INFLUENCE OF CONTACT POINTS OF SKID LANDING GEARS ON HELICOPTER GROUND RESONANCE STABILITY

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ABSTRACT
Soft-in-plane rotor systems are susceptible to a self-induced vibration phenomenon called ground resonance. This dynamic instability results from lag motions of the rotor blades coupling with airframe degrees of freedom while the helicopter is in ground contact. As an addition to previous slope landing studies and investigations of non-linear landing gear effects, this work focuses on a systematic study of partial skid contact using different landing modelling approaches and contact definitions. This paper is part of a larger study to investigate the influences of partial ground contact and soft terrain on helicopter dynamic stability during landings. It is the long-range objective to reduce the necessity of extensive flight tests prior to helicopter certification processes.

1. INTRODUCTION

The lead-lag motion of the rotor blade in the rotating system can be transformed into the non-rotating reference frame. This leads to a progressive $|\Omega + \omega_\zeta|$ and a regressive component $|\Omega - \omega_\zeta|$ of the lead-lag eigenfrequency, with $\Omega$ as the rotation frequency and $\omega_\zeta$ as the lead-lag frequency in the rotating system. Critical for ground resonance is the regressive lead-lag motion since its frequency can be in the same magnitude as some of the airframe motions. The ground resonance has a low-frequency characteristic usually located in a frequency range of less than 5 Hz. The dynamic behaviour of the helicopter airframe in this frequency range is largely determined by the landing gear elasticity and its contact to the ground. The models and simulation results in this paper focus on helicopters with skid landing gears as they are in general used for light and medium weight helicopters. Due to smaller nacelle inertias these helicopters are also more susceptible to self-induced vibrations phenomena. In comparison to helicopters with wheels they usually do not have additional landing gear dampers. The landing gears dynamic behavior is mainly determined by the structural stiffness and damping as well as its contact to the ground.

Full skid contact raises the eigenfrequencies of the helicopter fuselage, increasing the stability margin for ground resonance. For operative landing scenarios full contact conditions cannot be guaranteed. In rocky terrain the skids may only have partial contact to the ground, leading to fuselage eigenfrequencies closer to the regressive lead-lag eigenfrequency. Additionally, different friction and damping effects in comparison to full contact scenarios can also influence the dynamic stability of the helicopter. If ground resonance occurs, immediate take-off or abortion of the landing will stop the oscillation. Classical ground resonance has been extensively studied. However, there has been significantly less attention on stability analysis of helicopters in exotic, operational landing conditions. This encompasses landings in rocky terrain, in pits or on guardrails, for example during rescue operations.

2. PRELIMINARY STUDIES

As a first step to understand non-linear effects during partial ground contact, the author created a simplified helicopter model whose structure is sketched in Figure 1. The use of the multibody-software SIMPACK allows the straightforward definition of multibody-systems and the linear or non-linear dynamic simulation of finite-element structures and modal reduced flexible bodies. Nonlinear system behavior is expected due to contact conditions.

The model consist of a 4-bladed rotor with rigid blades, which are attached to a hub by spring-damper elements, as seen in Figure 2, as well as a rigid airframe and two non-linear spring-damper elements in x-direction, the longitudinal direction of the fuselage. The airframe only allows movement in the said direction.

The landing gear stiffness was chosen as $k = 370000 \text{ kg/s}^2$, the damper constant as $d = 110000 \text{ kg/s}$ and the airframe mass as $m = 1906.4 \text{ kg}$ to resemble a B105 helicopter, leading to the simple model seen in Figure 3. The deflection...
scripts for the analysis methods used for the study of varying contact areas. This encompasses time simulations with sweeps over the rotor rotation frequency, the monitoring of marker movements at the airframe, hub and landing gear as well as a first test for the determination of vibration decay ratios. These analysis methods are later used for more complex models and are described in detail in Section 3. Additionally, the model was used to reproduce the results of previous analytical studies with the multibody simulation tool SIMPACK. The first structural analysis confirmed that the model shows non-linear behaviour like the appearance of periodic solutions in time simulations for partial ground contact.

Preliminary time integrations showed that the variation of the spring-damper deflection height has a significant influence on the dynamic behaviour of the helicopter model, as described by \( g \). This indicates the significant influence of partial ground contact on ground resonance stability. Variations of this model were used to test contact modelling options in SIMPACK. This preliminary work motivates further and more advanced studies concerning more unusual ground contacts. These landing condition will be denoted 'operational landing conditions' in the following.

3. ANALYSIS

To expand the investigation of landing gear-ground interaction, the system's dynamic response to contact point and contact area variation is studied. The flexible landing gear model shown in Figure 7 is chosen for this task. It is attached to a rigid B0105 fuselage.

The contact forces are modelled using SIMPACK force elements. Figure 4 depicts the contact con-
figurations studied in this work. These conditions, originally defined by Donham\textsuperscript{10}, serve as a first set of operational landing conditions. They are intended to resemble real landing conditions on rocky terrain, in pits or on guardrails. Furthermore, in case of local contact, as shown in the top right corner of Figure 4, the position of the contact is varied along the skid. Typically in stability analysis for numerical landing gears, the models are linearized with respect to a working point. This neglects the non-linear effects due to partial contact or soft ground conditions. Therefore, the analysis method for the proposed paper follows the approach given in \textsuperscript{2}. To account for non-linear behaviour, time simulations are conducted and the time history signals of sensors at the landing gear, airframe and hub are monitored. In case of instability the divergence of this signals can give basic information on the involved, coupled modes. The model has limits to its possible physical behavior due to gravity enforcing ground contact and the ground itself, which restricts its motion. These physical constrains implies the system signal behavior. In full contact the system time response resembles the one of the classical ground model. The other extreme represents no contact at all with airborne condition. The study of the time signal within these boundary therefore resembles a bounded-input, bounded-output (BIBO) stability analysis.

This approach is suited for contact or friction, but does not account for the full set of modes. For every mode of interest a corresponding set of sensors has to be selected. The dynamic behaviour of each configuration is studied by the time response of the system after a sudden impulse excitation in blade lag direction. Vibration decay ratios are used as a measure for instability. This study is repeated in sweeps over the rotation frequency to visualize the save margin of frequencies. The resulting changes in fuselage frequencies are determined by a frequency analysis of the time response. They are correlated to frequency margins of the rotor blade regressive lead-lag motion in the non-rotating system $\zeta_{reg}$, which is shown in Figure 5. The eigenvalues in the nonrotating system are plotted over the rotation frequency. In addition to the collective and differential lead-lag motion $\zeta_0$ and $\zeta_d$, the progressive lead-lag motion $\zeta_{prog}$ and the regressive lead-lag motion $\zeta_{reg}$ are shown. Moreover, the eigenvalues of the translational hub degrees of freedom in x and y direction are shown. The transformation of the blade motion into the nonrotating frame and the calculation of the eigenvalues was done independently from the eigenvalue calculation of the hub motion in x and y direction. Therefore, the curves do not show the interaction of these degrees of freedom. Ground resonance can occur, where the curves of the regressive lead-lag motion and the hub motion cross.

![Figure 4: Donham contact cases\textsuperscript{10}](image)

![Figure 5: Eigenvalues in the nonrotating system dependent on the rotation frequency; collective and differential blade motion $\zeta_0$ and $\zeta_d$; regressive and progressive lead-lag motion $\zeta_{reg}$ and $\zeta_{prog}$, hub motion in x and y direction](image)

The above mentioned frequency analysis of the time signal serves as a systematic classification of critical landing configurations. In the end, the influence of contact properties like contact location and contact area are varied. The resulting changes in damping behaviour are compared to the reference case of full ground contact. This is done to provide a detailed study of the influence of the skid contact area on the helicopter’s stability in ground contact. Aerodynamic forces can be neglected\textsuperscript{11}. The goal of this investigation is not to accurately remodel ground terrain in detail, but to understand the influence of partial ground contact on reso-
nance stability and in order to find a usable analysis method for skid contact configurations.

3.1. Structural Model

The helicopter structure is modelled using the multibody-software SIMPACK to allow dynamic studies. The model consist of rotor, airframe and landing gear as shown in Figure 6. The elasticity of the landing gear dominates the low frequency spectrum of the helicopter model. Therefore, the fuselage is modelled as a rigid body. Its mass, inertia and size are chosen in reference to the BO105. The connections points for the landing gear model are located at the same position as the real landing gear attachments.

The time simulation uses two different rotor models. For preliminary studies a rotor with rigid blades is used. Spring elements at the blade-hub connection ensure a lead-lag mode corresponding to the real BO105 blade. In addition to that, an existing flexible rotor model is used. A detailed description of this blade model is given in Reference 13.

3.2. Landing Gear Models

As a first step to study the influence of contact conditions on the ground resonance of helicopters, the author modelled an elastic landing gear system as illustrated in Figure 7. The landing gear represents an assembly of aluminium tubes. It is modelled as 1D-Euler-Bernoulli beams in the SIMPACK-internal FE-module SIMBEAM. The cross-sectional diameters and material properties are based on the BO105. Since the behaviour of a skid landing gear is to be studied in general, there is no need for a perfect fit with the real helicopter skid landing gear during first simulations. This model is used as a first research basis and will be updated and improved continuously. The skids of the landing gear consists of 20 1D-Euler-Bernoulli beam elements. The rear and front boom are modelled as separate bodies by 14 finite elements. The landing gear is rigidly constraint to the helicopter fuselage.

In addition to the simplified landing gear model in Figure 7, contact studies are prepared for a EC135 landing gear imported into SIMPACK as a modal reduced flexible model. This FE-MBS coupling allows the simulation of complete mechanical systems. In the MBS analysis the flexible body's motion is described by a modal representation with considerably small number of modal coordinates in comparison to the large number of nodal coordinates in finite element programs. This allows to predict the dynamics of a mechanical system with relatively low computational costs. This modal reduction of a FEM structure is the standard approach to implement more detailed models in most multibody dynamic simulations.

To implement the landing gear model of DLR's EC135 Flying Helicopter Simulator (FHS) several processing steps in the finite element software ANSYS and SIMPACK are necessary. SIMPACK uses flexible body input files (.fbi) to enable the integration of flexible bodies from finite element codes such as ANSYS.

These files combine information about the original finite element mesh and geometry, the boundary conditions and the representation of the original structure in modal form. The latter is determined by a component mode synthesis (CMS) as described in 14. The CMS reduces the system matrixes to a smaller set of interface degrees of freedom and normal mode generalized coordinates. These information are provided by the finite element program ANSYS.

Starting with the original CAD data of the FHS as given in Figure 8, the geometry complexity was reduced. The CAD was origially created for construction purposes. For a modal analysis this level of detail only marginally improves the results and would not justify the massive effort to create a suitable mesh. Figure 9 shows the geometry simplification. In ANSYS geometrical contacts and structural compounds can be modelled by contact elements. However, SIMPACK is not able to process
such elements in the generation of the flexible body input files. Therefore, after the initial mesh generation, node merges were used to modify the mesh. The result is visualized in Figure 10.

To provide an interface between the FE structure and the MBS model, so called “master nodes” are explicitly selected during the reduction of the finite element structure. These nodes are later used as marker position in the MBS simulation. Bearings encompassing the landing gear brackets are defined and shown in Figure 11. The reference nodes of these bearings are defined as master nodes, because at this position the landing gear will be attached to the rest of the helicopter structure.

For the CMS the Craig-Bampton method is used, defining the interface as fixed. The reduced model, sometimes called superelement, considers the first thirty modes. The result file (.sub) containing the superelement, the result file of the recovery matrix (.tcms) containing the data recovery (nodal DOF solution) for all nodes and the FE geometry file (.cdb) are imported into SIMPACK and the .fbi-file is generated.

The resulting model in SIMPACK, visualized in Figure 12 gives a detailed representation of the original flexible model. The predefined interface nodes allow to attach SIMPACK contact force elements like 3D contact element which depend on the exact geometrical deformation of the given model. It is therefore essential to include such a model in the study of operational contacts.
3.3. Contact Simulation

In previous works dedicated grids of the skids were clamped to the ground. But this contact simulation has the disadvantage of unrealistic forces and moments that can build up in the contact due to constraint degrees of freedom. In flight tests similar contact conditions can only be achieved by dedicated pilot inputs forcing the helicopter into ground contact. To find alternatives to this approach, two types of contact representation were tested in the SIMPACK model. The SIMPACK force element "Unilateral Spring-Damper" is able to define the vertical (z-component) of the contact. It also allows to specify the area in which the contact laws are defined and can be used with friction models like stick-slip friction. This type is currently used for time simulations. The second contact type is the polygonal contact method (PCM). This force element is able to detect and model 3D multi-point contacts. It bases the calculation of contact forces on the parts' geometry, allowing the full description of skid contact in vertical and horizontal direction. This gives a more realistic representation of real world contacts. The contact type bases the calculation of the contact force on the model geometry and its material properties. This contact type is currently tested using the flexible modal EC135 landing gear model described in Section 3.2. Additionally, this contact allows a more detailed study of soft ground conditions for future studies, since it allows flexible-flexible multi-point contacts.

A representation of the model setup is shown in Figure 13.

![Figure 13: Visualization of principal of contact area variation](image)

The model is connected to the ground via the landing gear skids and its variable hatched marked contact areas shown in Figure 13. The size of these contact areas is varied, ranging from full contact, representing the classic configuration, to partial ground contact according to the Donham testcases described in Figure 14. The early studies described in this work use four contact patches of equal size, starting at both ends of the skid as visualized in Figure 13. In future studies asymmetrical configuration will be used as well. The contact forces are applied at the nodes of the 1D-Euler-Bernoulli beams which is exemplary shown in Figure 14. Additional friction elements act directly on these force elements, which are in the foreground of Figure 14. The contact elements are only applied to those regions of the skid which have contact with the ground represented as the ocker areas in Figure 14.

Figure 14: SIMPACK contact element applied to landing gear

4. DISCUSSION OF RESULTS

In order to review the generation of the flexible modal landing gear of the FHS and its usability in SIMPACK, the eigenfrequencies of the modal reduced model were compared to the one with an elastic bearing with a base stiffness of $3e08 \text{ N/m}^3$ at the landing gear attachment points. The eigenfrequencies in Table 1 show a significant difference between these two types of attachment. The relative difference of the elastic attachment is given with reference to the fixed one. For reasons of model simplification a fixed attachment is choosen for all landing gear models in this work. Therefore, this difference has to be keep in mind for all simulation results.

As a first preliminary analysis to verify the MBS approach for ground resonance studies, a Coleman-Feingold model was implemented in SIMPACK. This model encompasses four rigid rotor blades, which are elastically attached to a center mass. The system encompasses the lead-lag degree of freedom for the blades and the translational ones for the mass. As described in Section 3 the blade motion is transformed into the non-rotating system and an eigenvalue analysis is performed. Plotting the real part of the translational degrees of free-
Table 1: Eigenfrequencies of FHS landing gear modes for fixed boundary conditions

<table>
<thead>
<tr>
<th>Modes</th>
<th>Attachment</th>
<th>Elastic Attachment</th>
<th>Absolute Difference</th>
<th>Relative Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>18.818 Hz</td>
<td>14.610 Hz</td>
<td>4.208 Hz</td>
<td>-0.213</td>
</tr>
<tr>
<td>2</td>
<td>31.171 Hz</td>
<td>24.201 Hz</td>
<td>6.970 Hz</td>
<td>-0.224</td>
</tr>
<tr>
<td>3</td>
<td>32.045 Hz</td>
<td>26.628 Hz</td>
<td>5.417 Hz</td>
<td>-0.169</td>
</tr>
<tr>
<td>4</td>
<td>33.860 Hz</td>
<td>53.819 Hz</td>
<td>19.959 Hz</td>
<td>+0.589</td>
</tr>
<tr>
<td>5</td>
<td>35.764 Hz</td>
<td>59.856 Hz</td>
<td>24.092 Hz</td>
<td>+0.674</td>
</tr>
<tr>
<td>6</td>
<td>58.480 Hz</td>
<td>66.714 Hz</td>
<td>2.234 Hz</td>
<td>+0.038</td>
</tr>
<tr>
<td>7</td>
<td>62.454 Hz</td>
<td>69.958 Hz</td>
<td>7.504 Hz</td>
<td>+0.120</td>
</tr>
<tr>
<td>8</td>
<td>70.166 Hz</td>
<td>74.136 Hz</td>
<td>3.970 Hz</td>
<td>+0.057</td>
</tr>
<tr>
<td>9</td>
<td>72.956 Hz</td>
<td>78.998 Hz</td>
<td>6.042 Hz</td>
<td>+0.083</td>
</tr>
<tr>
<td>10</td>
<td>75.561 Hz</td>
<td>82.237 Hz</td>
<td>6.676 Hz</td>
<td>+0.088</td>
</tr>
</tbody>
</table>

Figure 15: Hub motion eigenvalues in x- and y-direction

To test the approach described in Section 3, time simulations for the simplified SIMPACK model were performed. The result of the filtered time signal of a sensor at the hub is visualized in Figure 16. A Butterworth filter of order 4 was used to eliminate high frequency components and to reduce numerical noise. The signal plot starts after a sudden impulse excitation at 63 seconds. For a large set of test cases the decay ratio can be calculated automatically by measuring the local peaks and their progression in time. This indicates whether a periodic solution, decreasing or an increasing oscillation occurs. In the presented case a periodic time response can be observed. This clearly shows the non-linear dynamic behavior due to partial ground contact. It has to be mentioned, that the decreasing amplitude at the end is a result of signal processing by the Butterworth filter. The results of this MBS model correlate with the results presented in chapter 5 of [7].

Figure 16: Filtered sensor measurement of longitudinal hub motion

The approach of Section 3 is applied to the SIMPACK landing gear model of Figure 6 with full ground contact. The model mass and the landing gear stiffness were chosen in a way to give similar frequencies as in the simplified Coleman model. The contact patches as illustrated in Figure 13 stretch the full length of the skids on both sides. The model is time integrated for 60 seconds to let the ground contact to "settle in". Assuming enough lead-lag damping the helicopter model should not get into resonance without artificial excitation at 62 seconds. A sudden excitation of 500 N in the chord direction of the first and third blade is applied as show in Figure 17. The excitation impulse is exemplary shown in Figure 18. The system reaction is measured for a rotation frequency sweep from 0.1 to 1.8 times the reference rotation frequency.
of 44.4 rad/s. Exemplary, the results for the test case at 14.208 rad/s is presented. Figure 18 shows the original signal of the marker at the hub in y-direction,correlating to the models roll movement.

![Graph showing original signal of hub motion in y-direction](image1)

**Figure 18:** Original signal of hub motion in y-direction

The signal is filtered using a Butterworth filter of fourth order as described above. The selected bandwidth is visualized in Figure 19, eliminating higher frequency noise. The resulting signal used for further processing is given in Figure 20.

![Graph showing used bandwidth for Butterworth filter](image2)

**Figure 19:** Used bandwidth for Butterworth filter

![Graph showing visualization of equivalent logarithmic decrement](image3)

**Figure 20:** Filtered signal of hub motion in y-direction with peaks

From this filtered signal a subset of peaks was selected to determine the decay ratio using the logarithmic decrement. It has to be mentioned, that the logarithmic decrement is a measurement parameter often used to calculate the damping coefficient of linear systems. Here, it is used in a general sense to visualize the systems damping behavior. It is plotted over the rotation frequency shown in Figure 21.

![Graph showing visualization of equivalent logarithmic decrement](image4)

**Figure 21:** Visualization of equivalent logarithmic decrement

For this contact configuration the presented approach delivers the expected results. The decrease at around 1.2 times the reference frequency matches the result of the classical model. The result shows unsteady, non-vertical course up to 1.1 times rotation frequency. The quality of the results has to be improved in the future to meet scientific standards. Therefore, additional tests are necessary.

When the contact area is reduced, one encounters several difficulties for this analysis approach. The signal of the hub motion shows sudden unsteady signal variations, as shown in Figure 22. Additionally, the peak finding algorithm has to be improved to avoid or at least reduce additional manual processing for cases as those in Figure 23. For this purpose other filter types, like a lowpass filter, are currently tested. Beside the analysis approach in this paper, additional analysis methods for the MBS model are tested like Ljapunow function ap-
proximation. These results summarize the current status of the project. The study of variable skid contact is still a work in progress. Improved and more extensive results will be presented in future publications.

5. CONCLUSION

This work represent the current status of the ongoing study of the influence of partial ground contact on ground resonance stability. It is a work in progress and has to be evaluated as such. At the moment SIMPACK models necessary for this study are defined and contact definitions are established. This includes a simple helicopter model with flexible landing gear and contact force elements including friction. Routines for the stability analysis of non-linear systems based on the measurement of time signals after sudden excitation are implemented. This includes signal post-processing like filtering the time signal. First analysis are conducted delivering correct results for the classic Coleman and Feingold model and the simplified non-linear model in SIMPACK. Typical nonlinear system characteristics could be reproduced in accordance with the literature results. The analysis methods for the finite element flexible landing gear model from Figure 6 produce reasonable results for a model in full contact. For a model in partial ground contact this method does not deliver the desired scientific results. The first results presented for these test cases illuminate the difficulties of studying the nonlinear contact conditions. The extension of the described analysis methods to these landing conditions is the focus of current efforts. In addition to the simulation based analysis approach of ground resonance stability methods to derive a mathematical model are studied. The tool chain to implement flexible modal landing gears based on complex finite element tools is working. Using these models and more sophisticated multi-point contact elements is expected to deliver better results and will be used as a basis for future landing gear models. The frequency analysis of airframe sensors as described in Section 3 is still pending but will be presented at the next European Rotorcraft Forum.

REFERENCES


