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Research paper

Helicopter modelling and study of the accelerated rotor

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A R T I C L E I N F O

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This work presents a helicopter dynamic model that captures the fuselage vibrations for an accelerated main rotor. Some rotor parameters are modified with the purpose of study their impact on the rotorcraft. Being this, a tool that allows to predict vibrations on the helicopter. The rotorcraft model has been built up by using VehicleSim, software specialized in modelling mechanical systems composed by rigid bodies. The rotors are articulated, the main rotor takes into account flap, lag and feather degrees of freedom for each of the equispaced blades and their dynamic couplings. The dynamic performance and the control action are embedded in a single code, thereby VehicleSim does not require external connection to other software package. This generates some advantages such as to reduce the compilation time. The control methodology makes use of PID controllers (Proportional, Integral, Derivative), which allows to use VehicleSim commands exclusively. The state space matrices have been obtained in order to analysis the uncoupled main rotor flap and lag modes. The detection of vibrations from the offset flap hinge as well as the lag hinge are not straightforward tasks and this helicopter model provides an accurate tool to study these. A short time Fourier transform processing is used to analysis the vibrations and these have shown to agree with the expected behaviour.

1. Introduction

Helicopters are adaptable for their different applications and these have been increased over the years. They have roles such as monitoring of traffic, air ambulance, fire fighting, etc. [1]. These trade demand the vibrations reduction to accomplish a better reliability of structures, efficiency and greater comfort [2]. It is well known that the rotorcrafts are prone to higher vibration levels than the aircrafts. In fact, the vibration level in helicopter is of the order of five times the vibration levels located in fixed wing aircraft [3]. It is found that these vibrations are due to the rotorcraft configuration as well as their varying velocities.

Faithful reproduction of the helicopter dynamical vibration requires a tough modelling process and the used of simulation techniques, which can be carried out by using the different software packages existent, see [4,5]. In fact, the interaction between the main rotor and the fuselage needs a particular attention. In order to reduce the cost of the experimental tests and to obtain more accurate outcomes, these type of simulations should be considered.

Practical examples can be found wherein the measure and the analysis of helicopter vibrations have been studied to identify defects on their operating components. Stupar et al. [6] presented and implemented a vibration testing methodology to figure out the correct performance of the rotating components. The tests were done on a military Gazelle helicopter SA-342. The practical methodology was carried out in the following steps: (a) To determine the rotating systems and subsystems the operating frequencies. (b) To select a number of locations on the structure for measuring the vibrations on the ground. (c) To choose an inner location at the structure, being this a specific point for the corresponding flight tests. This allowed to determine the helicopter features and the demands for any testing actions. The test was conducted with an equipment configuration such as 12 channels NetdB12 - 01 Metravib digital analyser and data collector, in order to measure the vibrations in real time. 5 accelerometers B&K type 4393 and 1 tachometer. Several accelerometers were set up for recording the configuration on different positions and helicopter directions. As a result, a technical review of their relevant components and a disclosure of the failures on its surface were done. Furthermore, this method of measurement and analysis could be accomplished on different kind of aircraft for extending their operational life expectancy. The damage detection methods have been used by dos Santos et al. [7] to put forward experimental outcomes related to a helicopter main rotor blade. The methods used were the modal strain energy, and the coordinate modal assurance criterion (COMAC). Modal parameters were derived using experimental modal analysis and damage was inserted on the blade by linking a small mass to it, thereby, their properties were altered. The helicopter

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blade features were displayed and an experimental modal analysis was done. The damage was simulated to establish the blade vibration modes, under the impact of an unbalance of mass. A comparison was carried out between the studied cases. As a consequence of this, the COMAC damage indicator was less sensitive than the strain energy technique, due to the damage index was not able to find out the exact location of the added mass. The modal strain energy formulation handles a lot of approximations to work out the final damage index, on the contrary, this supplied the adequate detection possibilities and sensitivity.

The estimation of the unbalance force and the unbalance itself of a rigid rotor system during acceleration is a cumbersome task that it must be dealt with. Vibration generated by mass unbalance is a relevant factor, which restricting the performance of the rotating system. Zhou and Shi [8] presented a new method of the unbalance estimation for the rigid rotor during acceleration. The estimated unbalance was figured out, as a consequence of this, unbalance forces and moments were obtained as the states of the augmented system. This method could be applied to active balancing schemes for a rigid rotor or the active vibration control. The features of the transition vibration of a rotor when it passes its critical speeds throughout acceleration encourage an interest of disciplines such as the rotor design, active real-time balancing and active vibration control. In fact, the rotor study under constant acceleration has been tackled by Zhou and Shi [9]. This work provides an analytical unbalance response of the Jeffcott rotor. An analytical solution was derived for the unbalance response of the Jeffcott rotor during acceleration. The obtained solution showed that the motion was made up of three parts: (a) a transient vibration at damped natural frequency. (b) A synchronous vibration with the frequency of instantaneous frequency. (c) A suddenly occurring vibration at damped natural frequency. Zhou et al. [10] put forward an active balancing method to offset the unbalance of the rotor system during acceleration using an electromagnetic balancer. In order to reduce the impact on a rotor when it passed through its critical speeds, which is able to damage the system. An assessment was carried out to validate this method and the validation outcomes were shown. In this scheme, “instantaneous” influence coefficients at different speeds were calculated and stored in a look-up table. Afterward, a gain scheduling strategy was taken into account to remove the unbalance-induced vibration during acceleration established on the “instantaneous” influence coefficient table.

Furthermore, variable speed rotor studies are a research field for the rotorcraft operations improvement as well as the fuel consumption reduction. According to Misté and Benini [11], there are two main variable speed concepts, fixed-ratio transmission and continuously variable transmission rotors. The effect of these types of transmissions on the helicopter performance is calculated when both are working at their optimal speeds. This can be carried out using two different simulation tools, a turboshaft engine performance code and a helicopter trim simulation code for steady-state level flight. After a study done by the authors, fixed-ratio transmission was presented as a well process to diminish the fuel consumption at intermediate advancing speeds. However, continuously variable transmission advantages showed to be relevant in hover and in high speed forward flight.

The vibration impact and its determination upon the helicopter structural components in terms of frequency characteristics have been recently studied, Khaksar et al. [12] have developed in ABAQUS a 3D finite element method for a 349 Gazelle helicopter model. ABAQUS is a program based on the finite element method. It is able to resolve problems ranging from relatively simple linear analysis to the most complex nonlinear simulations [13]. The main advantage of this model is that, it can be used to predict the natural frequencies of the full structure. The model provides a tool to test the frequencies of the helicopter with different components. Often, it is overlooked the vibrations and the human body, Ceruti et al. [14] have reported about this matter. The authors describe the standard range of the vibrations on helicopters. However, a novelty aspect is shown i.e., the whole-body acceleration [15] displays medium-low frequencies in a range of 2–20 Hz.

In order to understand the limitations and shortcomings of controller designs to capture helicopter performance, the following considerations can be done. The flight control systems are able to classify as linear or nonlinear, these are established according to the controller requirements and the helicopter model that is built up. The linear control design is more applied and it has been run on the majority of helicopter platforms. It is more used due to the simplicity of the controller design, which reduces the computational complexity and the modelling time. However, nonlinear controllers are demanded for their theoretical contribution to the rotorcraft control problem [16]. In fact, Chen et al. [17] have recently developed the adaptive neural fault-tolerant control approach for the three degrees of freedom model helicopter in the presence of system uncertainties, unknown external disturbances and actuator faults. The unknown external disturbances as well as the unknown neural network approximation error were processed as a compound disturbance that was figured out with a nonlinear disturbance observer. The simulation results showed the effectiveness of the proposed adaptive control scheme. Cui et al. [18] have also developed an observer based backstepping control scheme for the attitude control problem of three degrees of freedom model helicopter with unknown external disturbance, unknown modelling uncertainties and unknown states. Backstepping control law was set up based on the estimated values of observers to obtain suitable tracking performance. The results displayed effectiveness of the designed control approach. Despite of these recent works have demonstrated to be efficient, they have been carried out for helicopters with three degrees of freedom. Both approaches must be extended to six degrees of freedom, in order to be extended to helicopters model more complex. On the other hand, the application of these control schemes would involve to use external software packages to VehicleSim. In here, a PID (Proportional, Integral, Derivative) methodology is applied in various subsystems of the helicopter model, as it is strong to accomplish the required objectives. The PID control methodology is implemented in VehicleSim, the main argument is that this allows to program an single code, being not necessary to use any additional software.

VehicleSim is a multibody software specialized in modelling mechanical systems composed by rigid bodies. It is used as main software package due to the helicopter nonlinear behaviour and equations of motions are provided. In addition to this, the state spaces matrices are also derived, being these an additional advantage with respect other software that can be found in the literature, see [5]. Furthermore, operational modal analysis of the rotating helicopter blade can find a support tool in this software. Due to it can facilitate the studies carried out in this field, as for example the work presented by Agneni et al. [19]. The authors estimated the damping ratios, natural frequencies and mode shapes without to measure the input forces. In this way, the system modal parameters were able to establish its operative conditions. The capability to improve the operational modal analysis procedure was also studied through whirl tower experimental tests. The proposed approach allowed the study of both the rotating frequency as well as the damping ratios as functions of the rotating speed. Although the estimate of the rotating frequencies was not sensitive to the different estimation approach, at least for the experimental data, noteworthy differences in the damping ratio estimates were described. An underestimate of the damping ratio of the modes with natural frequency close to the one the identified operational frequencies was identified.