IDENTIFICATION OF HELICOPTER GROUND RESONANCE WITH MULTI-BODY SIMULATION

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Abstract

This paper reports on the investigation of the simulation of helicopter ground resonance with a generic multi-body simulation software LMS Virtual.Lab Motion. Therefore, a rotor model with 4 articulated blades was combined with a tricycle helicopter landing gear model. Based on the analyses the separate systems, a Coleman diagram was produced. The behaviour of the integrated helicopter model during simulations included the occurrence of the resonance phenomenon as predicted by the Coleman diagram. Additional simulations with different parameters variation verified that simulations can be used to study the occurrence and effects of design parameters on helicopter ground resonance.

1 Introduction

Helicopter ground resonance is a potentially destructive phenomenon that can produce catastrophic damages and result in the complete destruction of the helicopter. It is an aeromechanic instability usually occurring during helicopter landing, take-off and ground manoeuvres and is usually caused by the coupling of a rotor system vibration with an oscillation of the fuselage rocking on its landing gear. Traditionally, it has been difficult to predict the occurrence and the effects of ground resonance because the analysis of rotor dynamics is done in stand-alone specialised software which does not permit taking into account detailed design of helicopter structures.

The aim of the presented work is to investigate the identification of the helicopter ground resonance phenomenon with the multi-body simulation code LMS Virtual.Lab Motion. LMS Virtual.Lab Motion [4] is a state-of-the-art generic multi-body code [2] and is used to perform dynamic simulation of aircraft systems such as detailed models of a landing gear of aircraft and helicopters with integrated hydraulic models of oleo struts. In order to identify ground resonance, an integrated model of a helicopter is required. Therefore, a model of a large helicopter was built. It is composed of a tricycle-type landing gear model and a rotor model with 4 fully-articulated rigid blades, including non-linear lead-lag dampers.

In the next section, the background theory of helicopter ground resonance will be briefly discussed. In section 3, the composition of the different parts of the multi-body simulation model and the integration will be discussed. In the following chapter, the simulation results of the reference model are shown together with the results of parameter studies to increase the confidence in the model. In the final section, the main conclusions are discussed together with some potential future work.

2 Ground resonance theory

Ground resonance is an aeromechanic instability usually occurring during helicopter landing, take-off and ground manoeuvres [3] [7]. It is usually caused by the coupling between a rotor system vibration with an oscillation of the fuselage rocking on its landing gear.

2.1 Fully Articulated Rotor System

The first mode involved in the coupling is a vibration of the rotor system. As explained below, the ground resonance phenomenon only affects mainly helicopters with fully articulated rotor system. These systems have 3 hinges at the rotor hub to reduce the stresses in the blades and rotor mast during the flight. This is because they allow a blade to move in 3 independent planes: the flap hinge allows the blade to move up and down; the pitch hinge allows the blade to rotate about its feathering axis; the lag hinge allows the blade to swing forward and afterwards with respect to the rotor head rotation.

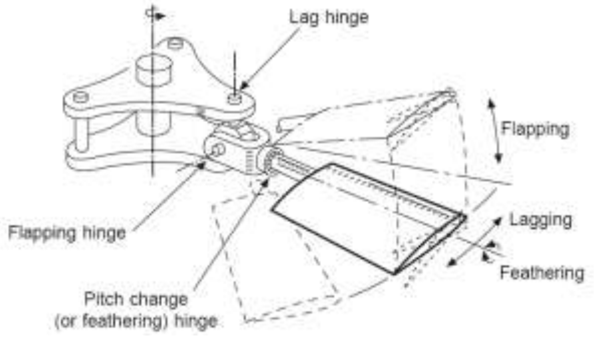

Fig. 1 Fully articulated blade hinges

The Lead Lag mode has a frequency ν related to the rotor speed frequency Ω by the following relation:

$$\nu = \sqrt{\varepsilon} \cdot \Omega \qquad (1)$$

where ε is the distance between the rotor hub and the hinge along the feathering axis of the blade.

The Lead Lag hinge allows the blades to lead and lag due to external disturbances, or Coriolis forces or aerodynamic drag variation on the blade. For this reason the blades can become not evenly spaced, out-of-phase, and cause a rotor imbalance (Figure 2).

The rotor can therefore show a progressive and regressive vibration mode, defined by

$$f_\nu = \Omega \pm \nu \qquad (2)$$

where, again, ν is the Lead Lag frequency and Ω the rotor speed frequency. The Regressive Lead Lag mode is involved in the coupling, and it can cause ground resonance instabilities, as is clarified later. It's interesting to note that hinge-less rotor helicopters are much less susceptible to ground resonance due to the absence of the lead lag hinge. As a result the lead lag motion has a frequency that is too high for resonance to occur.

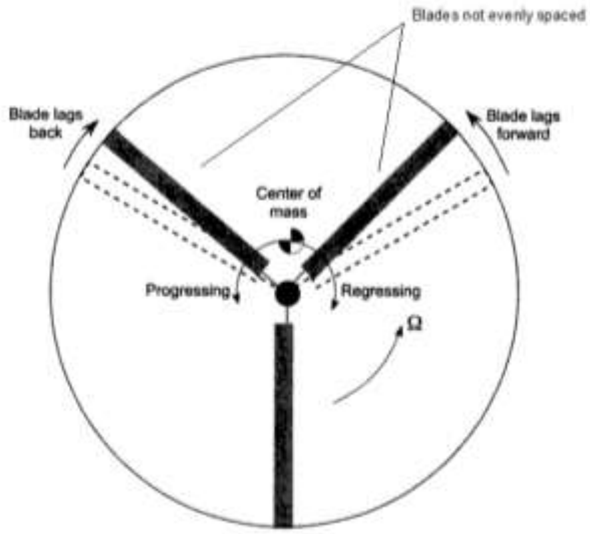

Fig 2 Out-of-phase lead-lag blade displacement

2.2 Fuselage Supporting System

The second mode involved in the coupling is an oscillation of the fuselage on the landing gear when in contact with the ground, hence the name ground resonance.

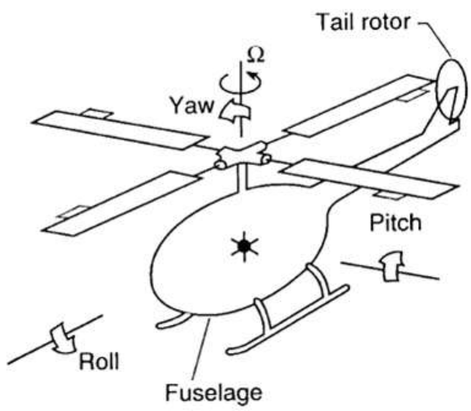

Fig. 3 Definition of helicopter rotation modes

With fully articulated rotors, the critical modes involving in the coupling are usually either the pitch or the roll motion of the fuselage. These modes are mostly caused by the flexibility of the tires and the Oleo Struts. As a result, the design parameters of the latter parts will influence the occurrence of the ground resonance.

2.3 Interaction between Rotor System and Fuselage System modes

The ground resonance instability is a result of a resonance of the blade regressive lag mode frequency with one of the fuselage mode frequencies. Ground resonance can be presented graphically in a form known as a Coleman diagram (Figure 4). This diagram shows the variation of the coupled frequencies for both progressive and regressive vibration mode rotor and fuselage flexible modes as a function of the rotor rotational speed. As the latter modes are independent of the rotor speed, these modes remain constant. The rotor vibration modes are based on the fundamental lead lag mode and hence their natural frequency varies linearly with the rotor speed. At the rotor speeds where the lines of the different systems cross, the modes can couple and consequently a resonance phenomenon can occur. As a result, the Coleman diagram can be used to identify critical rotor speeds at which ground resonance can occur. For the high frequency lead lag mode, the progressive mode, the coupling is smooth. On the contrary, instabilities only occur when the regressive mode is coupling with one of the fuselage mode frequencies (red rectangles in figure 4).

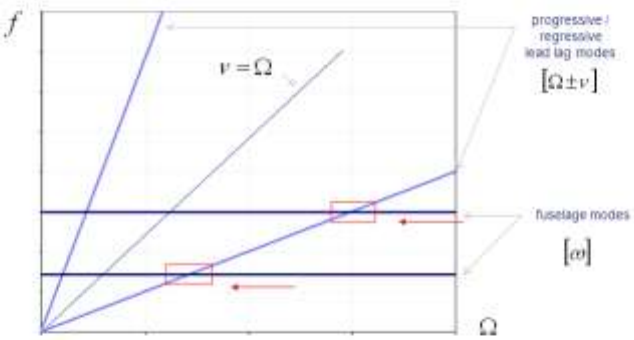

Fig. 4 Coleman diagram

3 Multi-body Simulation model

3.1 Rigid blade model

First, a multi-body model of an articulated rigid blade was created in LMS Virtual.Lab Motion. This model was based on blade definition [5] that was provided by AgustaWestland in the European research project JTI Clean Sky – Green Rotorcraft [1] where LMS is an associate member. The reason is that is a realistic description of a blade for a heavy helicopter and that the modal behaviour of the blade was available and hence the dynamic behaviour of the model could be validated. The blade is a fully articulated blade with the lead-lag, flap and pitch hinges at the same location. Therefore, this hinge was modelled with three coincident revolute joints. Each joint had a rotational spring associated with a non-linear stiffness curve to model the end-stops that limits the maximum deflection of the blade. As the lead-lag damper, a damper element associated with the specified non-linear damping curve was used. This damper is connected between the hub and the blade. Also a quarter of the rotating swash plate was modelled and connected to the blade with a stiff spring that represented the push rod with specified stiffness.

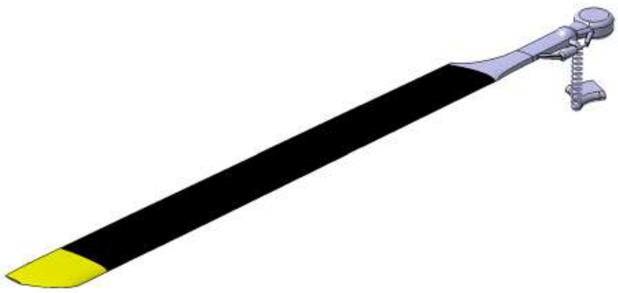

Fig. 5 LMS Virtual.Lab rotor blade model

In order to validate the dynamic behaviour of the blade model, a modal analysis can be performed to assess its natural frequencies of the fundamental lead-lag and flap modes at different rotational regimes. This can be compared with the data provided on reference blade in the Clean Sky GRC project. To determine the natural frequencies of the blades, a linearization was performed at every time step during a multi-body simulation. Consequently, at every time step, the eigenvalues and eigenvectors of the blade are obtained at a specific rotation speed. This is plotted in the Campbell diagram as shown in figure 6 for the fundamental lead lag and flap mode. Also the pitch mode can be derived by is not shown. The

Coleman diagram that was shown in figure 4 can then be derived.

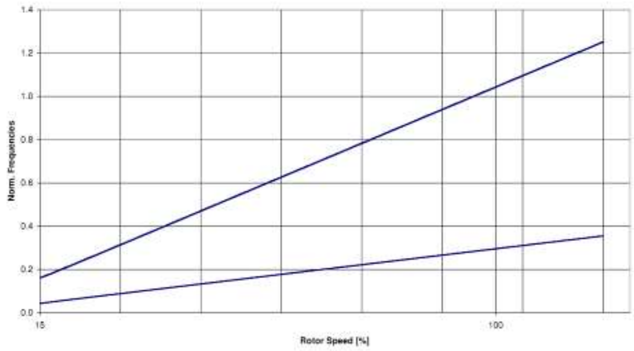

Fig. 6 Campbell diagram with first lead-lag and first flap mode

Comparison with the reference data of the blade from AgustaWestland, indicated that the computed frequencies at nominal rotation have an error of less than 1%.

3.2 Landing gear model

For the landing gear, an already existing model of a heavy helicopter tricycle landing gear was used [6]. This model is composed of a main landing gear (MLG) with each wheel an oleo strut and a nose landing gear (NLG) with also an oleo strut. The configuration is shown in figure 7 below.

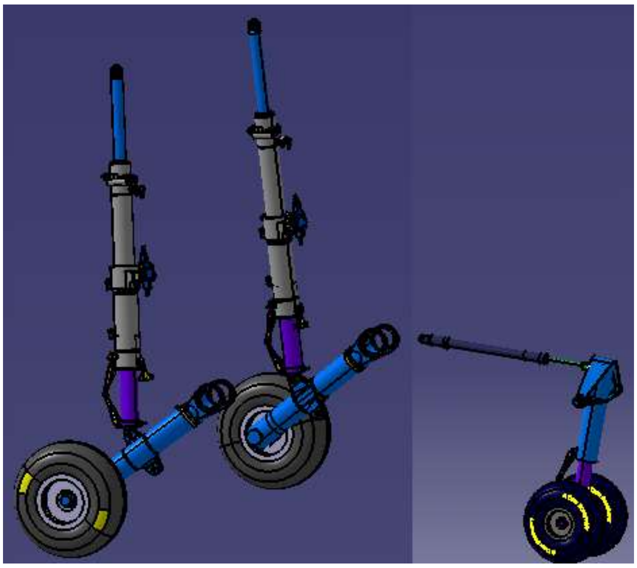

Fig. 7 LMS Virtual.Lab landing gear model

In the original model, the oleo struts were represented by a detailed hydraulic model and therefore could account for its non-linear behaviour. However, in this investigation, the detailed non-linear behaviour was in first instance not required. Therefore, the detailed hydraulic models of the oleo struts were replaced by simple spring model to decrease complexity of the model and computational time. Furthermore, the flexibility of the landing gear also included the tyre models however these were kept from the original model.

To obtain the pitch and roll modes, a simulation with linearization was performed on the landing gear with fuselage model. The total mass of the rotor was added a lumped mass at the location of the rotor hub. As the fuselage was considered rigid, the roll and pitch modes of the fuselage are the results of the stiffness of the oleo strut and the tyres. It is noted that there are 2 pitch modes of the fuselage: 1 mode is the pitch of the fuselage around the main landing gear and the other mode is the pitch around the nose landing gear. Furthermore, there is a roll mode due to the flexibility of the main landing gear.

Rigid fuselage mode	Resonance frequency
Roll Mode	0.9 Hz
Fuselage Pitch on NLG Mode	1.8 Hz
Fuselage Pitch on MLG Mode	2.2 Hz

Table 1. Rigid fuselage modes

3.3 Integrated model

To obtain a model that could simulate ground resonance, the landing gear model needed to be combined a rotor model that is based on four blades as described above. Therefore, the sub-mechanism functionality was used. This means that a stand-alone simulation model can be inserted multiple times as a sub-mechanism into new or another simulation model. In this case, this means that blade was introduced 4 times at 90deg into the landing gear model to achieve a full helicopter model with a 4-bladed rotor. Furthermore, a static swash was also added and connected to the rotating swash plates in the blade models. The vertical position and lateral and longitudinal angles of the static swash plate can be controlled and consequently the pitch of the blades. Finally, a velocity driver is used to impose a variable rotation on the rotating swash plate and rotor hub.

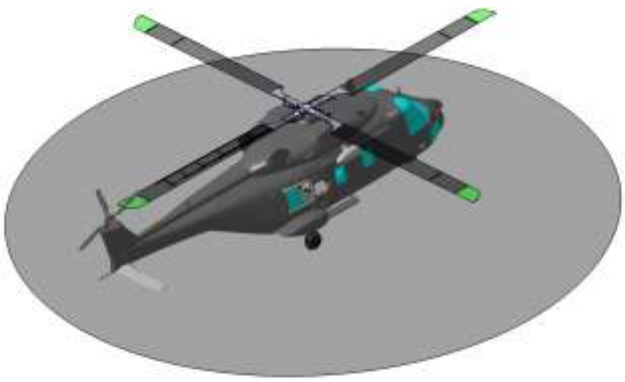

Fig. 8. Integrated helicopter model

4 Simulation results

4.1 Reference model

The simulation of the reference model was done in two analysis steps. The first analysis let the helicopter settle down on the ground without rotor rotation. The second analysis then used a “restart solution” from the previous analysis and subsequently increased the rotor speed. This approach was also used in the parameter studies that will be discussed in the next paragraph.

The reference model simulation was done with the rotor speed up from 0rpm to 300rpm in 500sec. This time was chosen in order that the transient effects would be minimal while the total simulation time would not be too long. During these simulations no linearization was performed but the behaviour of the model in the time domain was studied. In particular, the amplitude of pitching and rolling of the fuselage were of interest as this would indicate the excitation of the corresponding modes. Therefore, any peaks in this behaviour would indicate the occurrence of ground resonance. As the rotor speed varies at a predefined rate, the timing at which these peaks occur will indicate the critical rotation speeds. These speeds can be compared to the rotor speeds that are predicted by the Coleman diagram.

In figure 9a, the Coleman diagram shows the regressive lead lag mode (the blue line in the image) and the fuselage modes (green and light / dark orange lines) based on the linearization of the separate rotor and landing gear models. Figure 9b shows the roll amplitude of the fuselage as a function of time which corresponds with the rotor speed in figure 9a.

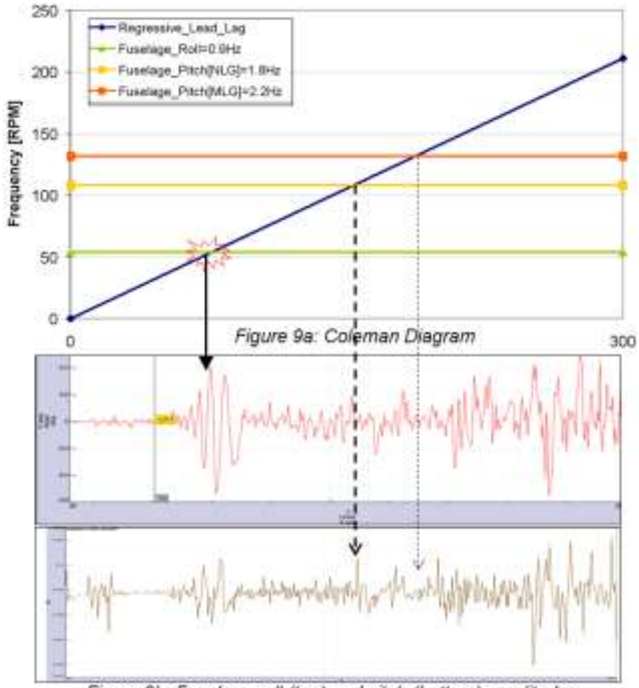

Figure 9a: Coleman Diagram

Figure 9b: Fuselage roll (top) and pitch (bottom) amplitude

As can be seen in the above figure, at the rotor speed where the Coleman diagram indicate an interaction between the regressive lead lag mode and the fuselage role mode, a large excitation of the roll amplitude occur during the simulation of the rotor blade. This also has an effect on the pitching of the helicopter. As the rotor speed further increases and hence moves away from the critical rotor speed, the roll behaviour reduces again. As to rotor speed passes the critical speeds for fuselage pitching, some peaks in pitch amplitude occur but this is less pronounced. Consequently, it can be observed that the multi-body model of the integrated helicopter seems to correctly simulate the ground resonance behaviour of the helicopter. However, to increase to confident in the simulation results and to ensure that the results were not merely a coincidence, a set of parameters studies were performed and the results compared with the corresponding Coleman diagram.

4.2 Parameter studies

4.2.1 Lead lag damping

The damping in the lead lag damper of each of the 4 blades was decreased. As the main purpose of these dampers is to reduce the lagging amplitude of the blade, it is anticipated that this would have a major effect on the roll amplitude and so vibration level during ground resonance. However, it would not affect the Coleman diagram and hence the critical rotor speeds as the natural frequencies of the blades and fuselage are not affected by the lead lag damping.

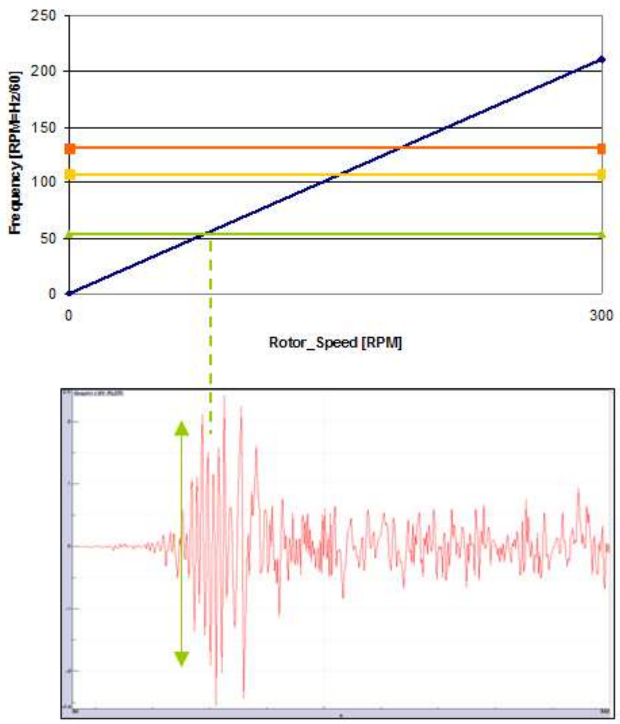

Fig. 10. Reduction of lead-lag damping

The results depicted in figure 10 shown that the model behaviour corresponds with the expectation as described above. This means that the timing and therefore the rotor speed at which the roll resonance occurs is not change but the amplitude is much increased due to the decrease of the damping in the lead lag damper.

4.2.2 MLG Stiffness

In this simulation, the stiffness of the main springs in the main landing gears was reduced. As a result, the natural frequencies of the roll mode and pitch mode around the nose landing gear decrease. The Coleman diagram indicates then that the 2 corresponding critical speeds will be lowered.

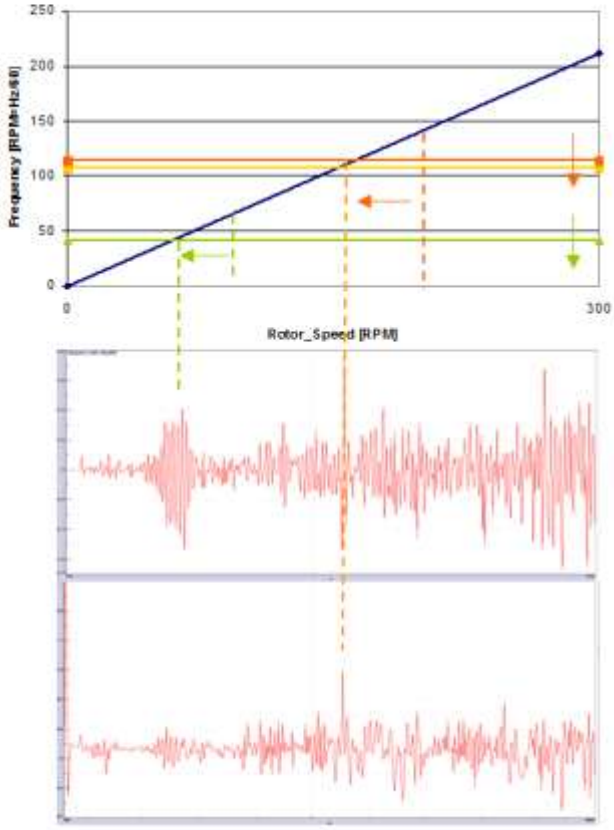

Fig. 11. Reduction of MLG stiffness

The results in the figure above show that the roll excitation occurs now earlier corresponding to the Coleman diagram.

4.2.3 Helicopter mass

In the final simulation, the total mass of the helicopter is reduced. As a result, all three fuselage modes are increased and consequently, the Coleman diagram predicts an increase in the critical speeds. However, the critical speeds due to the coupling of the rotor mode with the helicopter pitching modes are now higher than the nominal rotor speed. Hence, ground resonance can now only occur due to roll mode of the helicopter.

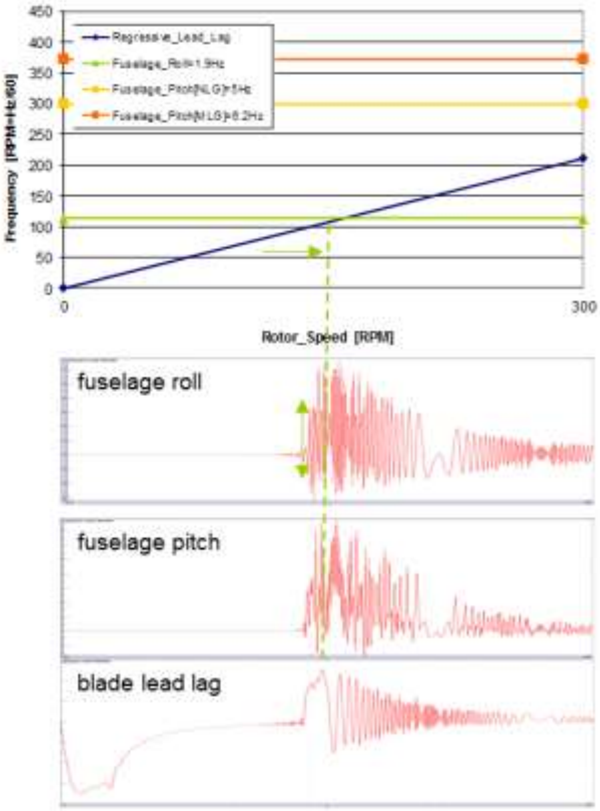

Fig. 12. Reduction of helicopter mass

Again, the simulation results are corresponding to the Coleman diagram. At the bottom of figure 12, also the amplitude of the lead lag angular displacement is shown. Furthermore, note that the amplitude of the fuselage vibration has increased considerable due to the lower weight of the helicopter.

5 Conclusions

5.1 Results

In conclusion, the process used to analyse the ground resonance phenomenon led to encouraging results, that lays the groundwork for future ground resonance investigations. Indeed, with LMS Virtual Lab Motion, it is simple to create a rotor model with rigid blades and validate the fundamental modes. It is also easy to identify the landing gear modes with the linearization of helicopter model. Moreover it is straightforward to integrate the rotor model in the helicopter parent model using sub mechanisms. The integrated model shows coupling effects due to the resonance between the regressive lead lag mode of the blade, and the excitation of roll and pitch of the fuselage at the correct rotor speeds as predicted by the Coleman Diagram.

Further parameter studies showed coherent ground resonance behaviour of the integrated helicopter model for all investigated configurations at different rotor speeds that resulted in a shift of the coupling point. This has increased the confidence in the results but validation is still required. Consequently, it confirms that LMS Virtual. Lab Motion can be used to simulate ground resonance of helicopter by coupling multi-body models of the landing gear system and the rotor system with rigid blades. Therefore, the occurrence of ground resonance can be more easily predicted for different configuration and conditions and design changes can be evaluated.

5.2 Future Work

Future work can continue with parameter studies to confirm the model behaviour, e.g. including the effect of flexible fuselage. Furthermore, simulations could be undertaken with an LMS Imagine.Lab AMESim co-simulation for an accurate hydraulic model of the oleo strut. Moreover, it would be very interesting to investigate the simulation of ground resonance during lift-off and landing which results from the non-linear stiffness of the landing gear. However, therefore the integrate helicopter model would have to be extended with a tail rotor to compensate for the main rotor torque and this will also require a controller to ensure the stability of the helicopter during flight.

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