned into potentially catastrophic events, or could have even resulted in accidents. The benefits/return on investment in HUMS may include a reduction in inspections and maintenance test flights; and a decrease in unscheduled interventions. The advantages can be grouped into three main approaches: reliability, operational availability, and lower operating costs.

A- Increased reliability and flight safety level

Scheduled inspections (by calendar or lifecycle) in preventive maintenance are necessary for the reliability of components and systems, favoring flight safety. However, sometimes no damage (cracks, corrosion pits, deformations, etc.) is encountered, and also unforeseen failures may occur between two inspection deadlines, a situation that may culminate in accidents, as shown in Figure 18.

The employment of HMS-type tools, such as HUMS, offers constant monitoring which enables the identification of a future failure trend, according to some deviation from the known behavior pattern of the system. In this way, a predictive maintenance intervention could have been performed according to an established schedule, thus avoiding the occurrence of a failure, while still protecting against latent risks associated with manufacturing defects. Therefore, from the point of view of aviation safety, the main advantage is the fact that the components are always replaced before failures. Hence the potential of HUMS to improve safety and reliability, and reduce operating costs.

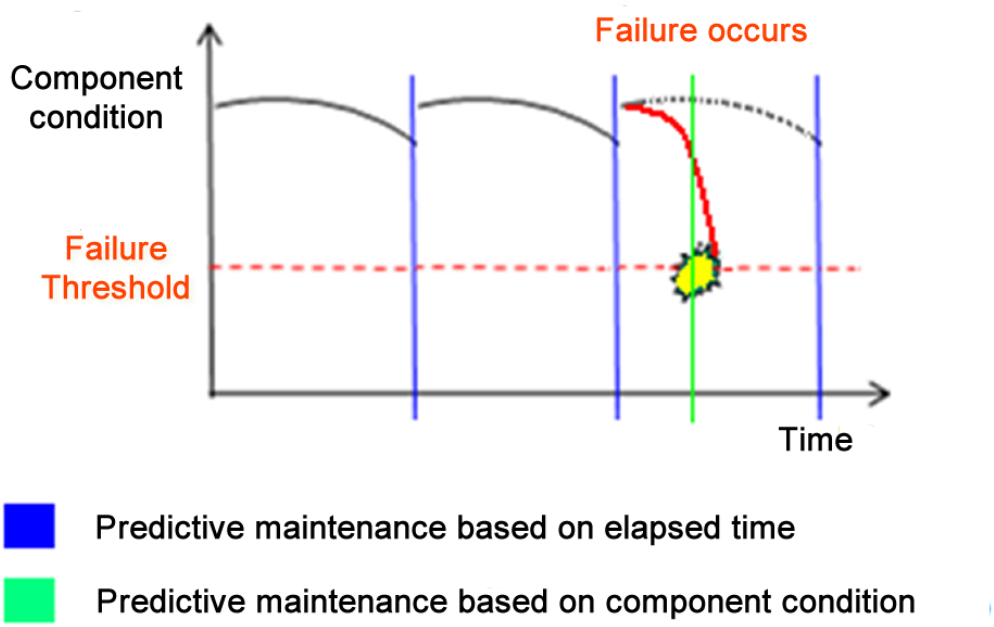


Figure 18: Condition (state) of the material over time using scheduled maintenance, based on time/cycles; and using predictive, condition-based maintenance (Adapted from [9])

B- Operational availability

The early identification of trends/variations in the amplitudes of aircraft vibration frequencies related to rotor assembly problems in helicopters often eliminates the need to carry out rotor flights for tuning the dynamic sets (balance and tracking adjustments). It should be noted that this feature allows the management of a Reliability Centered Maintenance (RCM) program to evaluate the possibility of defining the best opportunity to stop the aircraft, considerably increasing its availability in a company's operating schedule: operating units equipped with HUMS may fly more missions and may maintain a higher availability rate than units not equipped with these systems.

C- Reduction of operating costs

The maintenance cost reduction attributed to HUMS is a consequence of the reduction of dedicated or non-scheduled intervention actions themselves, due to scheduling optimization and the corresponding logistic support coordination, which allows the reduced use of consumable material (sealants, O-rings, lubricants, cleaning items, etc.), man-hours and spare parts storage.

This cost reduction is obtained through accurate and automated condition monitoring of equipment use; reduction of false failure events known as NFF (no-fault-found); reduction or consequential damages with the aid of early diagnosis; and improvement of the analysis of lessons learned from the trinomial event/incident/accident.

The use of HMS-type programs reduces maintenance delays and flight cancellations, avoids unnecessary maintenance, and reduces the price of insurance due to the reduction in the number of accidents and incidents and related expenses arising from claims.

Furthermore, when associated with systems such as HOMP via satellite (offshore activity), which monitors aircraft information (position, altitude, minimum altitude alert, take-off, and landing notifications), the system offers mission planning reports and reports of possible occurrences of non-conformities and condition alarms, which allow full control of the fleet, including computerized analysis of prevention reports.

The FAA estimates that aircraft employing state-of-the-art condition monitoring equipment may provide significant cost savings per year due to reduced fuel, maintenance, and direct costs related to accidents.

From the point of view of the manufacturer or the maintainer of an aircraft engine, who usually needs to provide warranties regarding the engine, it is desired to follow exactly the life condition and any possible abuse or misuse of the equipment.

3.6 HUMS disadvantages and limitations

There are records of incidents whose investigation pointed to the HUMS as contributing factors. In one of these cases, a sensor was inoperative. In another case, there was a serious incident due to the inability of the crew to confirm the correct diagnosis of the ongoing problem.

This latter case highlights the importance of considering and monitoring, also, the benefits of research on human factors and the cabin, crew, or corporate resources management (CRM), and/or the maintenance resources management (MRM), as both cases may affect predictions and the decision-making intrinsic to flight safety.

Therefore, the need for training and the challenges inherent in a change of organizational culture are decision-making factors whose costs should not be discarded.

Introducing fault detection information without the risk analysis associated with the severity of failure or their prognosis can be seen as a disadvantage due to the potential to increase unnecessary maintenance needs from the perspective of not compromising the continuity of airworthiness.

No operator wants to deal with the situation of an accident related to a known fault, no matter how well reasoned and structured the decision-making process, because will be charged for has been not having acted before.

The resulting civil liability would be unacceptable, with potentially dire ramifications for new insurance contracts, and the image and subsequent survival of the organization, in terms of continuity of its business.

Thus, forecasts with updated limits and continuous monitoring and diagnostics are essential resources to an HMS.

Another potential disadvantage of the HMS relates to the limits of prognosis. If, within the maximum level of uncertainty established for the continuous operating safety, they translate values consistently lower than half the range of traditional scheduled maintenance, the opportunity targeted for significant flexibility in maintenance management will be reduced and may limit the application of the HMS - unless the definitions of those intervals are based on statistical failure probabilities (based in the historical performance) and should be more conservative than the limits of prognosis adopted for HMS.

HUMS false alarms linked to NFF created by software or sensor errors also negatively affect operational availability, so that a rate of 10% of those in, for example, a fleet of 122 aircraft, would reduce operational availability by 4% (five units and 2,000 hours of flight/year).

With its current limitations, the maturity of the HMS philosophy still does not guarantee monitoring that covers the entire aircraft. For reasons of compromise between accuracy and cost viability, the HMS may never be able to provide the desired cost-effective follow-up of a component of a particular system or subsystem, and therefore it may always be necessary to require a combination with time-based maintenance. This limitation will vary depending on the nature of the system/subsystem and needs to be evaluated properly.

It is worth mentioning, considering the advantages mentioned in the previous section, that disadvantages and limitations will always be identified as new technology is adopted in the operational theater. The actors involved (manufacturers, maintainers, suppliers, users, and civil aviation authorities) should tirelessly discuss and refine these disadvantages and limitations to create viable alternatives to circumvent them or reduce them to acceptable risk levels, reaching a positive balance in favor of aviation safety.

3.7 HUMS certification challenges

Certification is understood to be proof that the project meets the requirements for its safe operation. The basic requirements for type certification (of an aeronautical product) are:

- qualification and installation of the system/equipment that collects, stores and presents the information;
- activities of validation/demonstrations of compliance with requirements (which involve the understanding of the physics involved in the failure mechanism) and of the methodology (means of each compliance by which it's analyzed how well HUMS can dictate maintenance actions based on the analysis of the condition and of use of data); and
- instructions for continued airworthiness, which implies, among others: instructions for operation life cycle and control for each item; procedures in case of inoperability; and training program and requirements for mitigation actions.

The criticality is defined here as the level of severity of the unintended consequences of using the HUMS in-flight safety. Through a Functional Hazard Assessment (FHA), this term is classified by the FAA into five categories (in decreasing sequence): catastrophic, potential danger, major, minor, and no effect), which determine the rigor of the certification process for the aeronautical product (equipment, software, or systems).

In this context, the unique challenge of certification lies in the creation and analysis of different scenarios in which safety must be provided, under the worst hypotheses, where there is a huge complexity associated with statistical & probabilistic models, and with the integration of multiple subsystems, both on-board and ground-based.

For these reasons, HUMS have been the focus of attention of civil aviation regulation agencies, such as the FAA, which issued certification requirements for the transport helicopter category through the circular advisory (AC 29-2C) [16]; and CAA, which issued AAD 001-05-99 CAP 693 Acceptable Means of Compliance Helicopter Health Monitoring.

That AC focuses on the aircraft maintenance process and describes a guide to requirements needed to certify the installation of an airworthy HUMS, with instructions for its continued airworthiness of a wide portfolio of applications, aiming at the approval of the aeronautical authority of certification. It is anticipated that developers may suggest other methods of proof of requirements beyond those recommended in this document; however, any methods must be previously approved by the FAA. The following key criticality elements must be met to guarantee safety:

1. Criticality assessment at application boundaries and effects on the helicopter. In the past, the data from the HUMS were already seen as valuable, but they were not critical for flight safety, as they were used in parallel to traditional maintenance regimes, or, for example, as instruments for after-sales support in monitoring equipment under warranty. From the moment the HUMS output information can be used to adjust established maintenance practices or whether it may be the only means of indication of the condition of the aircraft to the crew, the criticality of the system must be determined, and the rigor of certification adopted. It should be noted that the certification process of this system must be judicious at the level of possible dangerous consequences of inappropriate actions, which can be taken into consideration, as well as the impact of its installation;

2. Special considerations for ground equipment are relevant, given that the same criticalities of the on-board items must be considered; and as for the so-called off-the-shelf items (taken directly from the shelf), that is, without a certified system, considerations should be adopted to circumvent the rigors of a software certification;
3. Validation of monitoring techniques, algorithms, parameters, and rejection criteria;
4. Intervention actions associated with the monitoring data of the HUMS, which constitute extending the life of an item beyond preventive maintenance scheduling, saving costs, or reducing the life to avoid failure earlier than anticipated in the time-based maintenance; and
5. Certification actions for mitigation, that is, the establishment of criticality compensation factors to a low level, which would be autonomous, continuous, and independent of the HUMS. With this, the FAA does not certify any system as catastrophic.

Even after completing the initial certification process, the effort needs to be continually supplemented by information and evidence associated with the operational life cycle reality (Service Difficulties), which must be analyzed in the judgment of the effectiveness of the HUMS (for the guarantee of issuance of compulsory application service bulletins).

It is expected that the costs of certification will decline as more project models benefit from HUMS and more experience is gained in this process.

Goodrich HUMS has been certified to perform under the DO-178B Standard (titled *Software Considerations in Airborne Systems and Equipment Certification*), a criterion created by the RTCA (Radio Technical Commission for Aeronautics) for embedded software certification, and rated level B (potential to cause potentially hazardous/severe failures, identified and related to system security). This document determines verification, validation, documentation, and management of the software configuration, and disciplines the quality assurance to be used in microcomputer systems, as detailed in the advisory circular (AC 20-115C) [20]. As the HUMS is an open-architecture project, third parties can develop their systems to integrate with HUMS and still transmit real-time data to ground stations, which use common personal computers.

3.8 Application perspectives for HUMS

The aeronautical authorities continuously pay attention to the definition of the minimum certification requirements to ensure the airworthiness of future-equipped aircraft.

The new generations of HUMS are moving towards acting with greater reliability and integration of functions, increasingly changing the way maintenance is implemented. The growth in the use of these systems depends on the increase in the reliability of the sensors. Therefore, the critical point is the accuracy of the sensors, which yields much-related research, to develop sensors that are more reliable, cheaper, and resistant to a range of temperatures, environmental contaminants, and aircraft vibrations.

The expansion of the HUMS functions and capabilities is being made by improving the algorithms to make greater use of the collected data. New directions include transition changes, such as detection of the conditions of failure and diagnostics to anticipate the indication of potential problems and the diagnosis aimed at the reliable and detailed prognosis of the maintenance needs; and automatic usage tracking logbooks for each component for its full management, effectively updated by the data collected on the aircraft.

Composite structures, such as the carbon-fiber-reinforced type, have had their adoption expanded in recent projects such as citing in ascending order, the B777, B787, and A380 because they are lighter than metallic structures and considered equally durable because they suffer less fatigue. However, they are also susceptible to wear, often in the form of cracks or delamination, which often are not visible to the naked eye. The technology for monitoring the structural health condition, commonly known as Structural Health Monitoring (SHM), is in continuous development. The studied technology detects invisible deformations or cracks through optical fibers that are used as embedded sensors or bonded to the aircraft's composite structure. SHM technology uses Artificial Neural Network (ANN) systems to emulate the pain signals sent to the brain by the human nervous system, when fractures, fissures, or delamination occur, which destroy the fibers, interrupting this way the light signal. This interruption, in turn, allows the anomaly is identified and located. Challenges in this technology focus on the adoption on a large scale at non-prohibitive costs, in the addition of extra weight, and in the commitment to the strength of the composite material itself.

Other structural monitoring technologies are being envisioned, including the premise of using acoustic emission sensor devices attached to the surface of this type of structure to capture the energy released by crack propagation.

The near future of HUMS systems in the military arena also points to their integration with communication systems such as the Airborne Communications Addressing and Reporting System (ACARS), which consists of transmitting automatic in-flight data (thus eliminating the onboard storage of cards), to be analyzed in real-time by the monitoring stations on the ground. In this way, the operator maintains the immediate condition of its fleet, allowing the assessment of the safe length of time between revisions, or time between overhauls (TBO).

Shortly, the consolidation of the HUMS is a widely used item, even by the smallest operators (motivated by the most economical operation of their aircraft), is expected to contribute to the helicopter industry's goal of reducing the accident rate in the coming years.

HMS has arrived on the aviation market as something more than a new technology: it arrived as part of a philosophy that emerges in changing organizational cultures. Predictive maintenance, based on the life condition of the components and subsystems, in line with continuing technological advances, has met the incessant search for greater flight safety and availability of aircraft, and reduction of operating costs, all aspects essential to the improvement of the business aviation efficiency, both in the civil and military sectors.

The HUMS, besides the monitoring, also includes aircraft usage parameters and has earned more acceptance among aircraft operators, as their prognostic limits are expanded, and alternatives to current difficulties are discussed. In their various projects, the HUMS tend to become more accessible also with new possible low-cost options, culminating as a standard item in the helicopter industry. Under the unprecedented challenges required for the careful certification of the relevant authorities, even open-architecture projects can count on the guarantee of the required quality. HUMS/CVR/FDR integrations, automatic transmissions of data even via the Internet, and structural health (condition) monitoring (SHM) technologies in composites are just some of the perspectives that promise to guarantee the airworthiness of future equipped aircraft.

4 Vibration-based health and usage monitoring systems (HUMS) of dynamic components of helicopters: some numerical and experimental applications

This section is based on excerpts from Technical Reports [21] and [22], concerning the Offset Program of Transfer of Technology in Health and Usage Monitoring Systems (HUMS) of the aircraft EC-725, a program involving the companies AIRBUS HELICOPTERS (former EUROCOPTER), HELIBRAS, and also the Brazilian Universities UNIFEI and ITA.

4.1 Wavelet analysis

Transient events in time series data if well captured by algorithms provide a lot of information about the object that they refer to. The decomposing of a time series into time-frequency space enables the capture of both the dominant modes of variability and how those modes vary in time [23]. For example, an indication of an abrupt change in the data-generating mechanism makes it possible to detect and localize in time. Applications of this kind of analysis include faults in machinery and equipment, problems with sensors from acquired signals, financial bankruptcies in mass from economic time series, seismology, and many others.

In mathematics, the continuous wavelet transform (CWT) is a non-numerical tool that provides an overcomplete representation of a signal by letting the translation and scale parameters of the wavelets vary continuously [24]. In an overcomplete basis, the number of basis vectors is greater than the dimensionality of the input, and the representation of input is not a unique combination of basis vectors. Overcomplete representations have been useful because they present greater robustness in the presence of noise.

The MATLAB® command *cwt* (Continuous Wavelet Transform [24]) returns the continuous wavelet transform of a time signal [25]. The CWT is obtained by using the analytic Morse wavelet with the symmetry parameter, gamma (γ), equal to 3 and the time-bandwidth product equal to 60 [25]. The CWT is superior to the Short-time Fourier transform (STFT) for signals in which the instantaneous frequency experiences either a fast growth or decline [26].

Figure 19 shows an example of a reference signal that keeps its phase all along the timeframe shown in this figure. The signal designated as faulty is a departure from the reference signal by just a phase change beginning at time 13 s. Applying CWT to the faulty signal utilizing the analytic Morlet wavelet, the transient of the faulty signal is easily captured by the sudden rise in the magnitude of CWT coefficients (Figure 20).

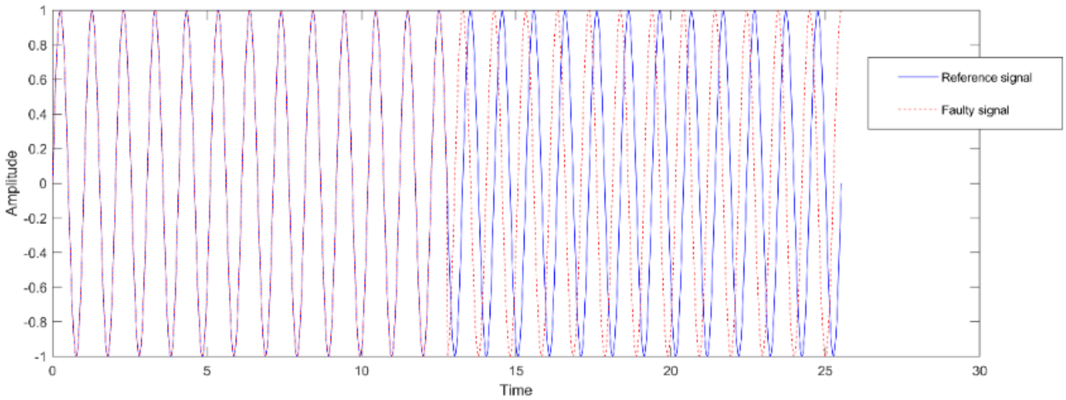


Figure 19: Example of a fault impacting a time signal

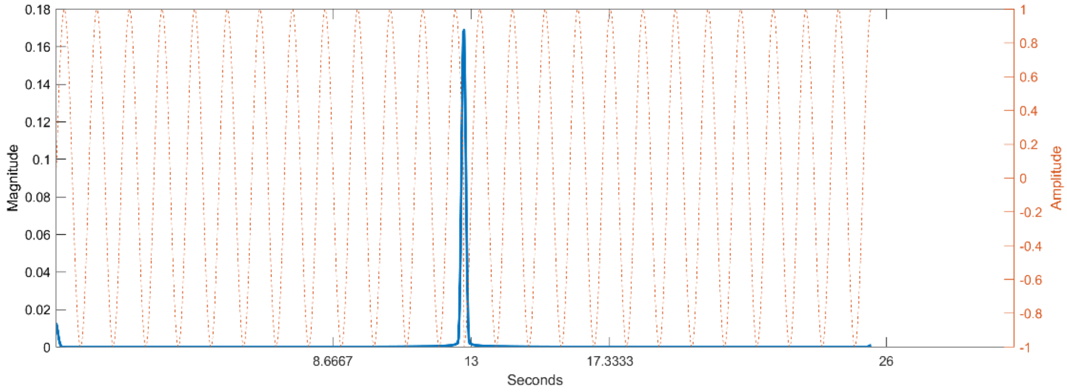


Figure 20: Finest-scale CWT coefficients

The CWT tiling of the plane is useful because many real-world signals have slowly oscillating content that occurs on long scales, while high-frequency events tend to be abrupt or transient. However, if it were natural for high-frequency events to be long in duration, the use of the CWT would then not be appropriate. The result is a poorer frequency resolution without gaining any time resolution. The human auditory system works this way because it provides much better frequency localization at lower frequencies and better time localization at high frequencies.

The MATLAB® command *wcoherence* returns the magnitude-squared wavelet coherence, which is a measure of the correlation between signals *x* and *y* in the time-frequency plane [27]. Wavelet coherence is useful for analyzing nonstationary signals. By using this command inputting the reference and faulty signals shown in Figure 19, the image in Figure 21 properly detects the phase change of the faulty signal relative to the reference one. The vectors change is a measure of the phase difference between the input signals (90º).

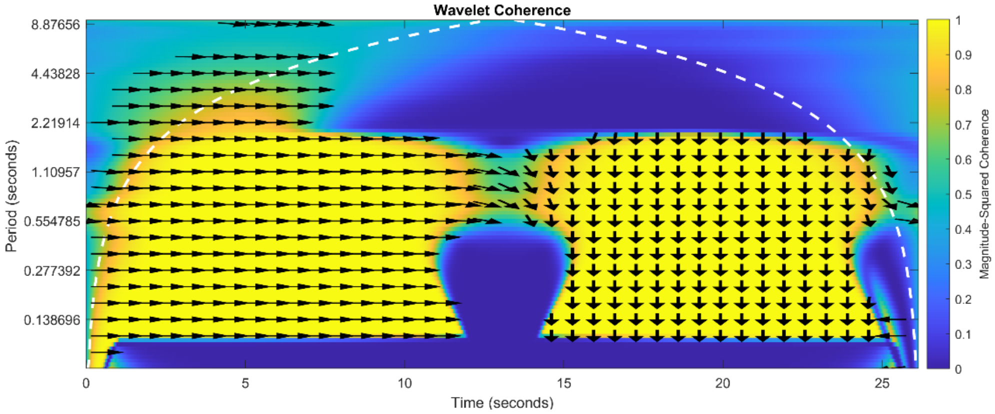


Figure 21: Wavelet coherence

Another example to demonstrate the capacity of wavelet analysis concerns the Earth's climate. Ice cores provide evidence for greenhouse gas concentration variations over the past 800,000 years. Both CO_2 and CH_4 vary between glacial and interglacial phases, and concentrations of these gases correlate strongly with temperature [28] [29] [30]. Figure 22 shows a data compilation of CO_2 concentration and temperature for the last 340 thousand years starting in the year 1870. The high correlation between the two variables is easy to observe. Higher temperatures due to higher CO_2 concentration lead to plant and algae proliferation, which, in turn, will absorb the carbon dioxide triggering a temperature drop in a second phase.

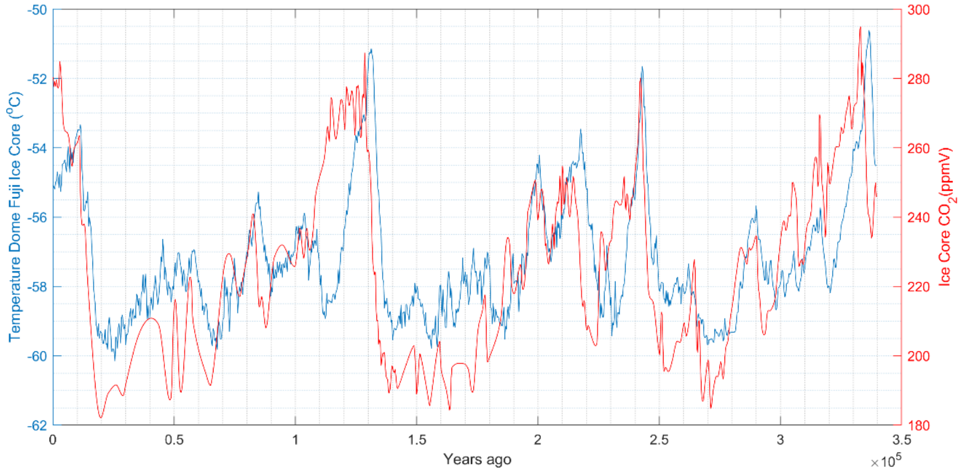


Figure 22: Ice core data indicate a strong correlation between temperature and CO_2 concentration [28] [29] [30]

The wavelet coherence and cross-spectrum showed in Figure 23 reveal a strong correlation along the time of the collected data for the periods ranging from 67 to 84 thousand years. This range encompasses three times the precession period of the rotation axis of the Earth. However, this correlation is not within the area delimited by the white circle and therefore it must be discharged. There is another high correlation coefficient revealed in Figure 23, for a period ranging from 16 to 33 thousand years with a time lag between the parameters. This fact should be taken into consideration, as it fits well with the precession period of the Earth's rotation axis of 26,000 years.

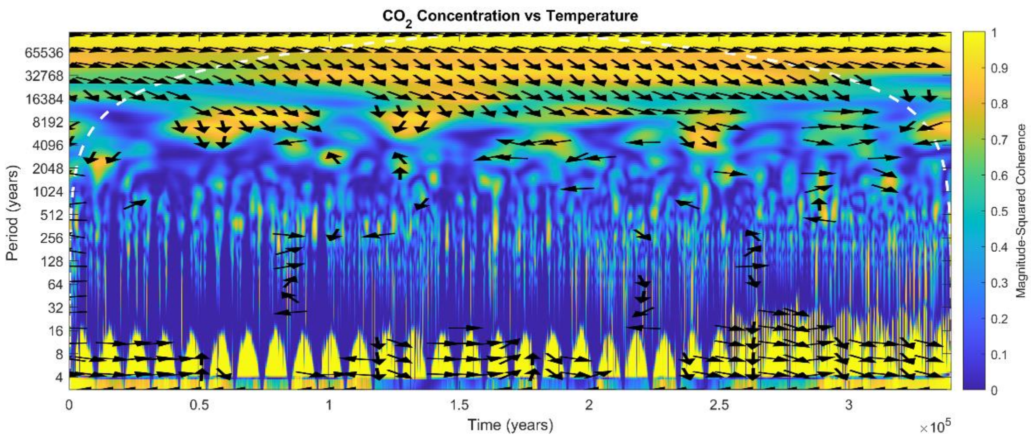


Figure 23: Wavelet coherence and cross-spectrum of CO_2 concentration and temperature data

Around the period of 10,000 years, some correlation is also tracked. This can be explained by a quick analysis of the graphs in Figure 22, as it reveals that the CO_2 concentration rise on some occasions is accompanied by the temperature surge with a delay of approximately 10,000 years.

Any time-frequency transform that uses filters, like wavelets in the case of the CWT, or modulated windows in the case of the short-time Fourier transform, necessarily smears the picture of the signal in time and frequency. The uncertainty in the localization of the signal's energy in time and frequency comes from the spread of the filters in time and frequency. Synchrosqueezing is a technique that attempts to compensate for this smearing by "squeezing" the transform along the frequency axis [31].

4.2 M’ARMS system

The Modular Aircraft Recording and Monitoring System (M’ARMS) is a sophisticated system that encompasses a HUMS subsystem.

The main objectives for the development of the M’ARMS were [32]:

1. Satisfy JAR OPS3’s compliances relative to flight data parameters
2. Automation of flights and their analysis
3. Provide a maintenance report and optimize help for maintenance
4. Deliver a diagnostic for the main mechanical “critical parts”.

The M’ARMS system is comprised basically of three subsystems:

1. HUMS
2. CVFDR (Cockpit Voice and Flight Data Recorder)
3. UMS

Functions of UMS and usage

- Monitoring Counters associated with helicopter components to inform maintenance about time reached and alarms displayed in flight
- Counting about Time in operation, counting flying time, counting landings, counting NR cycles, counting engines cycles N1(NG) et N2 (NF).

The main purpose is to monitor any exceedance of the usage threshold to:

1. Generate overshooting message in case of overshooting with the flight manual.
2. TQ1+TQ2 for Overtorque detection (damaging on MGB),
3. Engines exceedances (limitation on these 3 modes T4, NG, NF)
4. NR exceedance NR max (MRP damaging)

Engine Power checks basic functions on EC 225 will be done from VMS. M’ARMS system will record data for trend following. All these functions will be automatically linked with the operator after downloading data in the flight report. They will be saved inside GSC.

Reference [33] brings more details and information on fault diagnosis in helicopter HUMS, on some commercial solutions for HUMS, and specifically on the M’ARMS.

4.3 Description of the M'ARMS evolution: onboard MOD45 indicator.

A M'ARMS improvement enabled the HUMS systems on the EC225 and EC725 to indicate the cabin of a parameter during the flight. This is the first time that the HUMS system in a EUROCOPTER aircraft was used to control the condition of a specific component during flight. The certification of such usage was a technological step forward regarding the application of the HUMS [34]. Up to this milestone, the HUMS on helicopters has only been employed to provide maintenance crew with additional data to evaluate a possible degradation of the performance of different dynamic components, on the ground. Based on the scalar level of an indicator, the maintenance crew shall take actions to prevent an in-flight component failure. Thus way, the HUMS is considered a maintenance support tool, capable of monitoring and recording the usage and condition of different dynamic components. It mainly affects aircraft availability by providing a "no go." Thanks to this evolution, the M'ARMS system is now being used to improve the aircraft rate of dispatch.

The M'ARMS evolution described previously is presented in the Alert Service Bulletin No.EC725–45A008 and corresponds to mainly modifications 0726978 and 0726994. Its application is mandatory and is part of several improvements to the EC225/EC725 aircraft family following technical incidents that took place in 2012 [34].

Modification 0726994 installed two HUMS indicator lights on the instrument panel, which indicate the OM45 status for the pilot and copilot (Figure 24), while modification 0726978 consists of all the software and configuration updates to be performed. The application software version that was installed in the ACMS MFDAU++ at that time is version 1.6 and requires specific configuration files.

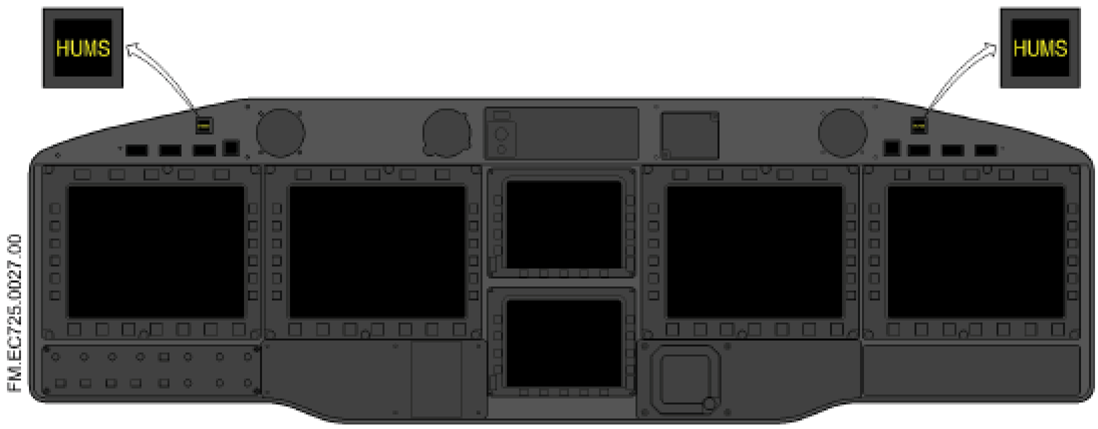


Figure 24: New "HUMS" indicator lights on the instrument panel, as presented in the EC 725 AP Flight Manual SUP 7 [34]

It is important to notice that the ACMS MFDAU++ software version 1.6 is compatible with a limited combination of software and configuration files on the FDRS MFDAU++ card and the VPU (Vibration Processing Unit). The Information Notice 2100-I-45 provides all the information necessary to define the applicable combination for each aircraft configuration. The Alert Service Bulletin also presents additional maintenance aspects related to the M'ARMS modifications, as well as updated Technical Publication material.

The continuous monitoring of the OM45 is only executed in flight. During aircraft power-up, the system starts the power-on built-in test (Pbit), to assess its proper functioning. From the moment the aircraft is energized to the moment the Pbit has successfully been performed, the HUMS indicator lights on the instrument panel and in the M'ARMS control panel will be lighted (Figure 25). When the message "TEST MOD45 DONE" is presented in the M'ARMS control panel, all the HUMS indicator lights are shut off.

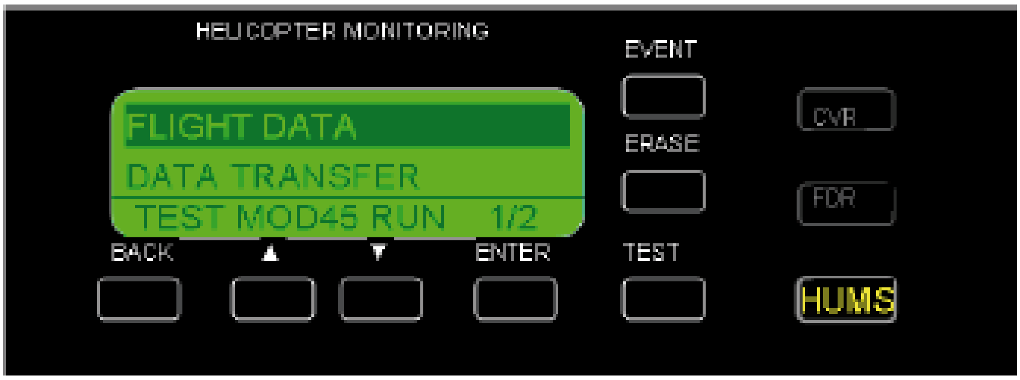


Figure 25: M'ARMS control panel, as presented in the EC 725 AP Flight Manual SUP 7 [34]

When airborne, the message "MOD45 RUNNING" is displayed when the indicator OM45 is being monitored. This happens approximately every five minutes when the aircraft is inside the monitoring flight envelope: indicated airspeed higher than 60 knots and torque over 60%.

In the event of OM45 acquisition exceeding the maximum threshold (0.5 grms), the message "MOD45 EXCEED" is displayed and the HUMS indicators lights light up. In this case, the maximum continuous torque is limited to 65% and in level flight must remain above 60 knots IAS. The maximum flight time in MOD45 exceed is limited to two hours.

Another possible situation is the failure of the in-flight OM45 monitoring. In that case, the airspeed must remain between 60 and 120 knots IAS (Indicated Airspeed), while torque is above 60% of maximum continuous torque.

4.4 System Errors (Signal/Electrical Errors): Case Study and Proposed Error Indicators

A- Introduction

In certain situations, the vibration signature obtained from a particular accelerometer may not represent a mechanical problem, but an error in the acquisition system itself, which may have appeared due to some type of signal failure such as an electrical problem in the acquisition system, problems in the sensors, problems in the signal processing, etc. In this Section, this type of problem is referred to as a “system error.”

The objectives of the present Subsection are:

1. Extract lessons from a case study: to investigate different real cases in which a possible system error may have appeared, and to present the typical characteristics of this signal, in terms of values and plots of the different functions of interest that may be evaluated from the signal data
2. Error indicators: to propose possible error indicators and study these different error indicators regarding:
    - their ability to point out correctly the situations in which the system error is present; and
    - Their robustness to variations in the signal properties coming from other error sources, such as mechanical failures (i.e., their ability to present low false alarm rates).

Several sets of vibration data were made available for study, as shown on Table 2.

Table 2: sets of vibration data

Helicopter model	Accelerometer name / position	Number of acquisitions	Total Flight Hours
Helicopter # 1	MGB LH first reduction pinion	208	291,5
Helicopter # 2	MGB Bevel Shaft and Wheels #6	5263	3514,9
Helicopter # 2	MGB Bevel Shaft and Wheels #6	4528	3555,2
Helicopter # 2	MGB Bevel Shaft and Wheels #6	12169	6499,8

The vibration data refers to the bevel wheel and shaft, a vertical shaft rotating at 2401 rpm, with an upper bevel wheel of 45 teeth and a lower oil pump wheel of 70 teeth, as shown in Figure 26, adapted from Reference [1]. The vibration data refers to accelerometer Nº 17 (11RK8), with synchronization at 2405 rpm, according to Reference [2].

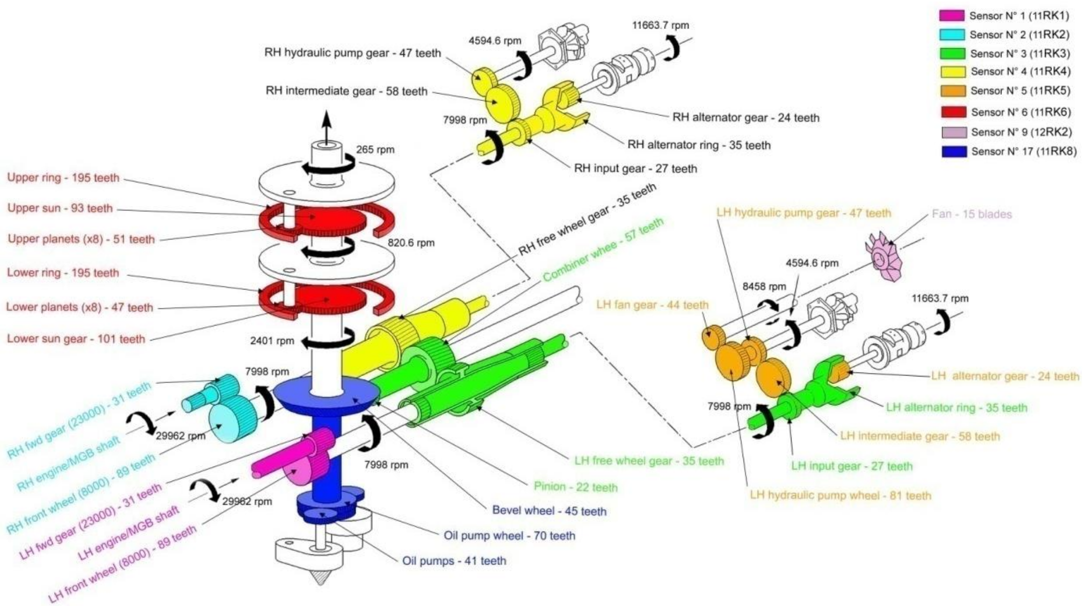


Figure 26: MGB Health monitoring and related sensors [33]

The vibration data available is processed data, obtained after a synchronous averaging procedure on the raw vibration data. This procedure is shown in Figure 27, adapted from Reference [35]. The objective of the synchronous averaging procedure is just to eliminate random vibration, keeping the periodic components which are multiples of the shaft rotation speed. For example, each revolution may be sampled generating 1024 points. After N samplings, an average of the N values is evaluated for each sampling point, generating a plot for the 1024 points of the signal average.

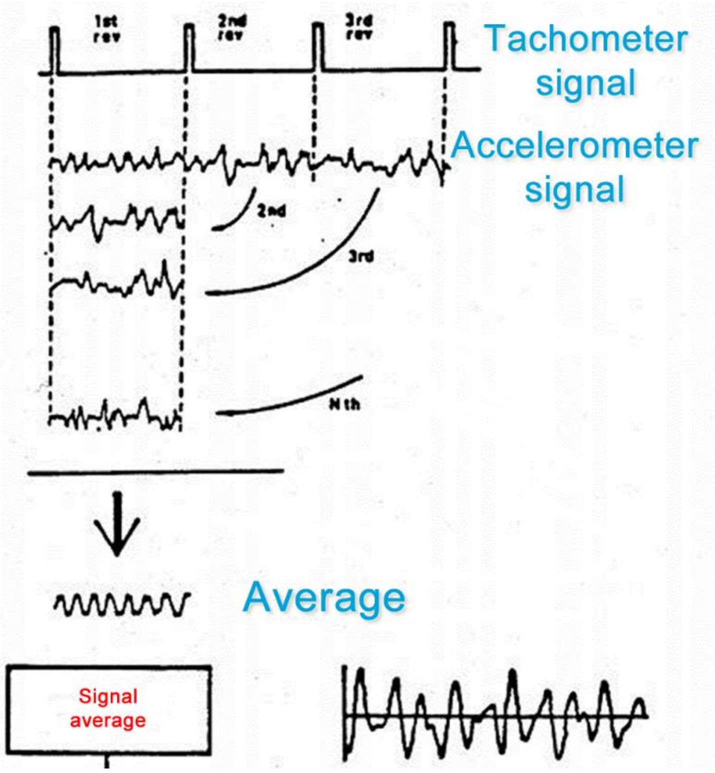


Figure 27: Signal treatment: synchronous averaging for eliminating random vibration [35]

For the averaged signal, a root-mean-square (RMS) indicator is evaluated. The value of RMS represents the total energy of the signal. Typically, most faults involving damage will increase the energy of the vibration signal. The RMS indicator can be evaluated as the area below the curve of the signal, either in the time domain or in the frequency domain. Figure 28 (adapted from Reference [1]) shows a plot of the signal in the frequency domain (obtained applying a Fast Fourier Transform (FFT) on the original signal in the time domain). The energy of the signal (the RMS value) is related to the area below the plotted curve.

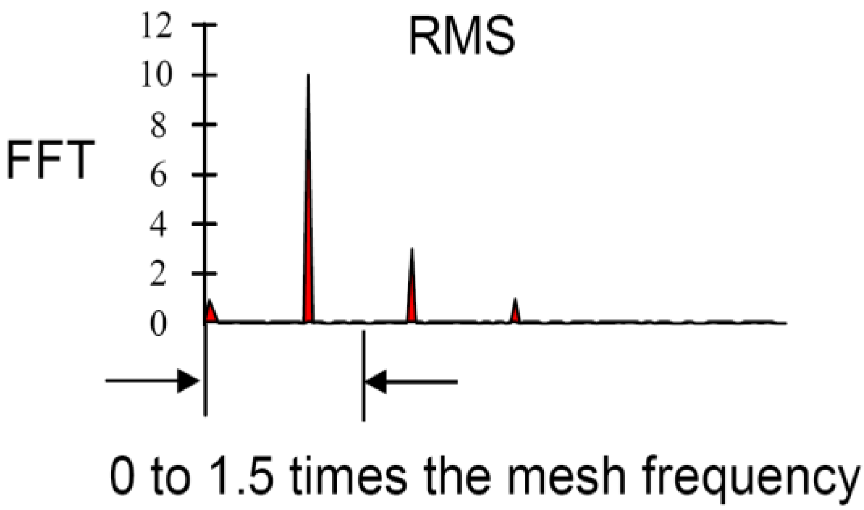


Figure 28: RMS value of the signal: area below the curve [35]

A plot of all the RMS values, for the 12169 cases available in the data described in Table 2, for the vibration of the bevel wheel and shaft, is shown in Figure 29.

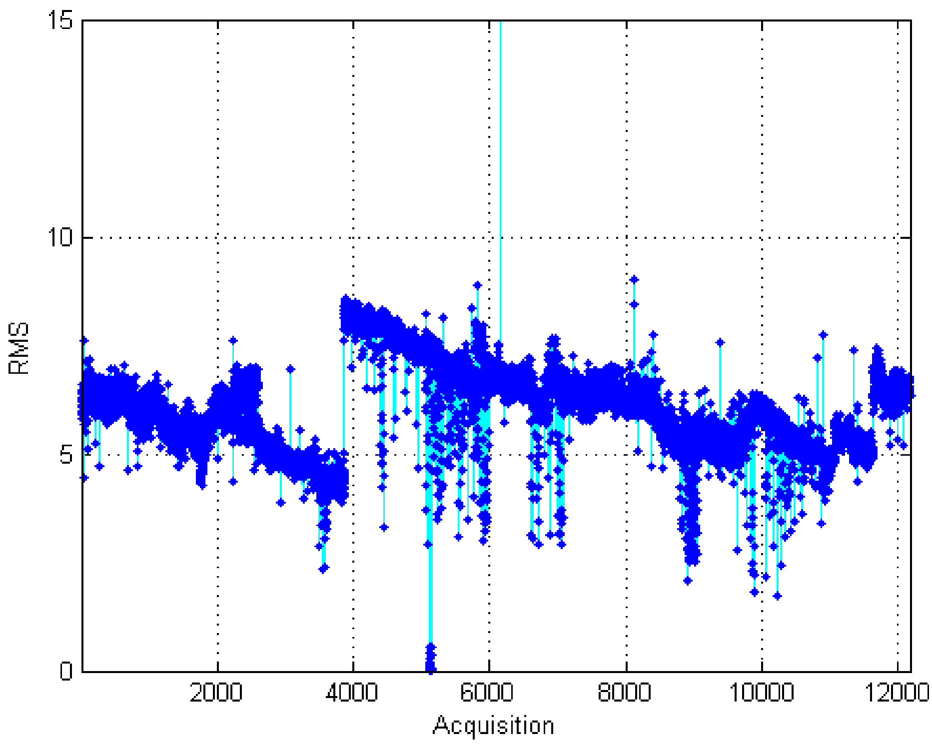


Figure 29: Bevel wheel & shaft RMS vibration (Helicopter # 2) [21]

From Figure 29, one can see two different cases:

1. The case in which the energy of the signal was high (thus, an alarm was triggered). In this case, with this RMS indicator only, if the energy of the signal is physically reasonable, no conclusion could be made whether the problem is of mechanical origin or system origin. Only when the energy of the signal is too high (which would be physically impossible) then one could infer that the defect was due to a system failure.
2. The case in which the energy of the system was too low (thus, no alarm was triggered). The system should be still vibrating, and it's not possible to have such a low level of energy, leading to the conclusion that there must be some type of system failure.

The RMS values for the vibration of the other aircraft described in Table 2 are plotted in Figure 30 to Figure 32.

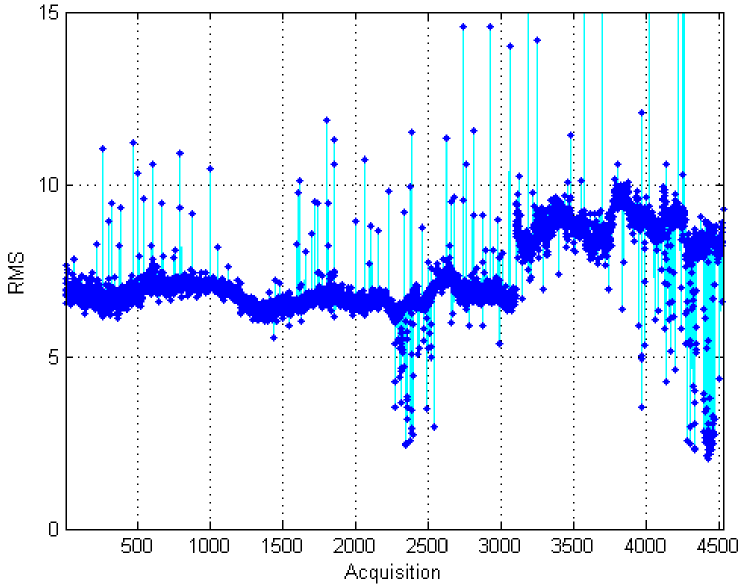


Figure 30: Bevel wheel & shaft RMS vibration (Helicopter # 2) [21]

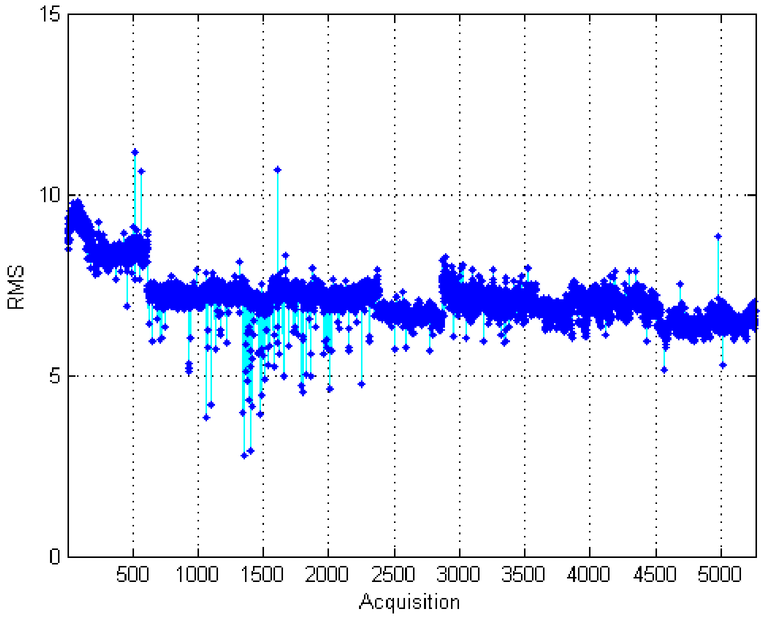


Figure 31: Bevel wheel & shaft RMS vibration (Helicopter # 2) [21]

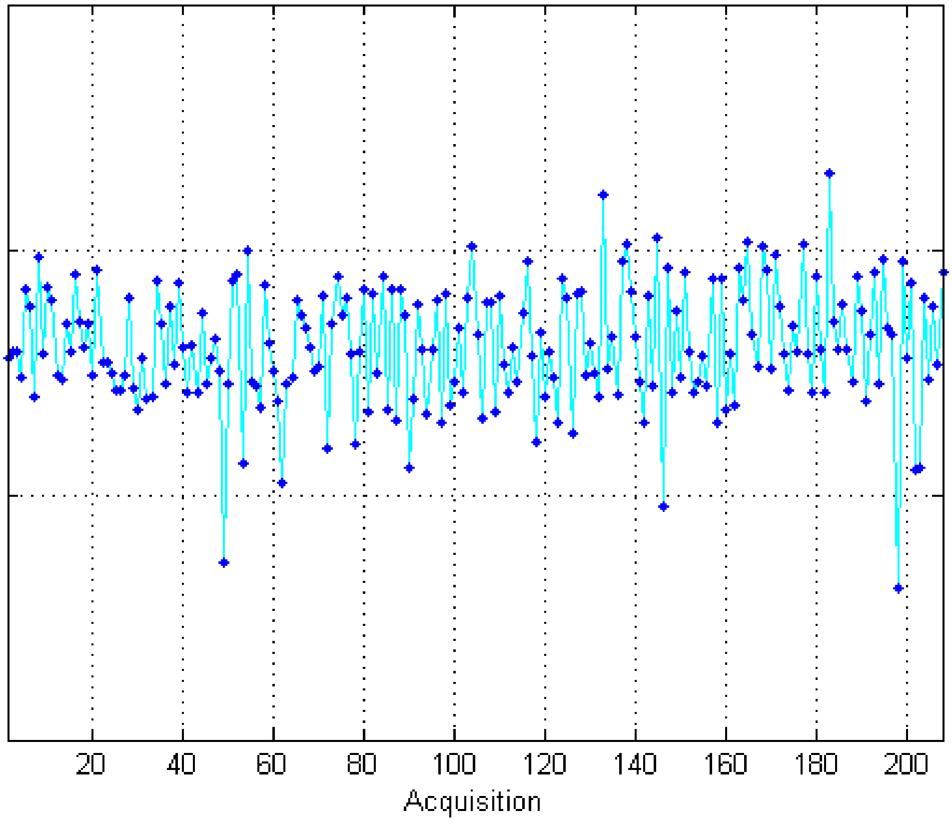


Figure 32: MGB LH first reduction pinion RMS vibration (Helicopter # 1) [21]

B- Signal analysis: parameters and characteristics of interest from the signal data

In this Subsection, a signal treatment is proposed, using correlation functions and phase diagrams, and error indicators are proposed, to capture the characteristics of a typical signal with system failure, trying to separate this case from the case of the signal that would come from mechanical failures.

Autocorrelation of signal x: $R_{xx}(t)$

Goal: To present a cleaner plot (of R_{xx} versus t), in which noise was filtered (comparing to the original signal), keeping the periodic characteristics of the original signal.

For a continuous case, the cross-correlation function is defined in Eq. (3) as

$$R_{xx}(\tau) = \lim_{T\to\infty} \frac{1}{T} \int_{-T/2}^{+T/2} x(t)x(t+\tau)dt \qquad (3)$$

where τ is a parameter related to time.

For the cases being discussed, the available signals are presented in a discrete form, where N points are available, and the discrete cross-correlation function is given in Eq. (4) as

$$R_{xx}(k) = \frac{1}{N+1-k} \sum_{i=0}^{N-k} x_i x_{i+k} \qquad (4)$$

where k is a time lag, and the sequence will have $(N+1-k)$ terms.

Cross-correlation between signal *x* and *y*: R_{xy} *(t)*

Goal: like Subsection A, to present a cleaner plot (of R_{xy} versus *t*), in which noise was filtered (comparing to the original signal), keeping the periodic characteristics of the original signal. In this case, the coherence between the periodic characteristics of the original signal x and the new signal *y* is enhanced. Thus, if signal y preserves the same periodic content as signal *x*, the correlation plots of R_{xx} and R_{xy} are expected to coincide. On the other hand, if signal y has different periodic content than *x*, the amplitude of the cross-correlation R_{xy} is expected to be small for all time t (the same behavior for R_{xy} is expected if y presents no periodic content at all, such as in the case of random signal). For a continuous case, the cross-correlation function is defined in Eq. (5) as

$$R_{xy}(\tau) = \lim_{T\to\infty} \frac{1}{T} \int_{-T/2}^{+T/2} x(t)y(t+\tau)dt \tag{5}$$

where τ is a time parameter.

For the cases being discussed, the available signals are presented in a discrete form, where *N* points are available, and the discrete cross-correlation function is given in Eq. (6) as

$$R_{xy}(k) = \frac{1}{N+1-k} \sum_{i=0}^{N-k} x_i y_{i+k} \tag{6}$$

where *k* is a time lag, and the sequence will have *(N+1-k)* terms.

Phase diagram for the correlation R: plot of *dR/dt* versus *R*

Goal: this diagram presents:

- a clearly defined plot of a smooth curve, for the case of the correlation function of a periodic signal;
- similar (almost identical) plots for the phase diagrams of the autocorrelation R_{xx} (of the reference signal) and the cross-correlation R_{xy} (between the current signal - at some time later - and the reference signal) if the periodic components of the signal have not changed between the two cases. In this case, the signal preserves the same amplitude and phase for all its spectral components; and
- a cloud of points for the cases of the autocorrelation function of a random signal x and the lack of coherence between two signals x and y (signals x and y having different periodic content).

Hypothesis for the typical response expected from system error

The signal *y* is expected to change its behavior concerning the original signal *x*, for a system without error. Thus, if this hypothesis holds:

- the amplitude of the cross-correlation R_{xy} is expected to be small, and
- the phase diagram of dR_{xy}/dt versus R_{xy} is expected to present a cloud of points without clearly defined curves.

Simulated example

An example of the expected typical response for signal error was simulated, in which a periodic signal (with noise) was simulated, and the signal was modified as a non-periodic signal, with erratic steps. The original signal x and the error signal y were generated and analyzed. The results of this simulation are presented in Figure 33 to Figure 35.

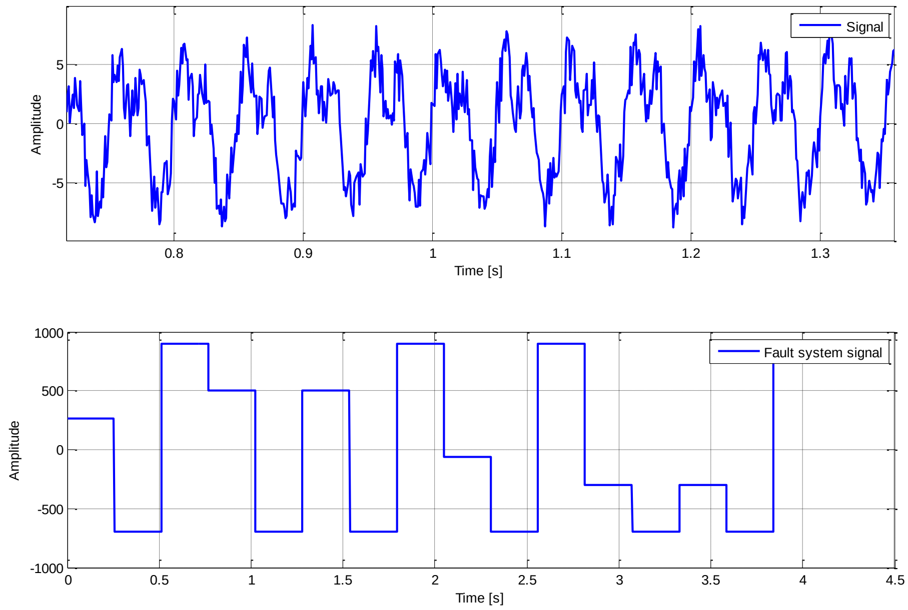


Figure 33: Plot of the original signals x and y [21]

From Figure 33, one can see that not much information can be obtained directly from the original signals, without processing.

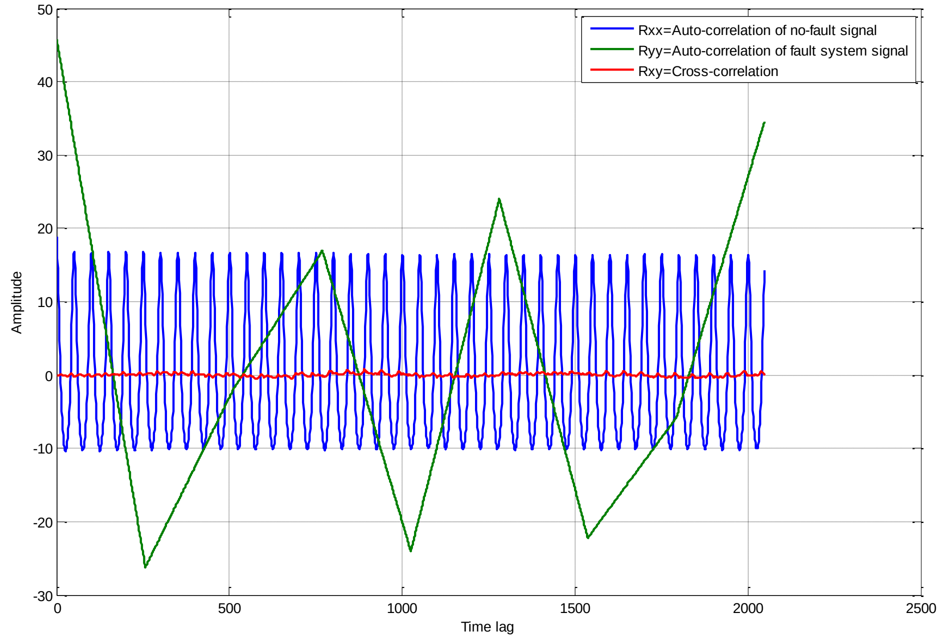


Figure 34: Plot of the correlations $R_{xx}(t)$ and $R_{xy}(t)$ [21]

From Figure 34, one can see the very low values of the cross-correlation coefficient, relative to the original autocorrelation, as expected.

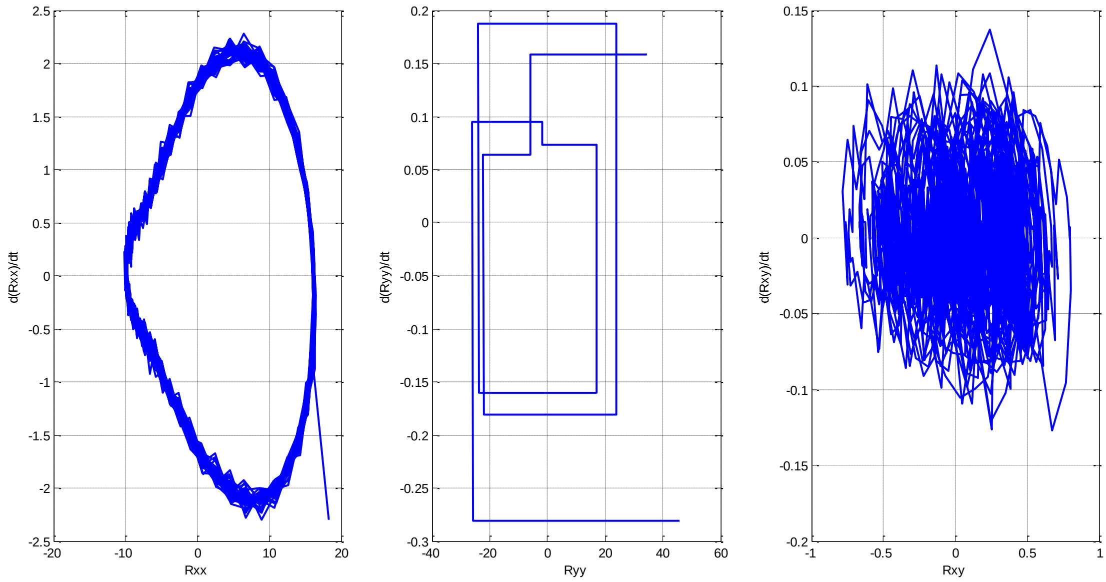


Figure 35: Plot of the phase diagrams of: a) dR_{xx}/dt versus R_{xx}, b) dR_{xy}/dt versus R_{xy}, and c) dR_{yy}/dt versus R_{yy} [21]

From Figure 35, one can see the neat curve plotted in the phase diagram of the original autocorrelation (case a), and the cloud characteristic present both in the cross-correlation plot (case b) and in the autocorrelation of the error signal (case c), as expected.

C- Cases studied

From the RMS data of aircraft Helicopter # 1 (Figure 32), one possible system failure was identified, described in Subsection C.1.

From the RMS data of aircraft Helicopter # 2 (Figure 29), several possible system failures were identified, described below in Subsections C.2 to C.5.

The available RMS data for aircraft Helicopter # 2 (Figure 30) and Helicopter # 2 (Figure 31) were not used in the discussion in Subsection C and will be used later for evaluation of the error indicators proposed in Section D.

C.1 Sampling errors: frequency sampling may be too low

This case refers to helicopter # 1, where the data (Figure 36), representing correlation functions of the signal, does not present clear periodic curves, which would be expected from the vibration of the helicopter mechanical component. The shape of the obtained curve suggests the presence of an error of conversion from the continuous signal to a discrete set of points (analog to digital conversion). This type of error typically is present when the sampling frequency is too low and does not follow Shannon’s theorem, which states that the sampling frequency must be at least two times higher than the highest frequency component present in the analog signal (Reference [4]).

In this case, all signals analyzed contain this problem, including the reference signal x, used to obtain the cross-correlation functions plotted in Figure 36.

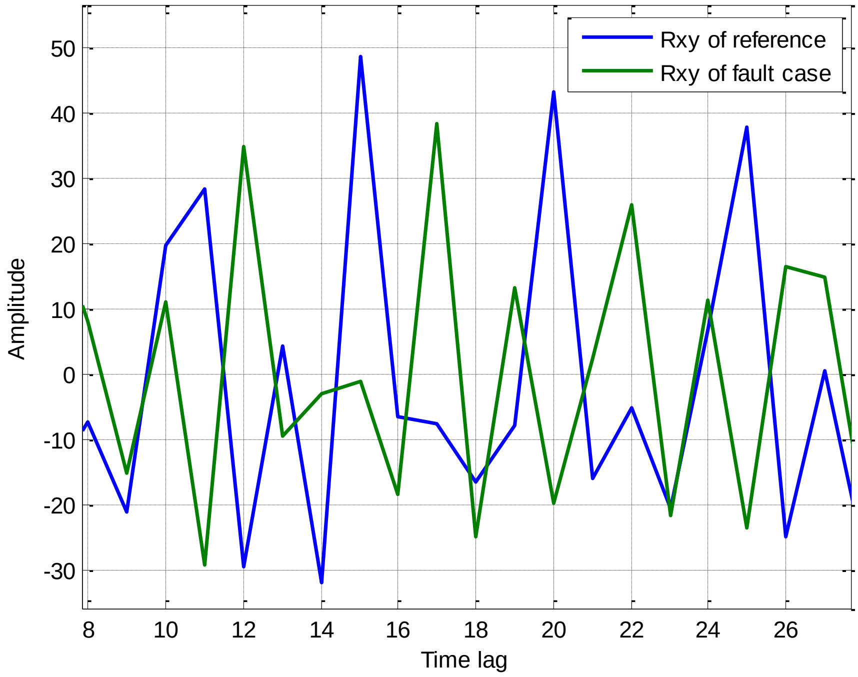


Figure 36: Correlation function for signals (Helicopter # 1) [21]

The phase diagram for this case (shown in Figure 37) indicates that the periodic components are not correctly represented, after the digitalization of the original signal. The hole in the plot shows that the lower frequencies are still well represented in the digital signal, but the cloud of points (around this hole) indicates that the high frequencies are not well represented in the digital signal. A good representation of the lowest frequencies combined with a poor representation of the highest frequencies corroborates the fact that there is a frequency sampling error in this data.

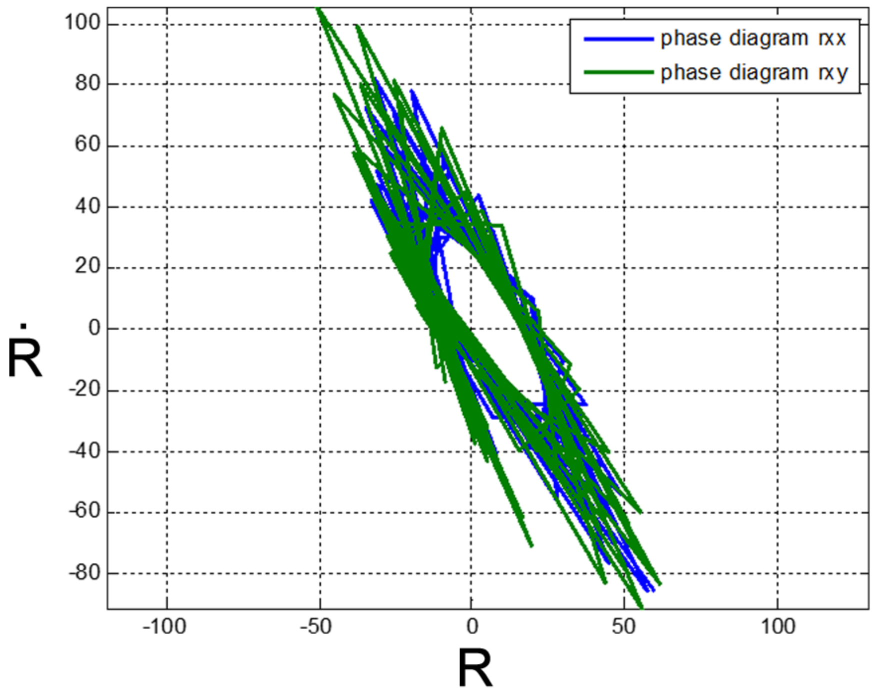


Figure 37: Phase diagram of correlations R_{xx} and R_{xy} (Helicopter # 1) [21]

C.2 – Signal with low gain errors: amplification gain may be close to zero

This case refers to Helicopter # 2. In Figure 29, some cases were identified as having a signal with a very low RMS value. Figure 38 and Figure 39 show a comparison between the reference case and one of these faulty cases. In Figure 38, the cross-correlation R_{xy} (between the faulty and the reference signal) is compared with the autocorrelation R_{xx} (of the reference signal).

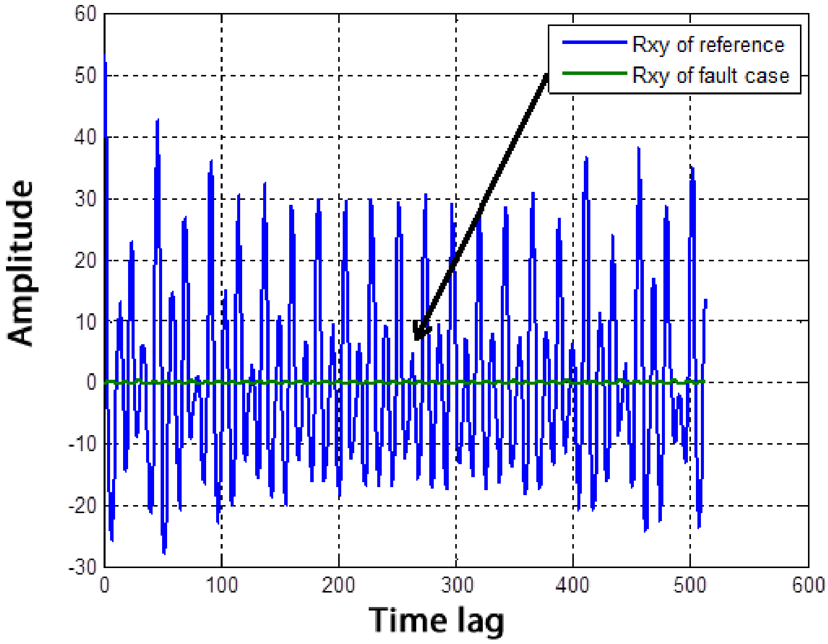


Figure 38: Correlation function for signals (Helicopter # 2) [21]

In Figure 39, the phase diagrams of R_{xy} (between the faulty and the reference signal) and R_{xx} (of the reference signal) are compared.

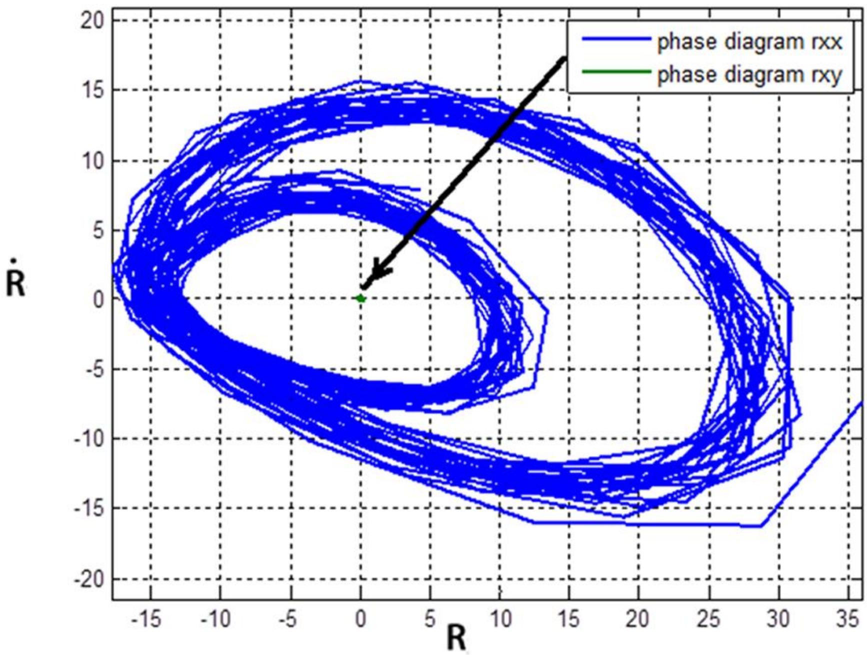


Figure 39: Phase diagram of correlations R_{xx} and R_{xy} (Helicopter # 2) [21]

The plot of the cross-correlation function presents a very small amplitude in Figure 38 and a very small size (almost like a point, as indicated by the arrow) in Figure 39. If the picture is enlarged, one can see that the format of the green plot, relative to the phase diagram of the cross-correlation function R_{xy}, is similar (almost identical in shape) to the phase diagram of the autocorrelation function of the reference signal, except for a scaling factor. A non-faulty signal should present a correlation function and phase diagram almost like their equivalent plots of the autocorrelation function R_{xx}, as mentioned before. Thus, Figure 38 and Figure 39 suggest that, in this case, there is no mechanical problem, but a system problem, probably due to a low amplification of the electric signal generated by the accelerometer. In this case, the signal *y(t)* preserves the periodic components of the reference signal *x(t)*, only with a much smaller amplitude.

Investigating the available data recorded and other registers in the HUMS helped to clarify some issues. In this case, the data in Figure 29 presented several acquisitions with very low RMS amplitude. The data for the period reveals a fault described as "NO SIGNAL RECORDED," and a maintenance action related to ATA Chapter 45 was required (Central Maintenance System - CMS). After this acquisition point, the RMS results were back to normal values, indicating that the maintenance action solved the issue.

C.3 – Signal with time delay errors: may be due to poor synchronous averaging

This case refers to Helicopter # 2. Figure 40 shows that the two plots (of the autocorrelation function R_{xx} and the cross-correlation function R_{xy}) are quite similar, but one plot has a time delay concerning the other.

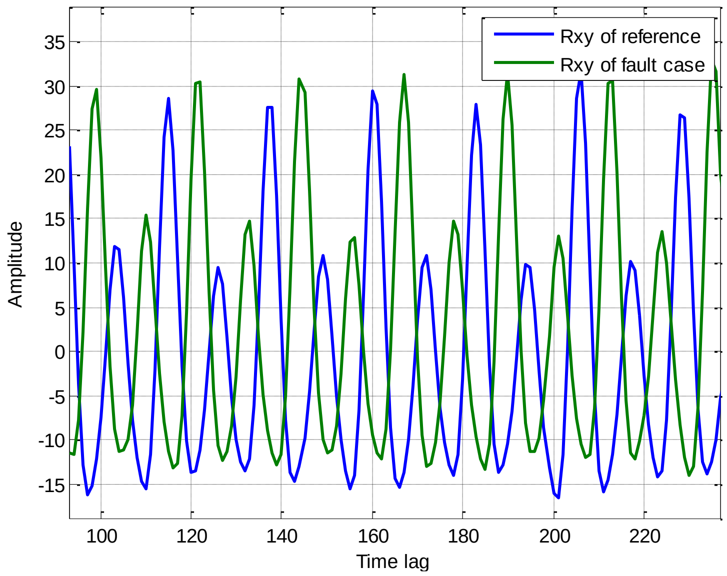


Figure 40: correlation function for signals (Helicopter # 2) [21]

This time difference in the correlation functions means that the starting time of the signal collection for the synchronous averaging process may be varying from one case to the other. If the starting points for the two cases were the same, the two plots should match, if there is no mechanical or system problem. By visual inspection, one can see that a shift of one curve on top to the other will give two curves very similar, which may indicate that there is no other problem with the aircraft component in the discussion, besides the difference in the starting point of the data collection for the two cases. Figure 41 shows the phase diagram of R_{xx} and R_{xy} for this case.

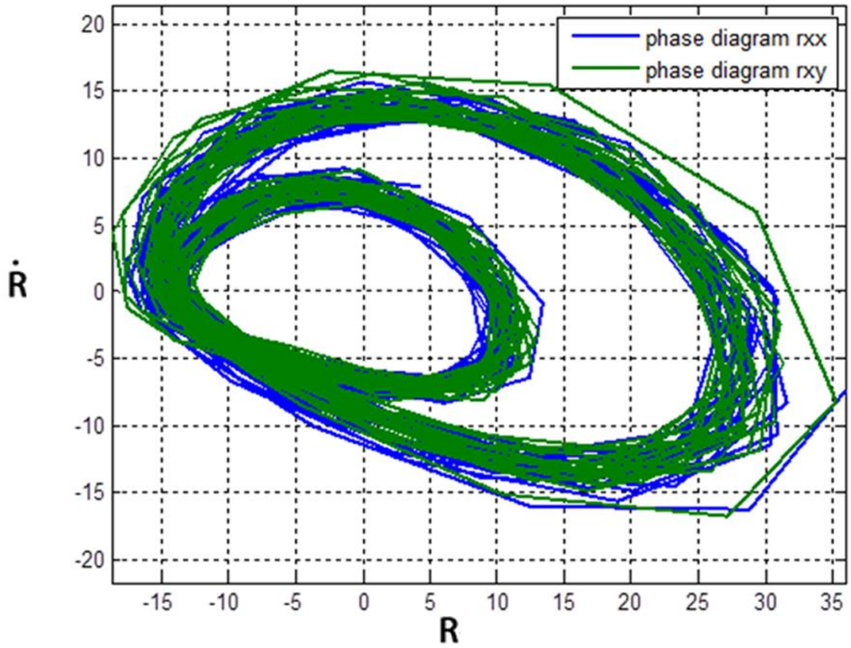


Figure 41: phase diagram of correlations R_{xx} and R_{xy} (Helicopter # 2) [21]

From Figure 41, one can note that the time difference, present in Figure 40, represents no significant difference in the phase diagrams of both correlation functions. This graph reveals that no physical difference exists between the two cases, except for the triggering time for the data collection, which can only be seen in Figure 41.

In this case, the acquisition is triggered by a magnetic captor located at the Phonic Wheel, giving a synchronization "top" to start and end the acquisition of the signal by the accelerometer.

According to maintenance staff, this problem does not represent a particularly critical problem, as it represents no mechanical or system failure. The only action that could be advised, in this case, would be to perform an inspection or maintenance procedure in the magnetic captor at the phonic wheel.

For this work, this type of problem might not be relevant to be captured or identified by the error indicators that would be proposed in Subsection D.

C. 4 – Signal high amplitude errors: signal amplitude may be too high, with peaks corresponding to a non-physical possibility (too much energy in the signal)

This case refers to Helicopter # 2. In Figure 29, some cases were identified as having a signal with a very high RMS value and having no physical significance. In this case, no physical system, when vibrating, will have such high energy, as compared to the energy of the reference case. Figure 42 and Figure 53 show a comparison between the reference case and one of these faulty cases. In Figure 42, the cross-correlation R_{xy} (between the faulty and the reference signal) is compared with the autocorrelation R_{xx} (of the reference signal).

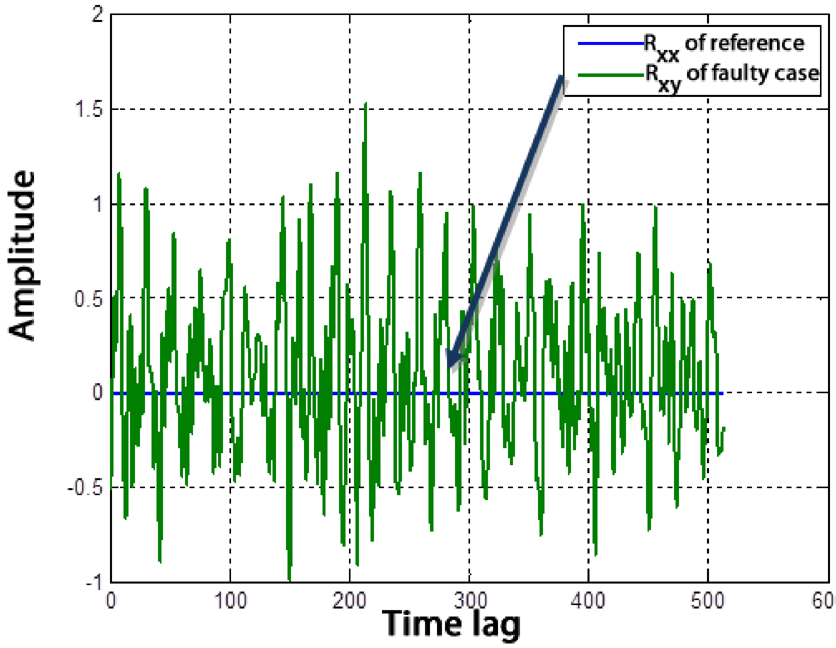


Figure 42: correlation functions for signals (Helicopter # 2) [21]

In Figure 43, the phase diagrams of R_{xy} (between the faulty and the reference signal) and R_{xx} (of the reference signal) are compared.

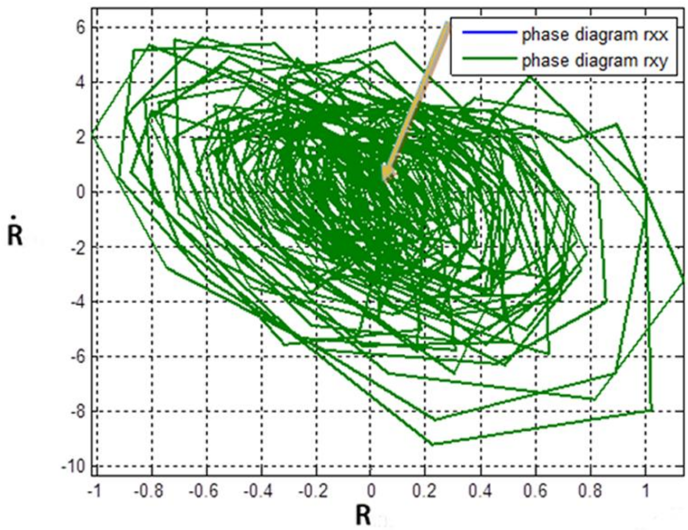


Figure 43: phase diagram of correlations R_{xx} and R_{xy} (Helicopter # 2) [21]

The plot of the autocorrelation function R_{xx} presents a very low amplitude (when compared to the cross-correlation function R_{xy}) in Figure 42 and a very small size (almost like a point, as indicated by the arrow) in Figure 43.

Differently from the low gain case seen in Subsection C.2, in this case, the signal y is random, as highlighted by the phase plot in the form of a cloud in Figure 43, for the cross-correlation function R_{xy}. The signal y does not preserve the periodic components of the reference signal x and has a very high amplitude.

Thus, Figure 42 and Figure 43 suggest that, in this case, there is no mechanical problem, but a system problem, probably due to the high amplification of a random signal generated by an error in the acquisition system.

C.5 – Signal with low amplitude and different periodic components

This case refers to Helicopter # 2 and concerns a case where a low RMS was noted, in Figure 29.

In Figure 44, one can see that the plot of the cross-correlation function R_{xy} presents lower amplitudes than the plot of the autocorrelation function R_{xx}. Also, different periodic components can be seen in the plot of the cross-correlation function R_{xy}, that were not present in the plot of the autocorrelation function R_{xx}.

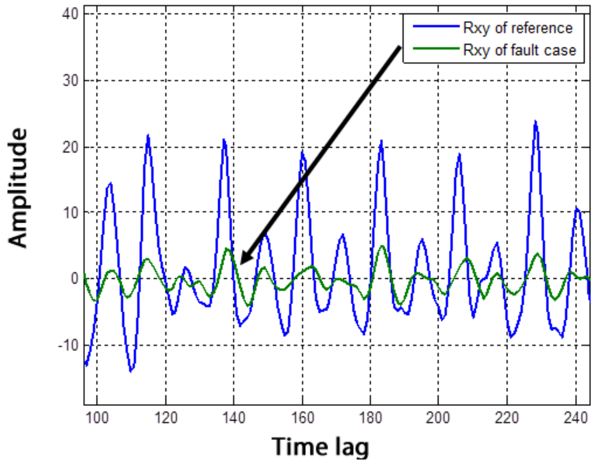


Figure 44: Correlation function for signals (Helicopter # 2) [21]

In Figure 45, the phase diagrams of R_{xy} (between the faulty and the reference signal) and R_{xx} (of the reference signal) are compared.

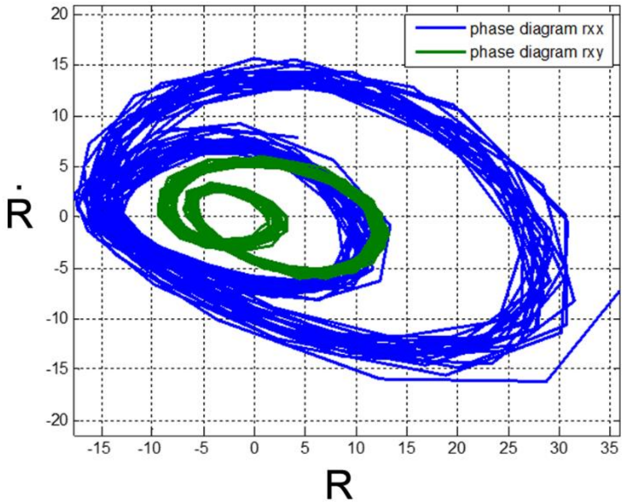


Figure 45: phase diagram of correlations R_{xx} and R_{xy} (Helicopter # 2) [21]

Figure 45 corroborates the fact that signal y has low energy (the size of the diagram is smaller, as both the amplitudes of R and dR/dt are lower for the cross-correlation R_{xy}, when compared to the autocorrelation R_{xx}). In addition, the change in the periodic components of the signal y is seen in Figure 45, as the shape of the phase diagram of R_{xy} has changed concerning the phase diagram of R_{xx}. The plot of the phase diagram of R_{xy} shows a clear change both in the correlation and phase and shows that y is not a random signal (as it has periodic components). Some of the periodic components of signal x are present in signal y, but signal y has additional periodic components, which were not seen in the reference signal x.

Figure 46 presents the correlation functions in the frequency domain, also indicating that the periodic components of signal x are still present in signal y (but with lower amplitude) and that a different component has appeared in signal y, at a high frequency (higher than the frequency components existing in signal x), which was not present in signal x.

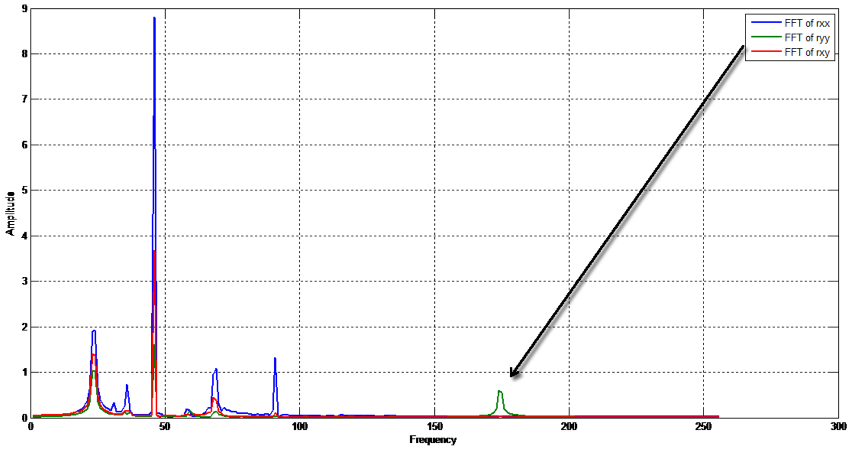


Figure 46: Correlation functions in the frequency domain (Helicopter # 2) [21]

The signal behavior seems to indicate both the possible presence of a system error (low amplitude of the cross-correlation R_{xy}, and different periodic components in signal y) and the possible presence of a mechanical problem (some periodic components of reference signal x are still present in signal y, although with a low amplitude). With the available information, no conclusion can be made regarding the origin of the defect being either a mechanical problem or a system error, or both.

According to maintenance staff, in this case, the RMS data in Figure 29 has not presented acquisitions with a clear problem. Instead, the problem for this case was only seen when analyzing the plots related to the data in the time domain, as seen in Figure 44 and Figure 45. No fault was detected in the period of interest, and no maintenance action was required to be performed, related to the component of interest or the acquisition system.

D – Proposed error indicator

D.1 – Indicator based on evaluating phase diagram plots of R_{xx} and R_{xy}

As described in Subsection C.3, the phase diagram for the correlation R is a plot of dR/dt versus R. A typical phase diagram for R_{xx} and R_{xy} is presented in Figure 47.

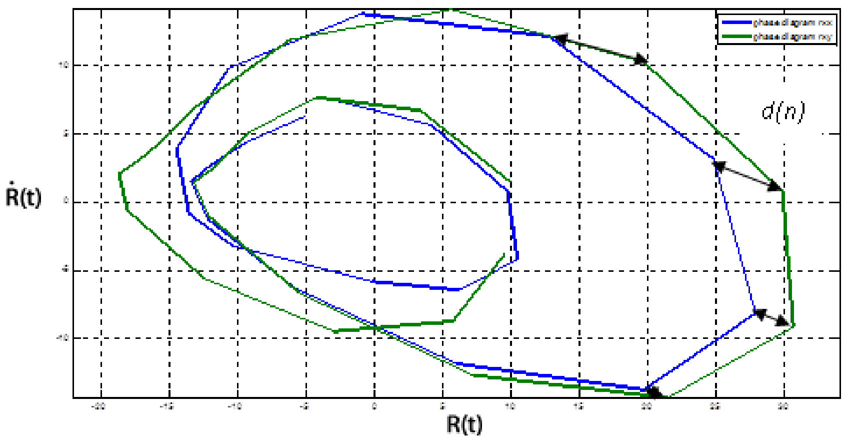


Figure 47: Phase diagram for R_{xx} and R_{xy} The arrows indicate the distances between points in the two plots for the same parameter n [21]

The proximity between the graphs is given by a point-by-point function *d(n),* which represents the distance between two points, one in the R_{xx} graph and the other in the R_{xy}, with the same parameter *n*. This distance is indicated by arrows in Figure 47. A residual case can be built as the summation of all distances *d(n)*, for all *n* points in the plot, as indicated in Equation (7).

$$D = \frac{1}{\boldsymbol{N}}\sum_{n=1}^{N} d(n) \quad , d(n) = \sqrt{[Rxx(n) - Rxy(n)]^2 + \left[R\dot{xx}(n) - Rx\dot{y}(n)\right]^2} \tag{7}$$

If the residual between the two curves is small, the autocorrelation R_{xx} and the cross-correlation R_{xy} are expected to represent a system with the same behavior, which means that both signal *x* and signal *y* would have practically the same periodic content, and thus signal *y* would not represent a system with errors (neither mechanical problem, nor system errors). On the contrary, if the residual is high, there are some causes:

i) The phase diagram of R_{xy} is very small in shape (when compared to the phase diagram of R_{xx}). This case may represent a random signal y with lower amplitude (phase diagram is a cloud, but is almost a point in the plot), or a periodic signal *y* with lower amplitude (phase diagram is a well-defined curve, but is almost a point in the plot);

ii) The phase diagram of R_{xy} has a shape of a cloud (with the same magnitude (general size) as the phase diagram of R_{xx}). This case may represent a random signal *y* with a certain amplitude (energy);

iii) The phase diagram of R_{xy} is very big in shape (when compared to the phase diagram of R_{xx}). This case may represent a random signal y with higher amplitude (phase diagram is a big cloud, and the phase diagram of R_{xx} is almost a point in the plot), or a periodic signal *y* with higher amplitude (phase diagram is a big, well-defined curve, and phase diagram of R_{xx} is almost a point in the plot);

In the above-described cases, a correlation is expected, between a change in the signal (from *x* to *y*, as in cases i, ii, and iii) and a high value of the residual. Thus, an error indicator may be defined by high values of this residual, while small values in the residual would not represent an error in the signal.

E – Numerical results for cases identified from given data

E.1 – Sampling errors: frequency sampling may be too low

Figure 48 shows the plot of the residuals of the correlations (R_{xx} and R_{xy}) in the phase diagram, for 208 cases of vibration data for Helicopter # 1. The plot of the residuals is given by the sum of the geometric distances between the pairs of points in the phase diagram, one given for the reference case, and the other for the faulty case, both for the same value of the time parameter. As seen in Figure 48, sampling errors were identified in this case, as the time plot presented a non-physical shape.

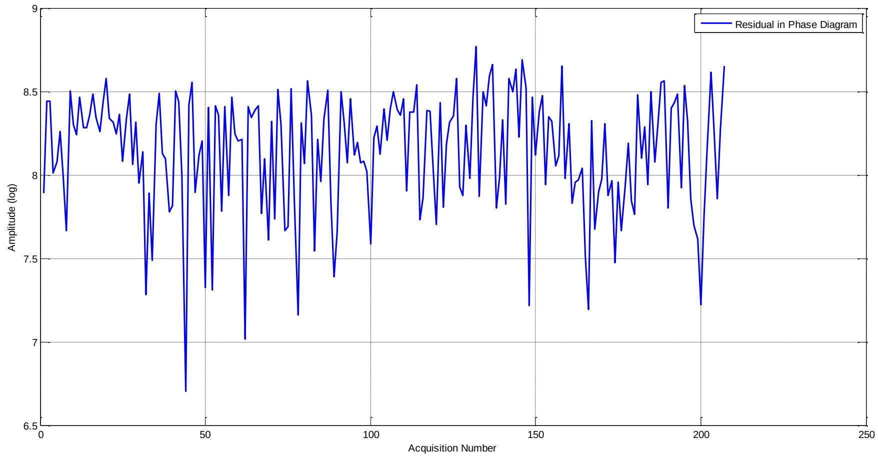


Figure 48: Residuals of distances in the phase diagram for vibration data with sampling errors [21]

In Figure 48, all acquisitions were poorly sampled (sampling frequency was not high enough, leading to errors in the analog-digital conversion), thus no clear information of possible system errors can be obtained from the residual in this case.

E.2 – Signal with low gain errors: amplification gain may be close to zero

Figure 49 shows the plot of the residuals of the phase diagram for the correlations (R_{xx} and R_{xy}), for 500 cases (out of the 12169 cases) of vibration data for Helicopter # 2, containing the case in which a signal with a very low amplitude was identified in Figure 3.4 (acquisition number 110, in Figure 49).

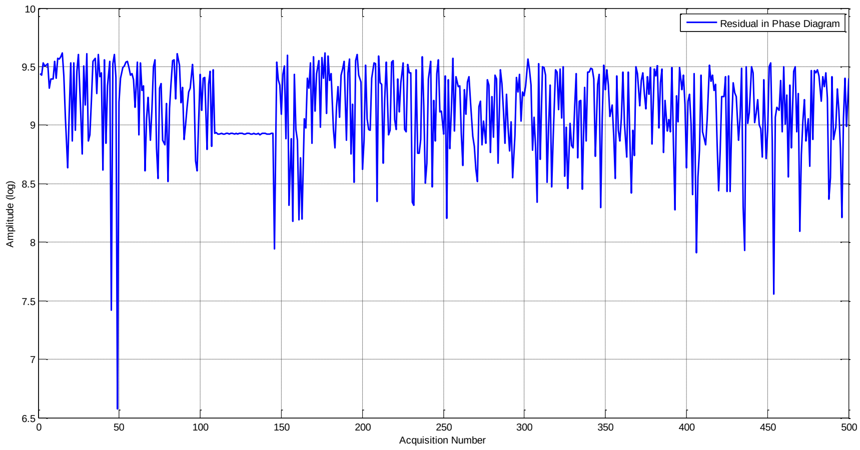


Figure 49: Residuals of in-phase diagram for vibration data with low amplitude errors [21]

In the discussion of cases 2 to 5, due to the high variation of the amplitudes of the residual, the vertical axis of the plot was set on a logarithmic scale, so all points (of high and low amplitudes) could fit in the plot.

The region where the signal has low amplification appears as a flat region in the plot (a "plateau", between acquisition numbers 110 to 145). One can see that the residual values in this region fit in the range of the residual values obtained in other regions, where no failure is envisaged. Thus, this indicator does not provide a clear indication of the failure region (in which signal amplification is low), as its value in this failure region remains inside the range of residual values typically obtained.

D.3 – Signal with time delay errors: may be due to poor synchronous averaging

Figure 50 shows the plot of the residuals of the phase diagram for the correlations (R_{xx} and R_{xy}), for 500 cases (out of the 12169 cases) of vibration data for Helicopter # 2, containing several cases in which a signal with a time delay (such as the one presented in Figure 5.3.1) was seen by inspection of the signals in the time domain. This case has appeared several times in the data analyzed.

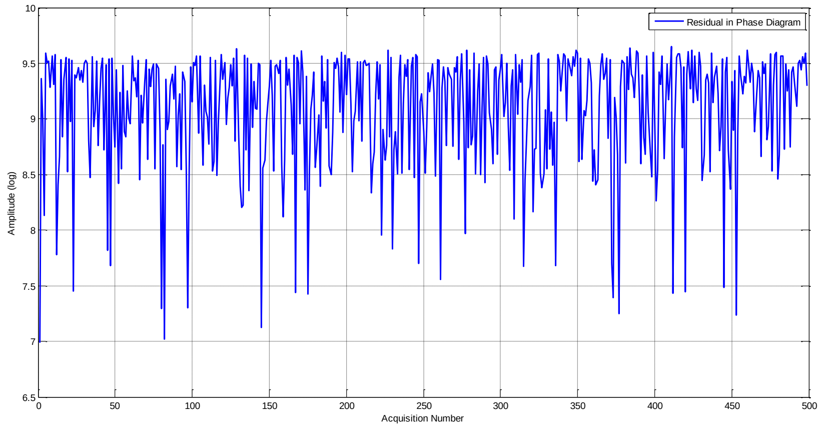


Figure 50: Residuals of in-phase diagram for vibration data with signal phase errors [21]

From expert information by the HUMS team, this problem does not represent a particularly critical problem, as it represents no mechanical or system failure, and typically no maintenance action is advised, in this case. For this case, the error indicator provided by this residual does not point to any region, and, thus, one can infer that this indicator is robust to this time delay error in the signal.

D. 4 – Signal high amplitude errors: signal amplitude may be too high, with peaks corresponding to a non-physical possibility (too much energy in the signal)

Figure 51 shows the plot of the residuals of the phase diagram for the correlations (R_{xx} and R_{xy}), for 500 cases (out of the 12169 cases) of vibration data for Helicopter # 2, containing the case in which a signal with a very high amplitude was identified in Figure 3.4. This case is represented in the plot of Figure 51 (acquisition case 155).

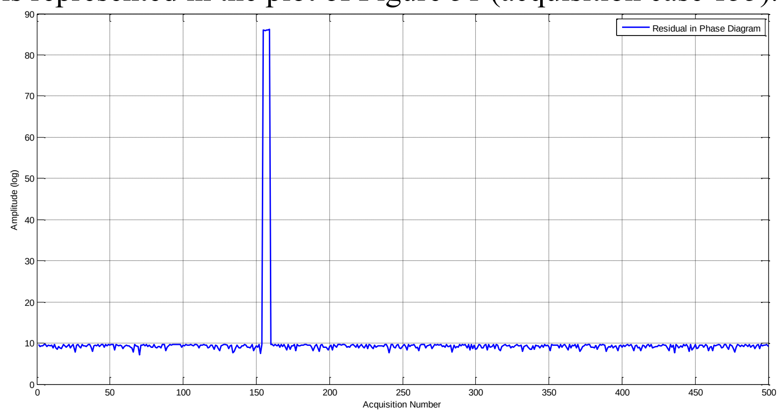


Figure 51: Residuals of in-phase diagram for vibration data with high amplitude errors [21]

The region where the signal has high amplification appears as a clear spike in the plot. Thus, the error indicator provided by this residual points out this type of system defect (in which signal amplification is high).

D.5 – Signal with low amplitude and different periodic components

Figure 52 shows the plot of the residuals of the phase diagram for the correlations (R_{xx} and R_{xy}), for 500 cases (out of the 12169 cases) of vibration data for the EC 225, containing one case in which a signal with low amplitude and different periodic components (such as the one presented in Figure 5.5.1) was seen by inspection of the signals in the time domain. This case is represented in the plot of Figure 51 as acquisition case 494.

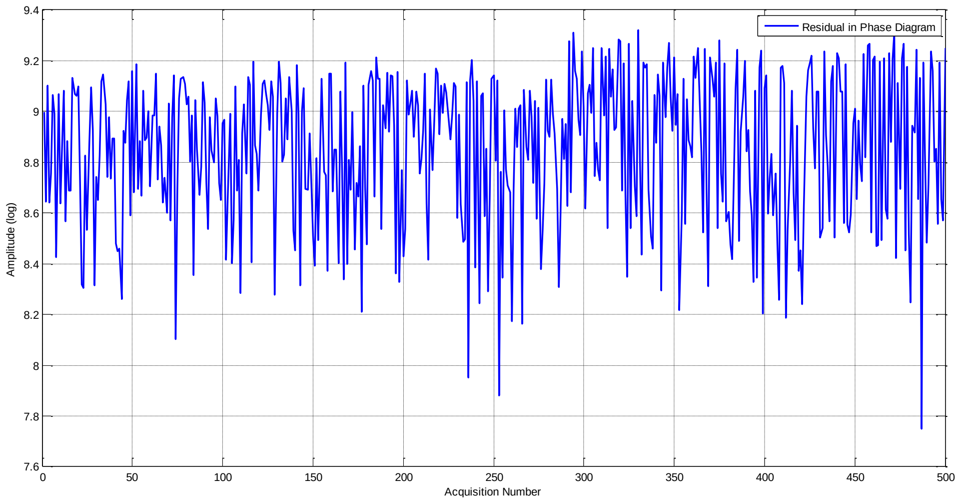


Figure 52: Residuals of in-phase diagram for vibration data with high signal noise errors [21]

From web HUMS information, no alarm was triggered at the time this acquisition was performed. For this case, the error indicator provided by this residual does not point to any region, and, thus, the indicator has not captured this type of system error.

5 Mechanical models for tail drive shaft

In this Section, the development of a mechanical model for helicopter tail drive shaft and Gaussian and Mixture Model algorithms are applied [36]. The phenomenon of the flexible coupling layer buckling is very complex, and it was analyzed using the software Abaqus®. The main objective was to check if the same opening between layers would be reproduced by the model. It is important to point out that this type of dynamic phenomenon may have an impact on the component life.

Statement of the problem

During a laboratory test, it was observed a buckling of the flexible coupling (Flectors) mounted on one side of the MGB shaft. A simplified diagram of the assembly is displayed in Figure 53.

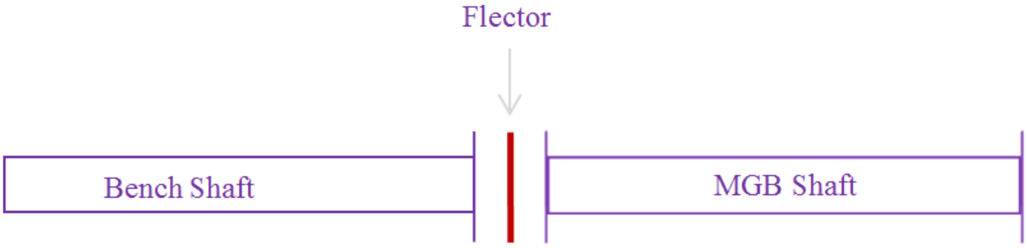


Figure 53: Schematic of assembly [36]

Since such a buckling would represent increased stress applied in the region, possibly anticipating fatigue damage, a study of the implication of misalignment and its relationship with the buckling phenomenon was performed.

It is assumed that the bench shaft bearing is rigid and the MGB shaft bearing is flexible. The main objective of the present analysis is to reproduce and explain buckling with radial and angular misalignment, as per Figure 54:

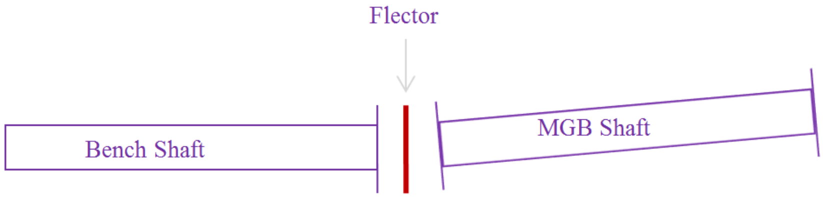


Figure 54: Misalignment modeling [36]

To properly verify the impact of such misalignment in the structure, a finite element model of the assembly was created on Abaqus®.

Finite element static model

A 3D finite element model was created to address the buckling issue [36]. The mesh was generated with Abaqus 6.12.1 [37]. The shafts are thin cylinders (4000 elements each shaft) and the Flector is modeled including layers (1900 elements each layer), bolds, and a washer (rigid link). Geometry and mesh are displayed in Figure 55.

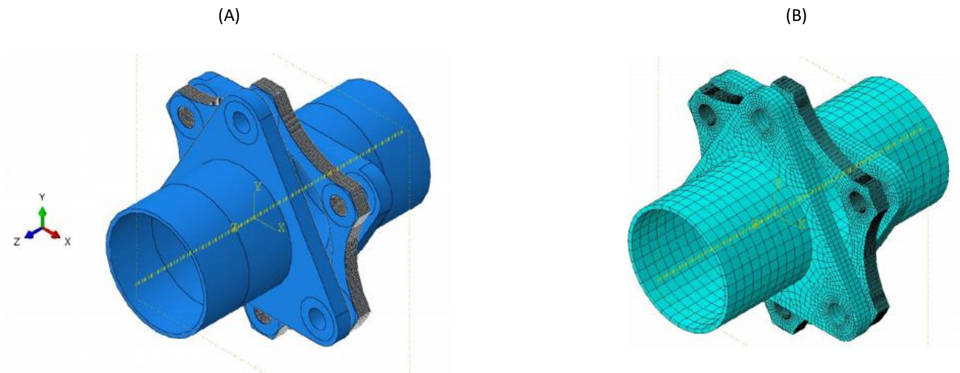


Figure 55: FEM model (A) Geometry (B) Mesh [36]

All degrees of freedom but the one related to axis rotation were set to zero on the left end of the shaft while a displacement was imposed on the other end as well as a torque equivalent to the one under which the structure is submitted when in operation, as displayed in Figure 56.

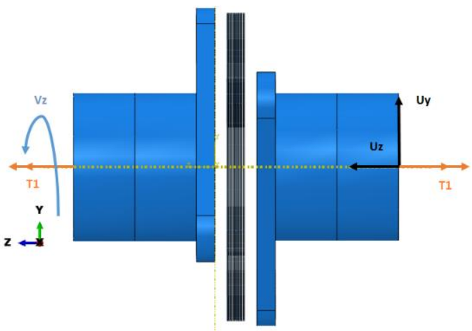


Figure 56: Boundary conditions and Loads applied [36]

The total displacement was set to obtain an angle of misalignment of 1°, for the shaft by determining U_y and U_z. And an analysis considering geometric nonlinearities and frictionless contact between each layer of the Flector was carried out. Due to the geometry of the problem, the zone expected to have the greater values for stress is right in the middle of the Flector, nevertheless, after 1^{9o} of misalignment is applied the response is as shown in Figure 57.

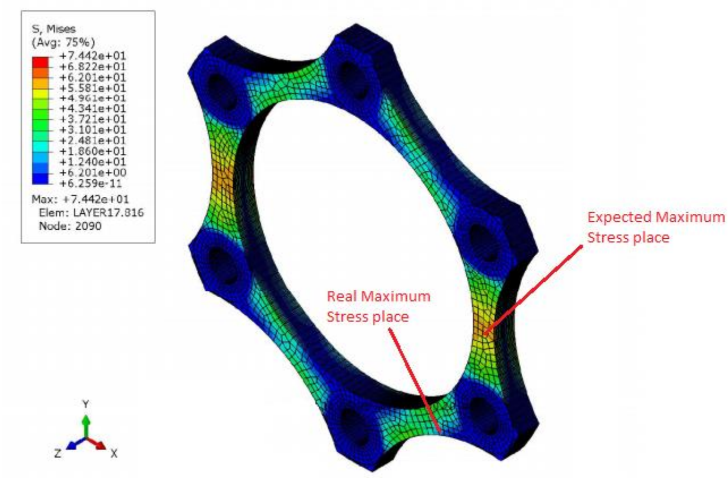


Figure 57: Difference on maximum stress spot – Expected vs. Calculated [36]

The unexpected stress concentration may be explained by a separation of the outer laminae of the coupling in what could be called a buckling phenomenon. One can check in Figure 59 that this buckling provides a stress concentration that increases the stress on that spot. The buckling observed by the model is coherent with the phenomenon observed in the laboratory.

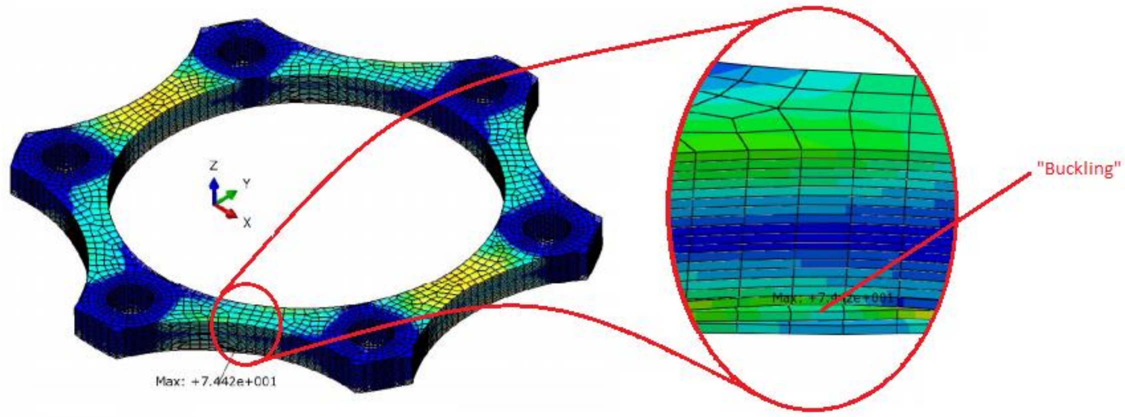


Figure 58: Maximum Stress spot after 1° of misalignment is applied [36]

By selecting the points right on the opening zone, a difference between their total displacements will be a good approximation for the value of the gap opening. This value is not exactly since one cannot guarantee that the maximum separation is not in the interior of the structure. The evolution of the separation while applying the displacement (Loads and boundary conditions as seen in Figure 56) is shown in Figure 59.

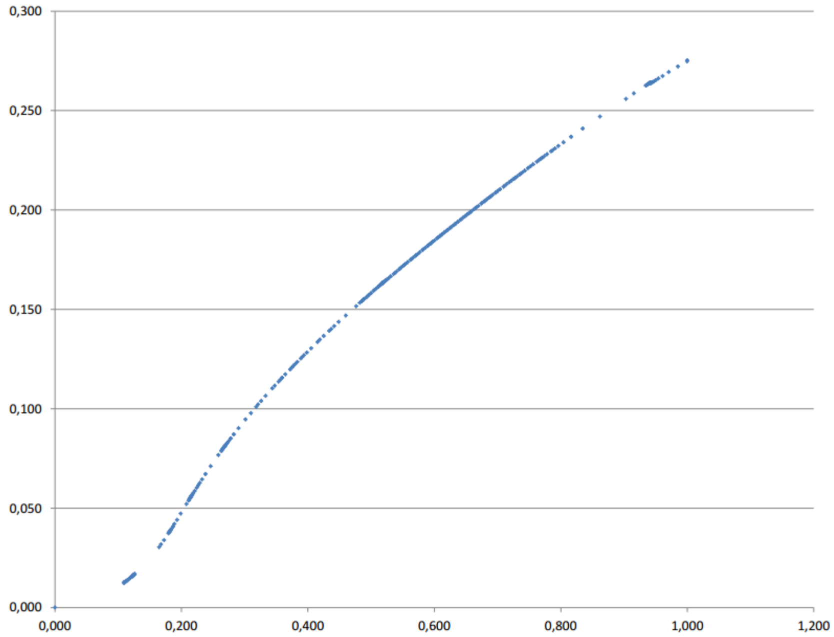


Figure 59: Evolution of the gap opening (mm) vs Degree of Shaft Misalignment [36]

One can notice, from Figure 59, a smooth, non-linear variation of the gap opening with the shaft misalignment. Along each revolution, the "breathing" of the gap between Flector layers will account for important phenomena which might require further dynamic analysis to determine the possible influence on the component vibration behavior and fatigue life.

Finite element dynamic model

The same model from Figure 55 was then submitted to dynamic analysis. Before the implicit dynamic step, a torque step and a misalignment step were carried out. A representation of the model may be seen in Figure 60.

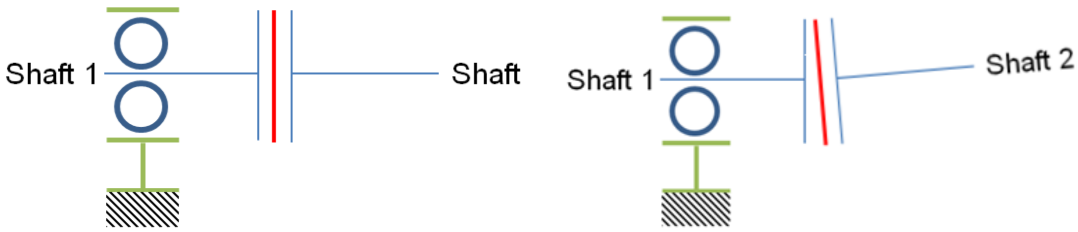


Figure 60 – Schematic modeling of the shaft for dynamic analysis [36]

In the model, the bearing and its support are considered rigid. Boundary conditions were applied similarly as displayed in Figure 56. According to the applied boundary condition, the reaction forces and moments are measured on the bearing region to simulate the response obtained in a real aircraft setup, which is presented in Figure 61.

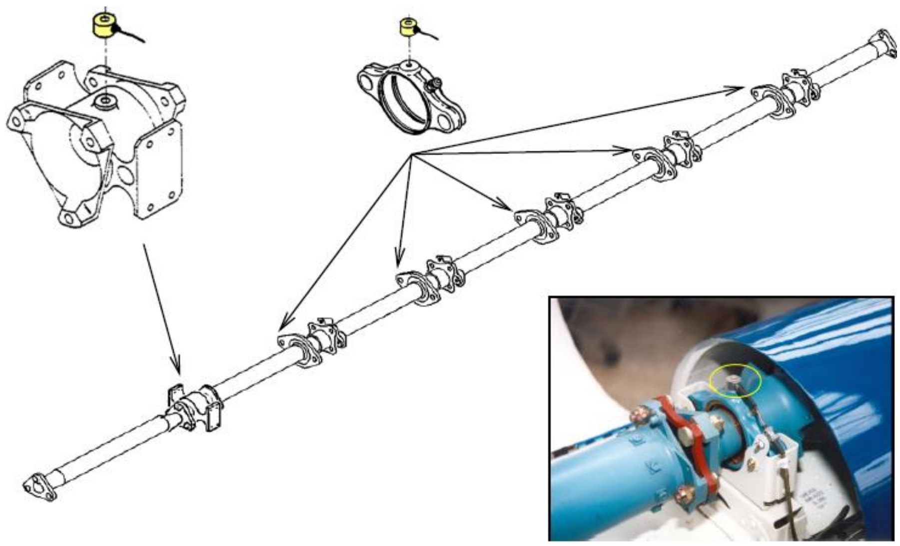


Figure 61: Aircraft simulated setup [36]

The procedure for analysis follows:

1. Static analysis is carried out in which displacements are imposed (black arrows) to simulate a 1° misalignment angle
2. Keeping the 1 degree of shaft misalignment, a torque equivalent to 28daNm is applied, simulating the torque transmitted through the tail drive shaft
3. A dynamic analysis is then started, with rotating speed increasing in a ramp, as displayed in Figure 62. The initial angular acceleration applied must be small, to avoid convergence issues to take place and to be physically consistent with the real operational conditions.

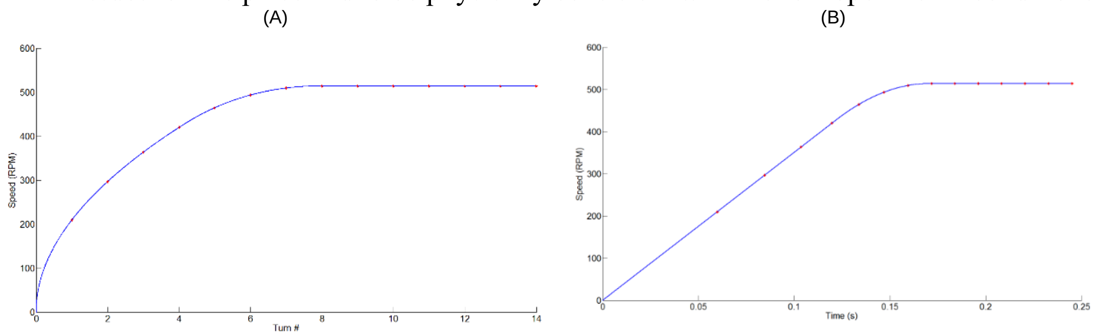


Figure 62: Initialization of applied rotational speed from rest (A) per revolution (B) vs. time (s) [36]

The results were analyzed and the Fast Fourier Transform of the force and moment response on the bearing location was calculated for the portion of the analysis where the rotational speed was constant. An average was made between the 6 turns similarly presenting constant speed as the synchronous average is calculated on the embedded system. This arrangement simulates an accelerometer set on the bearing and monitors the 6-axis of freedom on the region. The FFT of reaction response is shown in Figure 63.

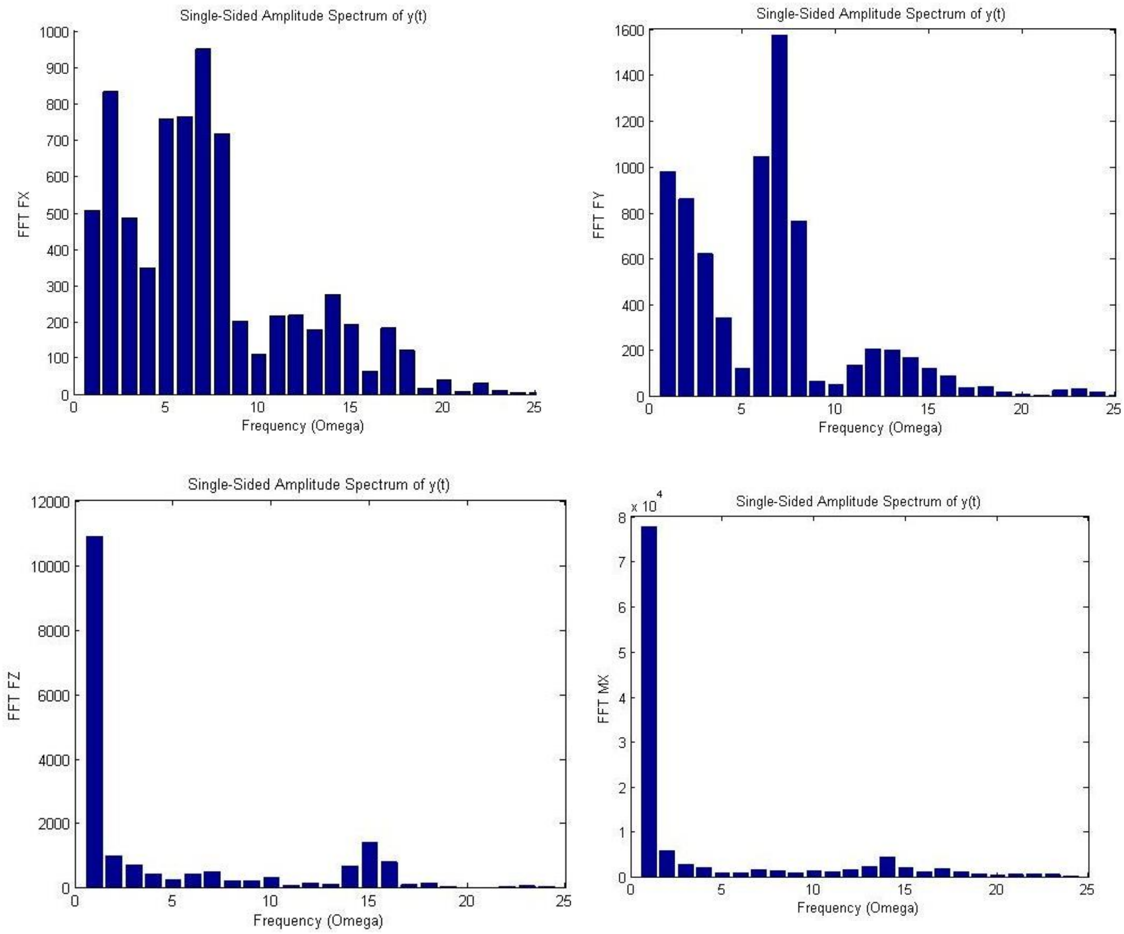


Figure 63: FFT of the reaction response for the 6 degrees of freedom [36]

From the figure, as expected and stated in the literature, a high peak at 1Ω and 2Ω are obtained. This is the typical response for a parallel-angular misalignment simulated by the conditions applied. The response is much clearer, and a special study must be carried out for *Mx* and *Mz*. These reaction moments presented high values that could be the root cause and explain the cracks that appeared on the coupling during the test. Another analysis, like the one here presented, is to be carried out with a crack on the outer layer of the coupling for the sake of comparison.

5 Concluding Remarks

This chapter presented a compilation of technical material and research work compiled or prepared by the authors and collaborators on the topics of vibration analysis and Health and Usage Monitoring Systems (HUMS) of dynamic components of helicopters.

The chapter concentrated on a discussion of vibration analysis techniques and the use of a framework of Health and Usage Monitoring Systems (HUMS) for helicopter dynamic components.

Some helicopter vibration reduction techniques focused on balancing and tracking the helicopter rotors are discussed in a separate chapter, concentrated on model-based parameter identification for balancing and tracking a helicopter's main rotor using once-per-revolution vibration data.

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