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DEVELOPMENT OF A DIDACTIC SCALED TWO-BLADED HELICOPTER PROTOTYPE TO STUDY THE DYNAMIC OF VIBRATION

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Abstract: *Vibration in helicopters is a concern of manufacturers and users which can be expanded for drones and any rotating blades aircraft. The vibration measurements represent a challenge in terms of dynamic characterization. The vibration suppression also represents technological challenges, mainly when acting in rotating parts. The literature reports the expected dynamic behavior of helicopters and highlights the challenges in vibrating suppression. To study the dynamic behavior of a helicopter rotor, that aims to study solutions to mitigate the effects of its vibrations in rotating parts, this research presents the design, building, and testing of a two-bladed rotor prototype using a low-cost indoor apparatus that simulate a helicopter in hover flight. The prototype relies on a helimodel rotor adapted employing blades produced by additive manufacturing. The control and measurements systems adopt a low-cost microcircuit accelerometer from the ADXL series and the Labview Platform, used as a measurement and control system that compounds a didactic structure to study the dynamic of this rotating system. The physical interface with the prototype is an acquisition USB board from National Instruments. The study identified the modal frequencies of rotating parts and identified the relationship between main frequencies and mechanical parts. In addition, performs the mechanism which shifts the pitch angle of the blades. The experimental results are aligned with the expected behavior registered by the literature, which expands the possibilities to build an indoor low-scaled prototype, useful for experimental research in rotating dynamics and, in particular, for rotating blades aircraft like helicopters and drones.*

Keywords: *mechanical vibrations, helicopter dynamics, rotating systems, instrumentation and control*

1. INTRODUCTION

1.1. Helicopter vibrations

The vibration phenomena are present in helicopters and observed in various aircraft models, regardless of scale. Welsh(2018) demonstrates in a review paper, supported by Bramwell et al. (2001) and technical papers in the American Helicopter Society (AHS), among other that the rotor corresponds to the main source of vibration. The intrinsic instability of helicopters results in dynamic effects, like vibrations, which represent a limit in performance, comfort, safety, and increasing maintenance costs. Thus, it is important to find out the root causes of these instabilities in other to eliminate or mitigate their effects.

The vibration are not intrinsic to the motor and gearboxes working, but also associated with temporary instabilities brought about by maneuvers (Caillet *et al.*, 2012). Vibrations increasingly occur during maneuvers of forwarding flight, reverse flight, and rolling, so that is important to itemize each root cause. The vibration levels should follow international standard limits regarding crew comfort and safety. In addition, the monitoring of such vibrations is an indicator of the machine's structural integrity (EASA, 2020; EASA, 2021; Pegado, 2010). Vibration reduction is a pursued goal and has been decreasing from 1955 to 1995 as described in Kessler (2011), highlighting the specifications of Utility Tactical Transport Aircraft System council and, the minimum vibration levels recommended by NASA: a huge target on 0.02g.

1.2 Vibrations source

In frequency wise, taking into account the rotor spin at frequency Ω, and if the blades were perfectly matched, the internal forces from all the blades cancel itself at the hub, except for those harmonics at multiples of $N\Omega$. These harmonics are transmitted to the aircraft where N corresponds to the number of the blades Thus, the rotor hub works as a filter, transmitting to the helicopter body only frequencies multiples of $N\Omega$.

Vibrations is not exclusively transmitted through the shaft but also through rotating frame mechanisms, associated with the simultaneous movements of the blade (from collective control) and individual movements of the blade (from cyclic control). The individual blade movements (lagwise and flapwise due to cyclic command) transmit vibratory loads to collective and cyclic systems, while vertical forces are transmitted through the shaft. The rotor's vibrations tend to rise in forwarding flight, as the speed increase. Otherwise, these vibrations tend to fall as the number of the blade rise. Thus, a helicopter that employs N blades exhibits fewer vibration levels than a model with N-1 blades, for instance.

Another source of vibration, which directly affects safety, is named ground effect: the dynamic instability involving a harmful interaction between the blade lag-mode with the fuselage motion during aircraft landing (Ciavarella *et al.*, 2018; da Silva *et al.*, 2020; Sanches, 2011; Souza *et al.*, 2014). Finally, general aerodynamic effects may induce vibration on helicopters as downwash movement of the air, that corresponds to changing of air flows through the main rotor reaching the aircraft tail, inducing vibrations on the structure or fluid-structure interactions when the aircraft is near to obstacles (Shahdin *et al.*, 2011; Zagaglia *et al.*, 2018).

1.3 Experimental vibrations benches

The more accurate method to measure helicopter vibration performs experiments in a real machine, as reported in many examples on the literature (Damy, 2006; Gębura *et al.*, 2017; Stupar *et al.*, 2012). However, studies and experiments with real helicopters may expensive and dangerous. An alternative to this challenge is to use numerical simulation (Anusonti-Inthra *et al.*, 2001; Liu *et al.*, 2017; Pomin *et al.*, 2001; Raghav *et al.*, 2013; Sinem *et al.*, 2018). Besides, the employment of physical prototypes in real scale (to compared with a real helicopter) or with reduced size (preserving the basic components) represents an intermediate solution that may help to understand the dynamic behavior of a real aircraft, once preserved the basic components, regardless scale. The facilities properly designed to carry on these experiments are named whirl towers.

The whirl towers are physical prototypes, with parts that mimic real helicopters, support experiments and supply substantial and reliable results. These facilities correspond to a physical prototype, generally compounded of the parts as rotor hub with its blades, which may take into account gearboxes and part of the fuselage in particular studies. The whirl tower sizes vary significantly and their dimensions depends on the experimental purpose, available in many example of literature (Cameron *et al.*, 2015; Ciavarella *et al.*, 2018; De Gregorio, 2012; Linghua *et al.*, 2020; Nitzsche *et al.*, 2013; Oliveira Neto *et al.*, 2021; Richter *et al.*, 2016; Straub *et al.*, 2018; Yücekayali *et al.*, 2013).

Based on the literature examples, and the demands for rotative machines vibration, specifically helicopters, this project aims to design and assembly a whirl tower that simulates a two bladed helicopter in an experimental apparatus to perform vibration measurements on a bench. The prototype simulates a helicopter in rover, dismissing aerodynamic aspects, once the goal is to observe the dynamic behavior of main rotor and its maneuvers mechanism. This prototype needs to follow low-cost and indoor use requirements in order to didactic applications. In addition, the dynamic response based on the measurements aims to stablish a reference condition that work as baseline for future vibration reduction solutions developed for helicopter rotors. The employment of a helicopter prototype supports the test of vibration suppression devices for future projects in dynamics.

2. DESIGN OF TWO-BLADED HELICOPTER PROTOTYPE

The project requirements concern viable installation in an indoor laboratory facility addressed to the Laboratory of Vibration and Instrumentation (LVI) at Federal University of Campina Grande (UFCG), Brazil. Figure 1 details the whirl tower flowchart design, where the project guidelines represent the first step witch source the basic requirements for each prototype subsystem.

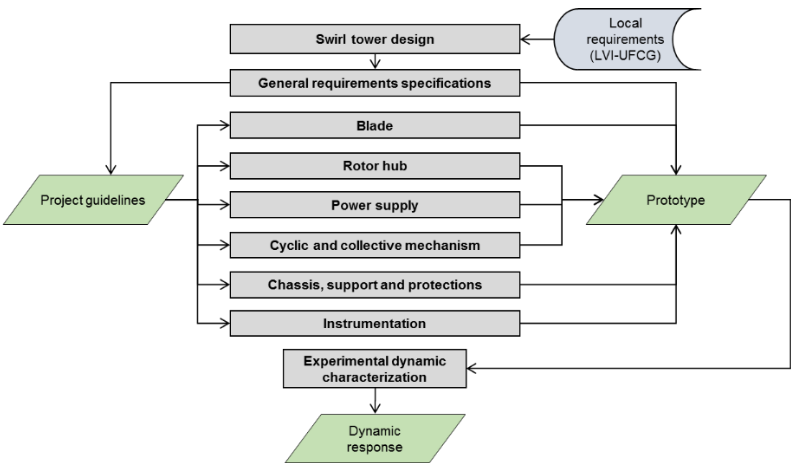


Figure 1. **Prototype design flowchart**

2.1 General requirements

The design of whirl tower carrying on under general requirements, considering infrastructure and didactic application, as follow:

- Compatible with laboratory installation indoor;
- Capable to represent basic and generic rotor hub mechanisms;
- Easy assembly and transportation;
- Size compatible with instrumentation;
- Influence of ground effect has to be negligible.

Based on the general requirements was estimated the general components, as depicted in Figure 2.

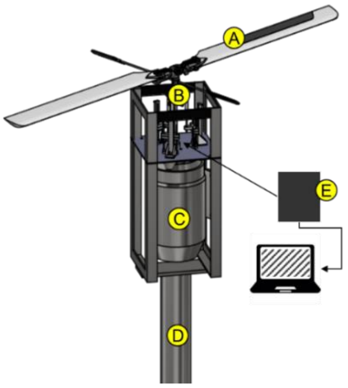


Figure 2. **LVI whirl rotor scheme**

The prototype exhibits the main rotor with blades (A), hub head, and swashplate mechanism (B). Power supply (C) without gearboxes, directly coupled with an electrical motor on the shaft. At least, no gearboxes avoid high frequencies components. The framework (D) should positioning rotor at a height from the ground enough to minimize the ground effect, and obstacle interactions. For this purpose, the rotor is positioned 1 meter above the ground reference. The ground reference is an inertial table, where the support has to be crimped.

2.2 Blades

The frequency harmonics are directly related to the number of the blades times the rotational speed. Besides, the number of the blades affects directly the dynamic response of the machine (Bramwell; Done; Balmford, 2001). In order to induce the worst vibration scenario, focused on highlighting vibrations effects, was adopted a two-bladed rotor.

The blades were built by additive manufacturing, in PLA(Polyacitic acid) as depicted in Fig. 3, with 49 grams, 442 mm length, 42 chord and 6 mm thickness, each one. Airfoil profile is NACA0012, according the dimensions obtained in Rosata (2015), compatible with a commercial helimodel named T-REX500. Although the geometrical characteristics of the blade are based on a commercial model, due to PLA, the prototype blade exhibits particular dynamic behavior.

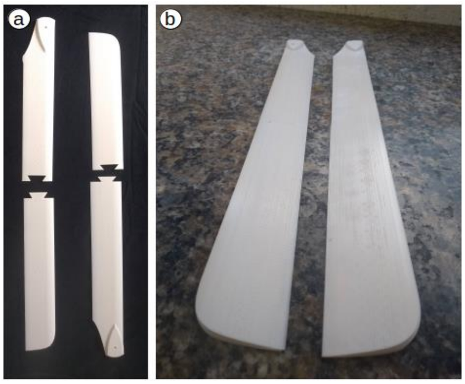


Figure 3 - **Blades: a) segments after additive manufacturing b) available to assembly in the rotor.**

The rapid prototyping was feasible by the Digital Manufacturing Lab of the Federal University of Paraiba (FabLab-UFPB), which produced the components in four separated parts (as shown in Figure 3a), for each blade, due to maximum size admitted by the printer. The total work spent amount of four hours.

2.3 Rotor Hub and blade mechanism

The rotor hub has to represent a common helicopter mechanism with blade hinge and mechanisms to feasible pitch angle shifting. The prototype employs a commercial model of rotor hub, compatible with the required dimensions. Figure 4 depicts the rotor hub and the associated mechanism. The application adopts a kit of helicopter hobby T-Rex 500 from Align® manufacturer (item 4 of Fig.4). The swashplate (item 2) is responsible to transmit the commands from non-rotational parts (from cyclic command – item 3), to rotating mechanism, through a stiff rod named pitch link (item 6).

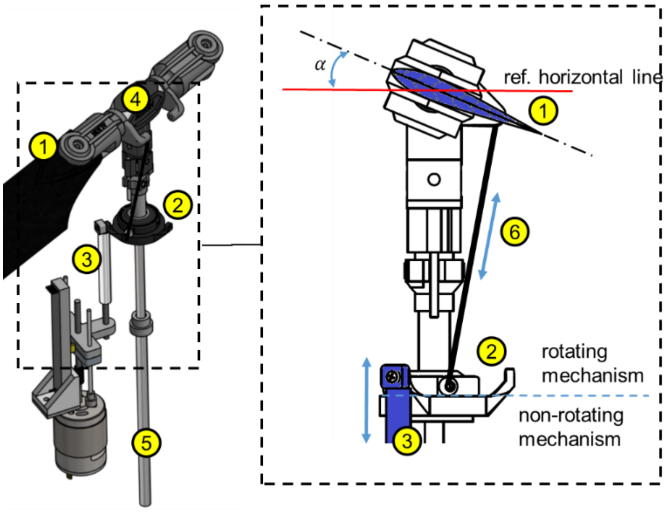
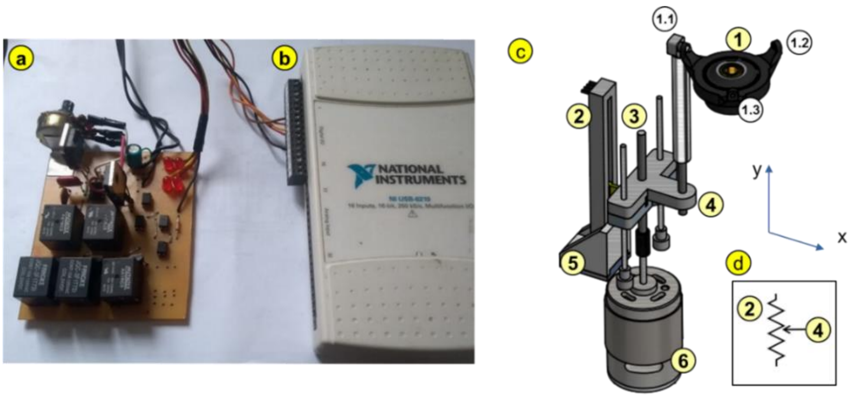


Figure 4 - **Blade mechanism: 1 – blade; 2 – swashplate; 3 – servo rod.**

During a helicopter flight, the maneuvers are generated by the pitch angle (α) shifting for each blade. When the pitch angle movement is performed for each blade individually, this command is named cyclic. When the movement take place for all the blades simultaneously, the command is named collective. To shifting the pitch angle, the main rotor counts with the swashplate and electrical servos.

The servomechanism was assembled with a drive board and a control board, according to Figure 5a. The board model National DAQ6210, 16 bits, 250Ks/s (Fig. 5b) works as interface from the control board and the computer. All of the inputs used are of analog signal. The drive board allows to control the servo motors speed (by a Pulse with Modulation - PWM) and its rotating direction. The Labview interface commands each of the three servos, independently (cyclic command) or simultaneously (collective command).



Tag	Component
1	Swashplate;
1.1 to 1.3	Swashplate linkage point with cursor;
2	Potentiometer;
3	Screw bar;
4	Cursor;
5	Potentiometer support;
6	Electrical 24V DC motor.

Figure 5 - **a) drive board b) Control Board DAQ6210 c) Servo Mechanism with its parts tagged d) potentiometer electric equivalent**

The interface allows to setup up the swashplate position and establishes a set point for each experiment, so that the previous position may be recovered to the next experiment. The cursor movement towards y-direction. The displacement of each motor is measured by a linear potentiometer (Fig.5c, item 2), that communicates the current vertical position of the cursor to DAQ6210 board. The detailing of Fig.5c, bordered by a dashed line is a simplified representation of the circuit used to cursor (Fig.5d).

The power to run the main shaft adopts an electrical AC motor WEG® model 63, 380Vac, 60Hz, 1/2cv, controlled by a frequency inverter WEG®, model CFW-10 to allows speed rotating control. The maximum rotation motor frequency is 60Hz, yet, the maximum main shaft rotation frequency is limited by the general structure of the whirl tower, links, mechanisms, and blade. Functional experimental tests target the maximum frequency of 12Hz to ensure tests with safety.

2.4 Chassis, supports and protections

Chassis has to support all the mechanisms, compounded of two parts: tower and frame. It is made of iron with welding joints, except in the flange between frame and tower. A metallic net is positioned around the prototype to protect the environment against losing parts during rotation, which causes damages to humans or equipment. The ground effect is a concern, studied in Chereseman *et al.* (1957), so that the minimum height of tower has considered: the tower height is 1m (more than the main rotor diameter).

2.5 Prototype assembly

According to the general requirements, the main parts of whirl tower are identified in Fig. 2. The rotating parts compounds blades, rotating frame (mechanism of rotor hub). The fixed frame compounds electrical motor, tower, protection net and inertial table, depicted in Fig. 6.

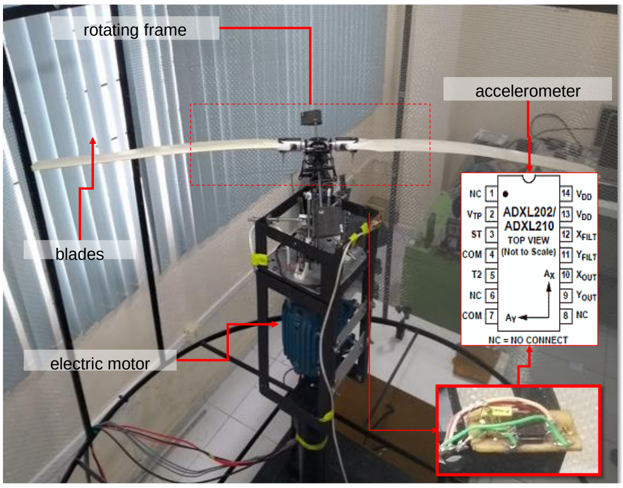


Figure 6 - **Prototype main parts and accelerometer detail**

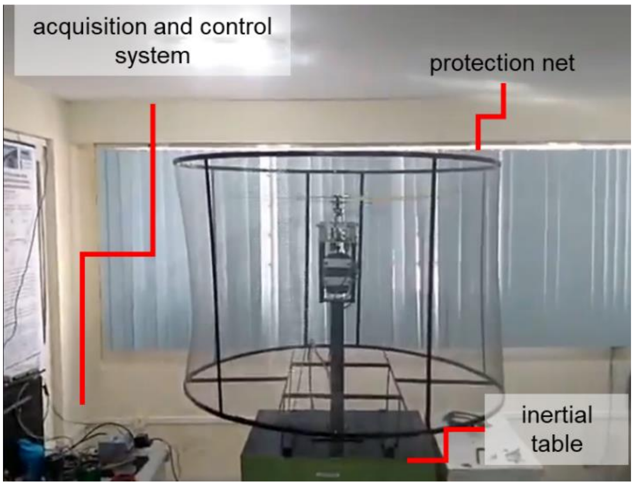


Figure 7 - **Experimental apparatus showing the Whirl Tower**

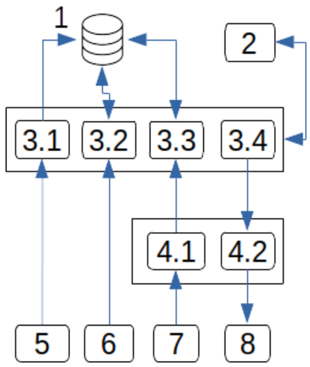
Figure 7 exhibits an overview of the experimental apparatus installed in the Laboratory of Vibration and Instrumentation of Academic Unit of Mechanical Engineer at Federal University of Campina Grande (LVI-UAM/UFCG), ready for the measurements with sensors and net protection around its frame. The prototype, including a circular protection net, is 1.4 m in diameter, 1.88 m in height. The acquisition and control system are installed close the prototype and cabled for sensors and controls.

2.6 Instrumentation

Figure 8 represents the instrumentation diagram that feasible real time measurements of rotating speed, vibrations signal and swashplate control. The database (Fig. 8 – item 1) is compounded of a text file, saved by LabView, which records in real time the swashplate position (set points), rotational speed and acceleration. Accelerations measurements are post-processed using Matlab, aiming vibration analysis. Labview 2013 64-bit package supports the Control Interface, which graphical appearance is showed in Figure 9. The control interface allows to controlling each swashplate actuator independently or simultaneously, similar to cyclic and collective controls inspired on a real helicopter. The setpoint of each actuator can be adjusted as a set point (Fig. 9 – tags “Sup”. and “Inf”.). In addition, the screen shows the acceleration values, in graphic mode. The software records all data in the database file for post-processing.

The board DAQ6210 (Fig.8, item 3) is capable to connect the accelerometer (Fig.8, item 5) directly in its analog input (Fig.8, item 3.1). To ensure the right value of acceleration, the package (accelerometer + interface) was calibrated by the portable modal shaker calibrator model PCB394C06.

The acceleration is measured by IC ADXL202 (Fig.8, item 5), which provides two-axis acceleration measurements. ADXL202 is installed directly on the measuring point, as exhibited in Fig.6.



1 Database;
2 Control interface;
3 DAQ6210 input/outputs;
4 Driver board;
5 Accelerometer;
6 Rotation sensor;
7 Potentiometer
8 PWM motor supply.

Figure 8 - **Instrumentation Diagram**

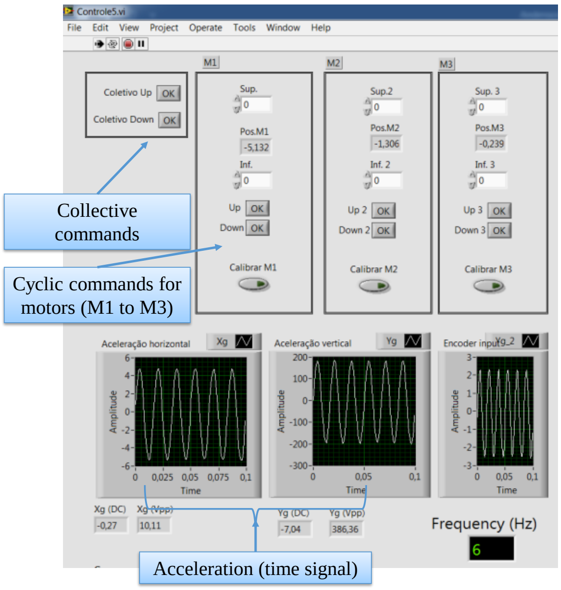


Figure 9 - **Labview Control Interface**

The digital outputs of DAQ6210 board commands each DC motor actuator (Fig.8, item 8), through the driver board (Fig.8, item 4). DAQ6210 is not capable to excite 24V DC motor directly due to power limitation. Thus, the driver board boosts the commands signal from DAQ6210 towards exciting the DC actuators motors. Another function of the driver board is to control the speed of DC motors by a PWM (Pulse Width Modulation) (Fig.8, item 4.2) power supply so that the rotational speed of each motor depends on the pulse modulation provided by the PWM. The adjustment speed is manual, by the setting on the control board.

The driver board is also used as a signal conditioner of cursor (Fig.5d) to allow the measurement of the electrical potential throughout the potentiometer (Fig.8, item 7).

3. RESULTS

3.1 Functional tests

The functional test performs a sweep in the main rotor frequency: the main rotor was excited from a minimum frequency, possible to generated by the motor (3 Hz), until the maximum safety frequency defined experimentally: in real time, was measured the maximum vibration amplitude for each frequency tested, obtained by Labview. The sweep detected a high increase in acceleration amplitude, when exciting frequency rises close to 12 Hz. This high level of vibration suggests the establishment of an operational limit (to preserve the safety of tests and integrity of structure was defined 12 Hz as de maximum safety frequency). For current vibration measurements in steady-state, for this characterization, the main rotor run at 10 Hz. In addition, the test aid to identify loosed parts, gaps, clearances, and abnormal noises. On the functional tests it was possible to identify eventual electrical problems, as electrical interference between the sensor signals and alternate current supply of peripheral systems.

3.2 Experimental Modal analysis

The modal analysis aims to identify the vibration-wise critical regions. The modal analysis was performed with the blades and swirl tower separately. The analysis in the prototype structure was performed in free vibration employing an accelerometer PCB model 352B10 and a hammer impact, both connected in a digital signal analyzer model 35670A. Figure 10 illustrates the points of accelerometer positioning. Each imaginary dashed line indicates the point of impact and the direction of the force applied by the hammer. Thus, the force was applied aligned with the accelerometer positioning, excepted in point 3, due to the necessity of torsional mode inducing, promoted by the misalignment between the application force point (dashed line 3) and the accelerometer position (point 3 placed in top of the tower).

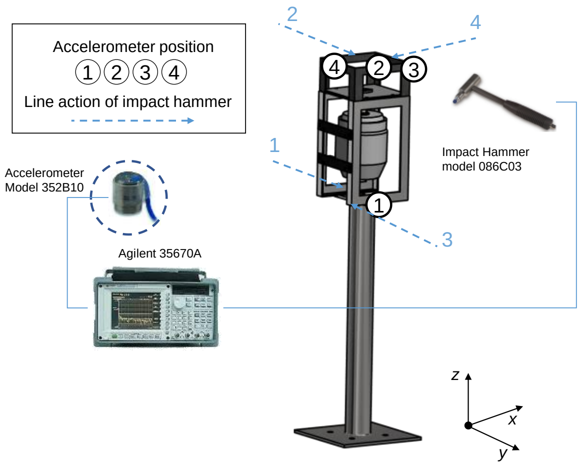


Figure 10 – **Experimental modal analysis of swirl tower: the bullets corresponds to the accelerometer points and dashed lines the hammer impact region, respectively.**

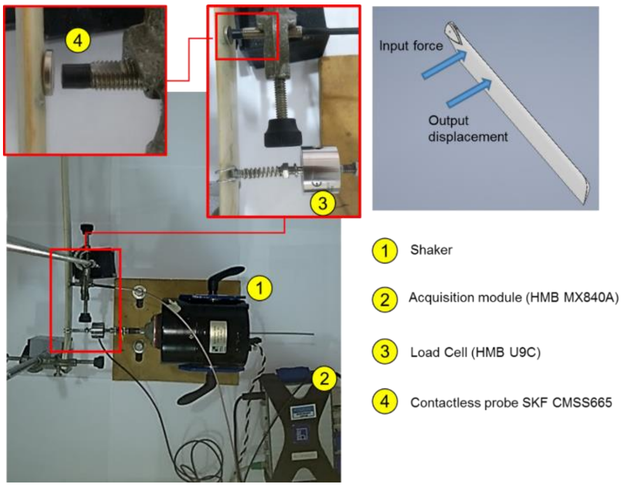


Figure 11 - **Forced vibration experiment scheme**

For swirl tower (only tower and rotor hub without blades) the free vibration frequencies measured are 20.88 Hz and 98.63 Hz, respectively. In this case, the first and second modes are directed associated to hub mass and tower height.

The blades were removed from the rotor, fixed in a support according to the scheme of Figure 11. Considering the two blades exhibiting the same mass and shape, as verified after rapid prototyping, the modal tests were performed with one blade. The experiment consists in forced vibration excitation with input force applied by a modal shaker and output displacement measurement using a contactless sensor (contactless sensor was used to avoid influence of probe mass). The displacement sensor was installed near the blade root, less 1/4 of total length, due to maximum displacement limit of sensor. The acquisition data carried out with HBM MS840 module, coupled by voltage input with contactless sensor SKF CMSS665. Input force measurement was performed with load cell HBM U9C. The apparatus was attached in an inertial table. Post-processing data was executed in Matlab to perform Fast Fourier Transform analysis.

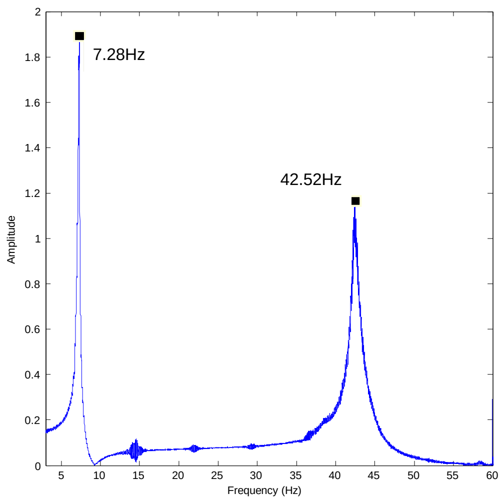


Figure 12 - **FRF from experimental results with first and second natural frequencies highlighted for the blades.**

The FRF of blades is depicted in Figure 12. The first mode in 7.28 Hz indicates the possibility of resonance in case of rotor operating close to 7 Hz, which predict the dynamic response in case of swiping greater than 7 Hz. The second mode (45.52 Hz), take place far from the operational frequencies, it´s not a concern.

Considering the expect operating frequencies below 12 Hz, these modes did not represent a concern in terms of maximum amplitudes vibration.

3.3 Dynamic tests in 10Hz

Therefore, the isolated free-response of blades and swirl tower aids to identify the individual contribution of these harmonics in the overall spectrum. Yet, the prototype spectrum, on steady-state of 10 Hz, as forced vibration, exhibit, among the frequencies identified in Fig.13, other frequencies related to the rotating parts like fly-bars, linkages, and multiples of harmonics, did not identified.

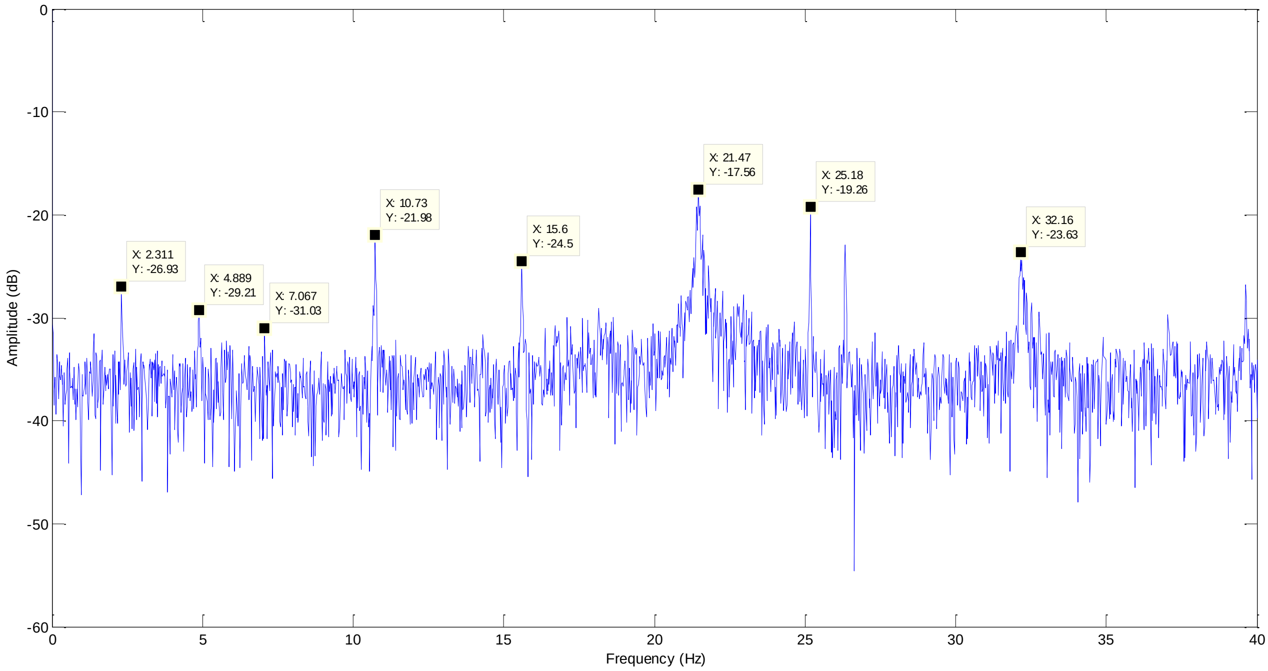


Figure 13 - **Power spectrum density of helicopter prototype under main shaft frequency at** 10Hz.

The main shaft frequency is exhibited (Ω =10.73 Hz). The prototype has two blades: thus, the frequency 2Ω (21.47 Hz) match with the blade's frequency (7.28 Hz – Fig.12) in a region of high energy density level, close to 20 Hz. There is a relationship between the frequencies of 7.06 Hz and 15.6 Hz, which may represent blades or fly-bars. In addition, other harmonics exhibited in Fig.13 are not associated with specific elements, so that, auxiliary methods, like numerical simulation aims to perform a completed dynamic characterization of the prototype.

CONCLUSIONS

The whirl tower as a prototype aimed to perform the behavior of a helicopter, even in hover flight, reaching the proposed goal, once the experimental results exhibits a behavior similar with the helicopter experimental results from the literature. The main shaft frequency at 10.73 Hz generates the harmonic in frequency at two times (21.47 Hz), regarding to the number of blades. According to the literature, the natural frequency of each blade it self-cancelled, despite a harmonic with no expressive amplitude about 7.067 Hz (Fig 11) which may suggest a possible unbalancing. The natural frequencies of structure are far from Ω and $N\Omega$ frequencies performed in forced vibration tests with the rotor in operation. The dynamic behavior in operational tests confirmed the statements declared by the literature. The size of overall facility, including the protection net did not exceed the available workspace, dismissing several modifications in the laboratory layout. Cyclic and collective commands work properly. The acceleration measurements exhibit low noise, good compatibility with Matlab, and feasible a good spectrum analysis what testify the effectiveness of measurement systems as also as the kit accelerometer ADXL+Labview feasibility for this application. The blades manufacturing testifies the effectiveness allows experimental modal analysis with mechanical parts obtained by rapid prototyping open opportunities for improvements. Thus, the modular constitution of the prototype is considered proper to dynamic tests and opens the opportunity to its improvements in forward works toward designs of devices or control strategies to reduce e mitigate the vibrating effects. The maximum limit of 12Hz stablished during functional test was due to the possibility of abnormal vibration amplitudes, related to resonant frequencies of other movable parts not identified in this study. Thus, in terms of a didactic experiment, this prototype open the opportunity to perform a group of dynamic tests in order to detail more the behavior of its individual parts and the influence of this parts in the overall system performance.

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