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ANALYSIS OF HELICOPTER CABIN VIBRATIONS DUE TO ROTOR ASYMMETRY AND GUST ENCOUNTER

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Abstract

The availability of a numerical tool capable to predict the vibration level inside the cabin due to main rotor-fuselage interaction is of great importance in helicopter design. Indeed, it would be a source of information concerning the fatigue-life of the structure, that in turn would allow a rough estimate of consequent maintenance costs. Furthermore, such a tool would be helpful also in the process of identifying design solutions aimed to the interior noise reduction, that is a crucial aspect for the widely-requested passenger comfort enhancement. In this paper, the simulation tool is obtained as a finite element structural dynamic model of the helicopter fuselage forced by vibratory hub loads, that are predicted through the aeroelastic analysis of the main rotor treated as isolated. In particular, the emphasis is on the evaluation of the incremental vibration level induced by rotor asymmetry and gust encounter, that could give raise to interior acoustic patterns annoying for passengers and to vibration peaks dangerous in terms of structural fatigue. All the results are obtained for two different flight conditions.

Introduction

Currently, in the process of helicopter design, particular attention is paid on the level of vibrations of the cabin structure, that are mainly induced by the engine and by the unsteady loads due to the main rotor dynamics and transmitted through the hub.[1,2,3] Indeed, the helicopter fuselage vibrations have a significant impact both on the fatigue-life of the structure (and hence on maintenace costs) and on the noise level inside the cabin (that could cause unacceptable ride discomfort).[4,5] This work is focused on the cabin vibrations induced by the unsteady loads at the rotor hub, and is aimed to the development and application of a simulation tool for their analysis. Specifically, the attention is paid on the examination of the incremental vibration level induced by rotor asymmetry and gust encounter, that could be responsible for both interior acoustic patterns particularly annoying for passengers, and vibration peaks dangerous from the structural point of view.

In the simulation tool developed for this work, the fuselage has been modeled as a high-modal-density aluminum-beam truss structure (inspired by that introduced in Ref. [6], typical for helicopter structures), and a finite-element approach has been used for its discretization. Assuming the helicopter in level, straight flight at uniform velocity, frequency response functions relating main-rotor hub loads to accelerations at different cabin positions have been also determined and hence, the aeroelastic hub loads have been applied to estimate the corresponding vibration level. In order to evaluate the loads transmitted by the main rotor, the main-rotor blade dynamics has been described by the nonlinear flap-lag-torsion slender-beam differential model introduced by Hodges and Dowell,[7] that is suitable for the dynamic analysis of flexible blades undergoing significant elastic displacements. The aerodynamic forcing terms appearing in this model have been predicted through a strip-theory based on a simple 2-D model derived from the quasi-steady Greenberg theory,[8] and enriched by the additional contributions arising in case of gust encounter. The blade aeroelastic model obtained in this way has been first integrated in space by applying the Galërkin approach, with bending and torsion free-vibration modes of a non-rotating uniform beam as shape functions,[9] and then integrated in time by the Newmark-β scheme, in order to determine the unsteady hub loads forcing the fuselage. Finally, the rotor hub loads to be used as input to the fuselage frequency-response functions described above, have been obtained in the fuselage frame, by combining the hub loads due to all the rotor blades.

The numerical investigation is focused on the analysis of cabin vibrations induced by rotor asymmetry and encounter of discrete gusts, at two different advance ratios. In the first case, we consider the effect of differences among the aerodynamic characteristics of the rotor blades, whereas in the second case we examine the effect of the presence of both horizontal and vertical gusts. The analysis will be performed in terms of structural accelerations at some cabin locations.

Theoretical Background

In this paper, the prediction of the helicopter cabin vibrations induced by aeroelastic rotor hub loads has been performed by coupling two simulation tools: one developed for the analysis of the structural dynamics of the fuselage, and the second devoted to the analysis of the aeroelastic behavior of isolated rotors (this means that, for a helicopter in rectilinear level flight at uniform velocity, in our work we neglect both the influence of the fuselage feedback on the blade dynamics and the aerodynamic interactional effects). Specifically, first the blade aeroelastic solution is obtained in order to determine the dynamic loads at the root (and hence transmitted to the hub), and then these are used as inputs in the dynamic response analysis of the fuselage, having the vibration levels at different cabin positions as outputs.

A brief description of the formulations from which these two prediction tools have been developed, is given in the following.

Aeroelastic model of the blade

Rotor blade aeroelastic modeling has been obtained by using the nonlinear flap-lag-torsion equations of motion presented by Hodges and Ormiston,[9] that have been derived by simplifying the more general model introduced by Hodges and Dowell.[7] That is a beam-like model that is valid for straight, slender, homogeneus, isotropic, nonuniform blades, with twist and both mass and tensile offsets.

However, in the equations of motion given in Ref. [9], the blade is assumed to be a cantilever, untwisted beam, with uniform distribution of mass, and with mass, tensile and aerodynamic axes coinciding with the elastic axis. In deriving their final form, these equations have been further manipulated. First, an ordering scheme has been applied in order to drop those terms considered to be of the third order with respect to the bending slope (an arbitrary small parameter) and not contributing to damping. Second, the radial displacement of the blade has been eliminated from the set of equations, by solving it in terms of local tension: this is equivalent to assume that the blade is inextensible for bending deflections, and that radial displacements are simply geometric consequences of the transverse bending deflections (see Ref. [9] for details).

Under the simplifying assumptions mentioned above, the final form of the dynamic system is a set of coupled nonlinear integro-partial differential equations suitable for describing the response of hingeless helicopter rotor blades[5] undergoing significant deflections, and having as unknowns the in-plane displacement of the elastic axis, $v(x,t)$, the out-of-plane displacement of the elastic axis, $w(x,t)$, and the cross-section elastic torsion deflection $\varphi(x,t)$. These equations of motion are further coupled by the presence of the aerodynamic forcing terms that, as well known, play a crucial role in the aeroelastic behavior of rotor blades. Here, the aerodynamic loads have been determined by a simple quasi-steady strip-theory, based on the low-frequency approximation of two-dimensional Greenberg theory.[8] This is an extension to pulsating free-stream of Theodorsen relations[10] for unsteady aerodynamic loads acting on a thin symmetrical airfoil. Indeed, following Ref. [10], the application of a quasi-steady, 2D strip-theory yields aerodynamic loadings explicitly expressed as functions of the unknowns w, φ, whereas using the Greenberg theory it is possible to introduce the aerodynamic effects due to in-the plane components of relative wind (given by combination of elastic motion, $\dot{v}$, and advancing velocity). The aerodynamic model is completed by including the effects of the flow induced by the wake on the blade angle of attack (here, a simple uniform inflow model is adopted). Note that, in this work the effects of the presence of a gust are included as modifications in the blade downwash appearing in the aerodynamic model, that in turn induce incremental aerodynamic loads and hence altered aeroelastic behavior and hub loads.

Applying the Galërkin method for the space integration with the non-rotating modes of the blade as shape functions, the resulting final aeroelastic system consists of a set of nonlinear ordinary differential equations of the type

$$\hat{\mathsf{M}}\ddot{\mathsf{x}} + \hat{\mathsf{C}}\dot{\mathsf{x}} + \hat{\mathsf{K}}\mathsf{x} = \hat{\mathsf{f}}\left(\mathsf{x}, \dot{\mathsf{x}}, \ddot{\mathsf{x}}, \theta, \dot{\theta}, \ddot{\theta}, \psi\right), \qquad (1)$$

where x denotes the vector of the Lagrangean coordinates (modal amplitudes), $\psi = \Omega t$ is the azimuthal position of the blade (with Ω being the angular velocity of the rotor), whereas $\theta = \theta(\psi)$ is the pitch controlled by the swash-plate.

Furthermore, matrices $\hat{\mathsf{M}}$, $\hat{\mathsf{C}}$, and $\hat{\mathsf{K}}$ describe the linear, time-constant, mass, damping, and stiffness structural and aerodynamic contributions, whereas the forcing term $\hat{\mathsf{f}}\left(\mathsf{x}, \dot{\mathsf{x}}, \ddot{\mathsf{x}}, \theta, \dot{\theta}, \ddot{\theta}, \psi\right)$ is the collection of all nonlinear and/or time-dependent-coefficient terms. These equations are integrated by the Newmark-β time-marching scheme, with the explicit evaluation of the right-hand-side terms.

Vibration model of the cabin

Once the aeroelastic deformation of each blade has been obtained from the analysis discussed above, the corresponding dynamics hub loads (*i.e.*, shears and moments at the root) may be evaluated in the rotating frame (by using the elastic-force/deformation relationships for the beam). Then, the unsteady hub loads inducing cabin vibrations are obtained by adding the contributions from all the blades expressed in the fuselage frame of reference. Denoting with S_x, S_r, and S_z, respectively the drag, radial, and vertical shear forces at the rotor hub and with N_F, and N_L, respectively the root bending and torque moments, for a N-bladed rotor the total forces and moments in the nonrotating frame are given by: [1]

$$\begin{aligned} T &= \sum_{m=1}^{N} S_{z\,m} \\ H &= \sum_{m=1}^{N} \left(S_{r\,m}\cos\psi_m + S_{x\,m}\sin\psi_m\right) \\ Y &= \sum_{m=1}^{N} \left(S_{r\,m}\sin\psi_m - S_{x\,m}\cos\psi_m\right) \\ M_x &= \sum_{m=1}^{N} N_{F\,m}\sin\psi_m \\ M_y &= -\sum_{m=1}^{N} N_{F\,m}\cos\psi_m \\ Q &= \sum_{m=1}^{N} N_{L\,m} \end{aligned} \qquad (2)$$

where T, H, and Y are, respectively, thrust, drag and side forces, whereas the rotor torque, and the pitch and roll moments are respectively denoted as Q, M_y and M_x.

The relations above are used to evaluate the aeroelastic hub loads forcing the helicopter fuselage vibrations, when the rotor blades are not identical (as well known, the harmonics different from multiples of N/rev disappear for symmetric rotors).[3]

Finally, the vibration levels inside the helicopter cabin are evaluated introducing the transfer function between unsteady hub loads and acceleration of the structure at a specified location. Specifically, this transfer function, $\mathsf{H}_A(\omega)$, is obtained through the finite element commercial code *MSC.NASTRAN* via evaluation of mass and stiffness fuselage matrices, M_F, K_F, and it is expressed as

$$\mathsf{H}_A(\omega) := -\omega^2 \left(-\omega^2 \mathsf{M}_F + \mathsf{K}_F\right)^{-1}. \quad (3)$$

Thus, the response of the fuselage is evaluated at different frequencies by the following relationship

$$\tilde{\mathsf{x}}_F \;=\; \mathsf{H}_A(\omega)\tilde{\mathsf{f}}_A \quad (4)$$

where $\tilde{\mathsf{f}}_A$ denotes the Fourier transforms of the hub loads, and $\tilde{\mathsf{x}}_F$ denotes the Fourier transforms of the second time derivative of the degrees of freedom describing the fuselage finite element model.

Numerical Results

The objective of the numerical investigation performed in this work is the examination of the cabin vibrations induced by rotor asymmetry and gust encounter. As already mentioned, the analysis starts from the calculation of the blade hub loads that then, are used as inputs to the frequency response functions relating them to the dynamics of the structure at specified points.

For the results presented here, the helicopter fuselage has been modeled as the truss structure introduced in Ref. [6] and depicted in Fig. 1, whereas a finite element approach has been applied for determining the frequency response functions of interest in our analysis (Fig. 2 illustrates the frequency response function between the vertical displacement at the port node (DOF 12_z) and the vertical force at the hub (DOF 65_z), which shows a typical high-modal-density behavior). Furthermore, Tabs. 1, 2, and 3 list the basic characteristics of the helicopter and the flight configurations considered, whereas the collective pitch θ_0, and the cyclic pitch angles, θ_{1c} and θ_{1s} used in the numerical simulations, are shown in Table 4. In addition, the helicopter is assumed to be capable to carry a 180 Kg-payload at three different advance ratios, and both two-bladed and four-bladed hingeless rotors have been analyzed. As an example of the results obtained from the blade aeroelastic analysis, Figs. 3 and 4, respectively for the two-bladed and the four-bladed rotor, depict the harmonics of the vertical shear at the rotor hub expressed in the shaft frame due to one rotor blade. As expected, these results show the presence of a $1/rev$ dominant component, as well as a magnitude that is proportional to the forward flight velocity.

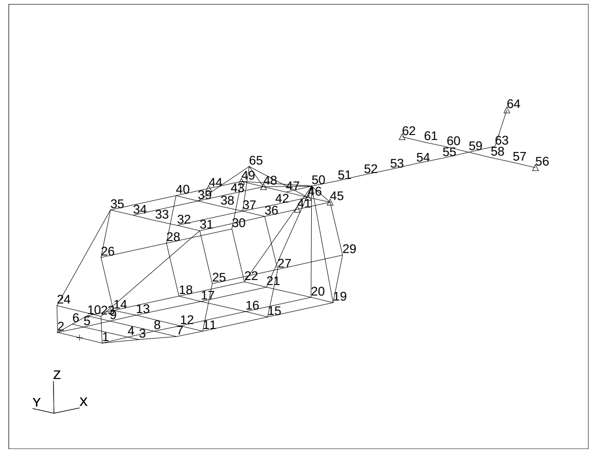

Figure 1: Finite Element Helicopter Model

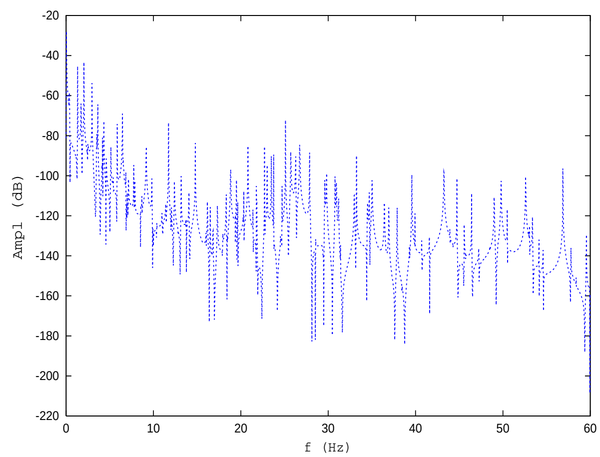

Figure 2: $H_{12_z,65_z}(f)$ FRF

Then, we analyze the effects on cabin vibrations of rotor (aerodynamics) asymmetry. Specifically, for the four-bladed rotor, we have assumed one of the

Total structural mass	420 Kg
Engine mass	180 Kg
Tail gear box	40 Kg
End plate	2 Kg

Table 1: Fuselage mass characteristics

Blade Radius	4.5 m
Blade Chord	0.27 m
ν	5.9 Kg/m
I Flap Nonrot. Freq.	0.5
I Lag Nonrot. Freq.	1.5
I Tors. Nonrot. Freq.	8.
κ_m	0.025
κ_{m1}	0.025
σ (solidity)	0.0382/0.0764
Ω (angular velocity)	44.4 rad/s

Table 2: Rotor characteristics

blades having a 2.5% difference in the lift slope with respect to those of the remaining blades. For the advance ratio $\mu = 0.05$, Fig. 5 depicts the harmonics of the vertical shear at the hub transmitted by the rotor. As expected, the blade asymmetry generates the arise of harmonics that would have been filtered by a symmetric rotor. In particular, in Fig. 5 we can see the presence of a significant $1/rev$ harmonic that in a rotor with four identical blades would be null due to the blade balancing effect (in that case, only the pN/rev harmonics, with p integer and N denoting the number of blades, would be different from zero). A similar result is shown in Fig. 6 for the advance ratio $\mu = 0.15$, but in this case the ratio between the $1/rev$ harmonic and the (fundamental) $4/rev$ one is much smaller than that in the $\mu = 0.05$ case, and therefore the asymmetry seems to have a reduced effect on the vibratory loads. Next,we examine the alteration induced by blade differences on the cabin vibration spectra. To this aim, first we consider a reference symmetric four-bladed rotor, and in Figs. 7 and 8 we show the Argand diagrams of the structural $4/rev$ vertical acceleration evaluated at the port and starboard cabin positions, respectively at $\mu = 0.05$ and $\mu = 0.15$. In these figures, the position of the end point of the segment sequence is representative of the $4/rev$ harmonic of the acceleration at the cabin location considered, with each segment representing the effect from one of the blade root load harmonics contributing to the $4/rev$ hub load (namely, for a symmetric four-bladed rotor, the $3/rev$ and $5/rev$ root lag shear, the $4/rev$ root flap shear, and the $3/rev$ and $5/rev$ root flap moment). Then, when an asymmetric rotor is considered, the cabin vibration spectra are enriched by lower harmonics, as it

α (shaft angle)	3 deg (nose–down)
γ (Lock number)	4.8

Table 3: Flight conditions

μ	2 Blade Rotor			4 Blade Rotor		
	θ_0	θ_{1c}	θ_{1s}	θ_0	θ_{1c}	θ_{1s}
0.05	15.0	0.26	-1.32	9.70	0.26	-1.32
0.10	15.0	0.54	-2.70	10.2	0.54	-2.70
0.15	15.0	0.87	-4.70	10.8	0.85	-4.17

Table 4: Pitch control angles (degrees) at trim configuration

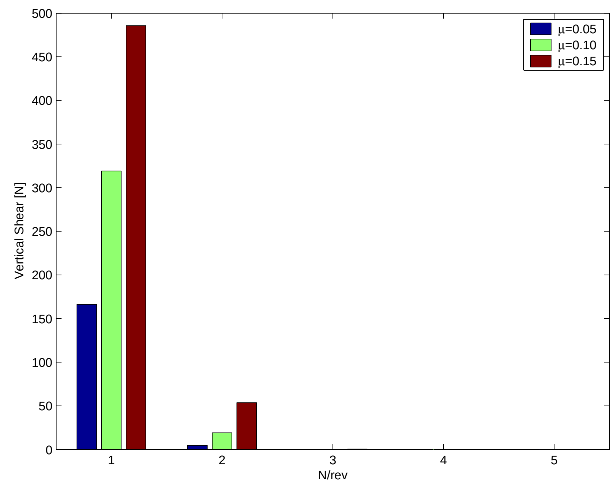

Figure 3: Two-bladed rotor vertical shear

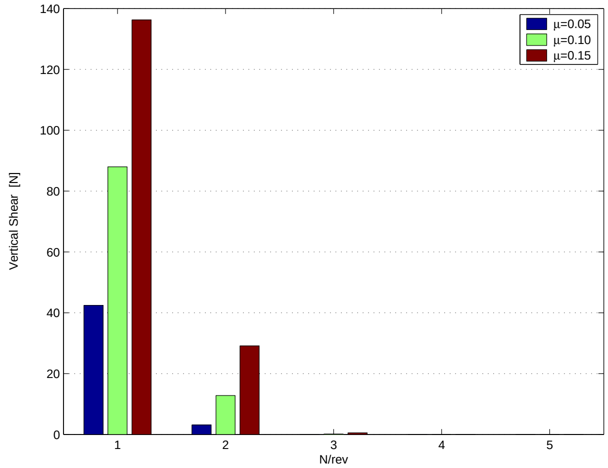

Figure 4: Four-bladed rotor vertical shear

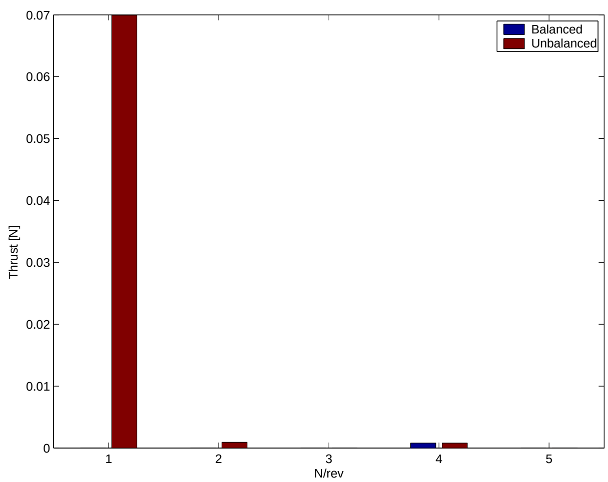

Figure 5: Four-bladed rotor thrust: effects of asymmetric blades. $\mu = 0.05$

is expected from observation of Figg. 5 and 6. Indeed, the cabin vibrates significantly not only at the $4/rev$ frequency (where the harmonic is not appreciably altered by the asymmetry), but also at the $1/rev$ one, for which we show the Argand diagrams of Figs. 9 and 10, for the flight conditions $\mu = 0.05$ and $\mu = 0.05$, respectively. The corresponding vi-

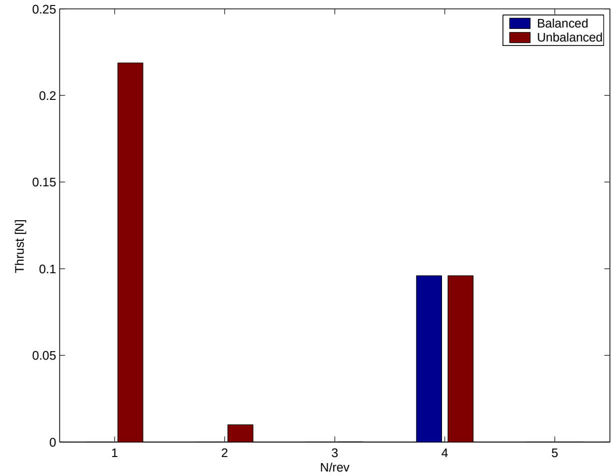

Figure 6: Four-bladed rotor thrust: effects of asymmetric blades. $\mu = 0.15$

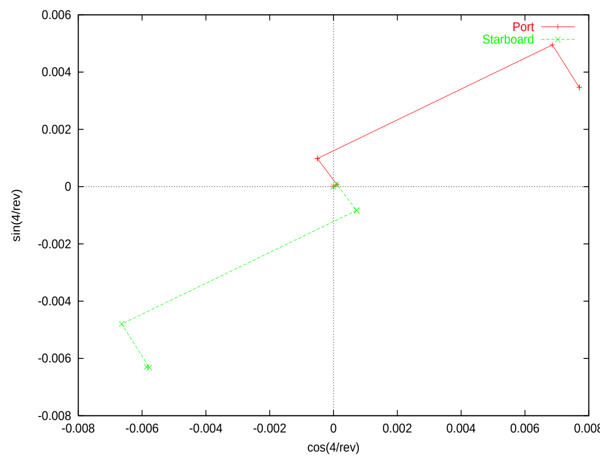

Figure 7: $4/rev$ vibrations (m/s^2). Four-bladed rotor with $\mu = 0.05$

bration levels of the vertical acceleration normalized with respect to the g value, are reported in Tabs. 5 and 6, where the $1/rev$ and $4/rev$ harmonics are compared. It is worth noting that, since the $4/rev$ vibration level is primarily induced by the hub velocity, it is proportional to the advancing ratio, whereas the $1/rev$ vibration level that is due to asymmetry

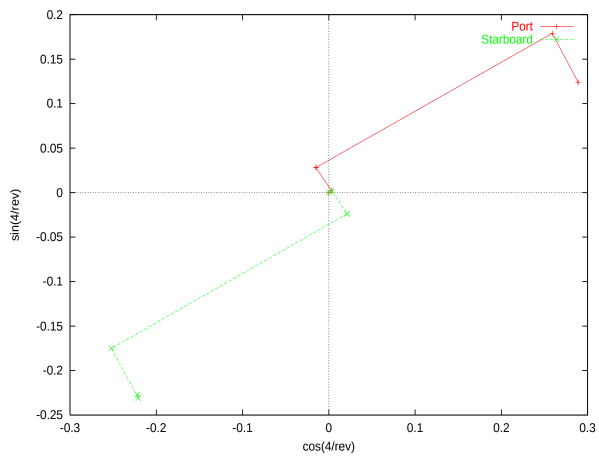

Figure 8: $4/rev$ vibrations (m/s^2). Four-bladed rotor with $\mu = 0.15$

and would be present even in hovering rotor condition, is primarily induced by the rotational velocity and is almost unaffected by changes of the advancing ratio. Finally, we examine the changes of the

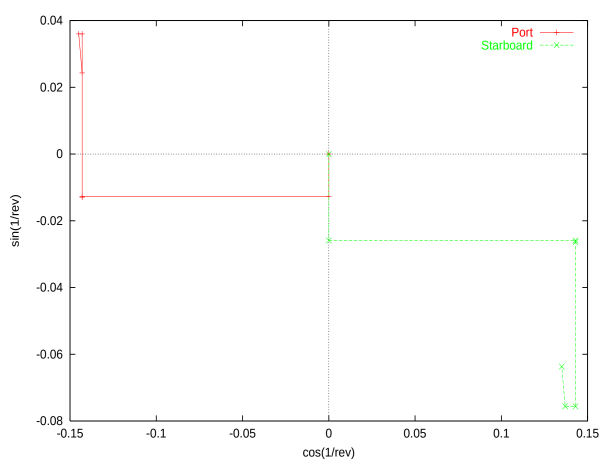

Figure 9: $1/rev$ vibrations (m/s^2). Four-bladed asymmetric rotor with $\mu = 0.05$

vibration levels due to gust encounter. The discrete gust profiles considered (both in the vertical and in the horizontal (front) directions) alter the local blade

n/rev	Port	Starboard
1	0.01480	0.0152
4	0.0009	0.0009

Table 5: Vertical acceleration (g). Four-bladed rotor with $\mu = 0.05$

n/rev	Port	Starboard
1	0.0144	0.0143
4	0.0321	0.0324

Table 6: Vertical acceleration (g). Four-bladed rotor with $\mu = 0.15$

velocity, and have the following $1 - cosine$ shape

$$v_g = V_g \left(1 - \cos \frac{2\pi\mu\Omega t}{25}\right). \tag{5}$$

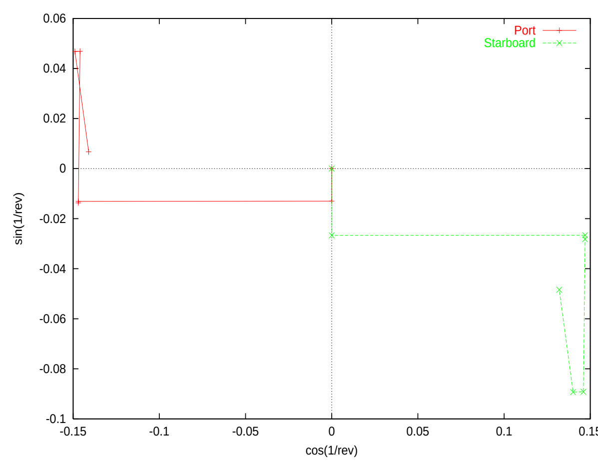

Figure 10: $1/rev$ vibrations (m/s^2). Four-bladed asymmetric rotor with $\mu = 0.15$

For a four-bladed rotor with advancing ratio $\mu = 0.15$, Fig. 11 depicts the influence on the blade tip flap deflection of a vertical gust encounter, that has been assumed to occur $t = 100sec$ later the sudden start of the rotor. Figs. 12 and 13, respectively for advancing ratios $\mu = 0.05$ and $\mu = 0.15$, show the spectra of the structural acceleration at the port side in the presence of a vertical gust. Noting that only the harmonic at $28Hz$ would exist for a symmetric rotor without gust effects, we can observe that the gust induces significant low-frequency vibrations of the structure (even greater than that at the fundamental harmonic), that are stronger at low advance ratio flight conditions.

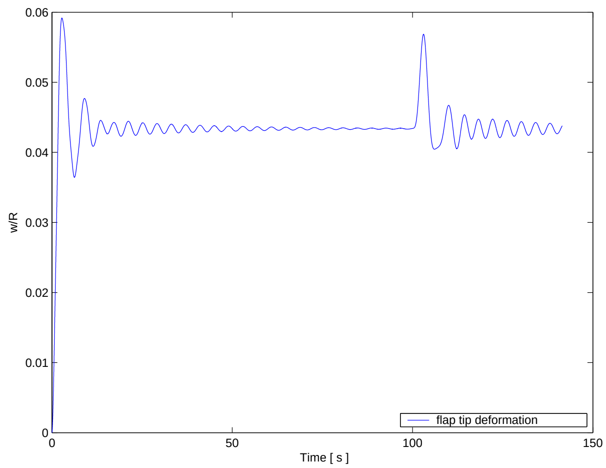

Figure 11: Time history of blade tip w/R. $\mu = 0.15$

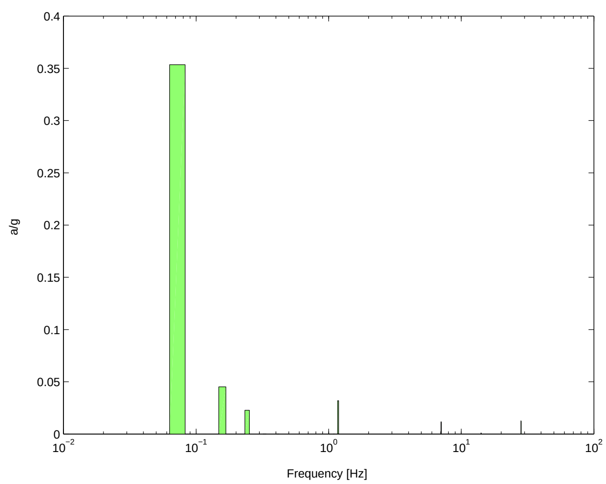

Figure 12: Response to vertical gust. Four-bladed rotor with $\mu = 0.05$

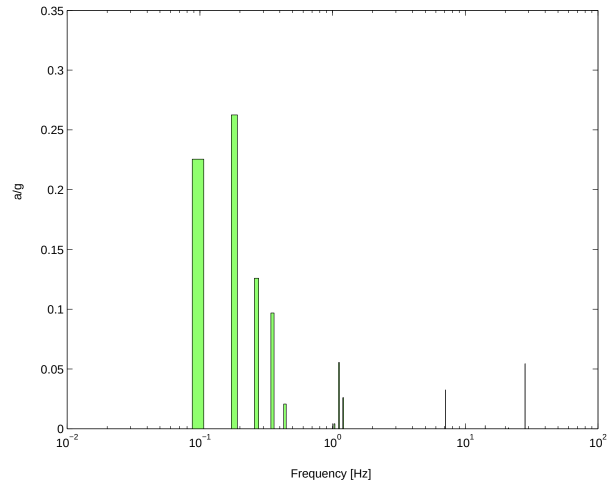

Figure 13: Response to vertical gust. Four-bladed rotor with $\mu = 0.15$

A similar behavior of the response of the helicopter cabin is predicted when considering a front horizontal gust. In this case, in order to emphasize the effects on the induced cabin vibration, a one-order-of-magnitude higher value of V_g has been used in the definition of the gust profile. Nonetheless, the vertical acceleration caused by this type of gust is weaker than that due to the vertical gust, and this is shown in Figs. 14 and 15, respectively for advancing ratios $\mu = 0.05$ and $\mu = 0.15$.

Concluding Remarks

In this work a simulation tool for the aeroelastic analysis of rotors in forward flight has been coupled with the finite element model of a helicpter cabin, in order to predict the cabin vibrations induced by the rotor hub loads. In particular, we have examined the vibratory effects due to rotor asymmetry and gust encounter, for two advancing-ratio conditions.

For the asymmetric four-bladed rotor examined (with one blade having aerodynamic characteristics different from those of the remaining three) the cabin vibration spectra have shown the arise of a significant $1/rev$ harmonic, in addition to the $4/rev$ one. It is possible to observe that the harmonic induced by the

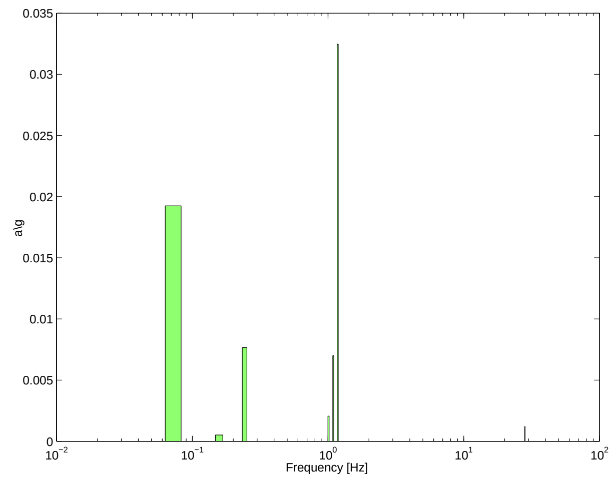

Figure 14: Response to horizontal gust. Four-bladed rotor with $\mu = 0.05$

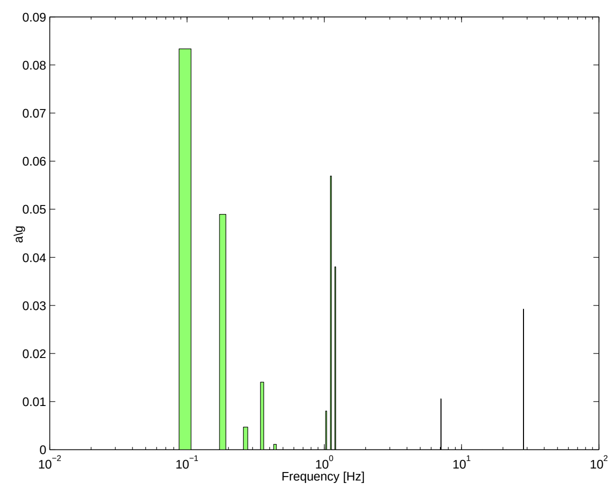

Figure 15: Rotor response to horizontal gust. Four-bladed rotor with $\mu = 0.15$

asymmetry has a magnitude that seems to be independent of the rotor advancing ratio, and for $\mu = 0.05$ is greater than the $4/rev$ one that would be present also with a symmetric blade configuration.

Furthermore, we have simulated the presence of discrete $1 - cosine$ vertical and horizontal gusts. In this case, the numerial prediction has shown that the incremental aerodynamic loads due to the gust velocity yield cabin vibration spectra that are enriched by the presence of low-frequency harmonics of significant magnitude (in particular, for the vertical gust case).

Therefore, this analysis has shown that rotor asymmetry and gust encounter may cause significant modifications to the cabin vibration spectra with respect to those caused by a rotor in standard operative conditions. These effects have to be taken into account in the helicopter design process, in order to avoid, for instance, a decrease in effectiveness of sensitive equipment and component fatigue problems.

Acknowledgements

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