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. Special focus is given to different methods of contact simulation, using 3d spring-damper elements and polygonal contact elements. 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 Ω as the rotation frequency and ω_ζ as the lead-lag frequency in the rotating system[1]. 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[2].
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[2]. 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[3]. 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[1,4,5]. 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, a simplified ground resonance model for helicopters was created as sketched in Figure 1. The use of the multibody-software SIMPACK allows the straightforward definition of multibody-systems and the linear or nonlinear dynamic simulation of finite-element structures and modal reduced flexible bodies.

Nonlinear system behavior is expected due to contact conditions[6].

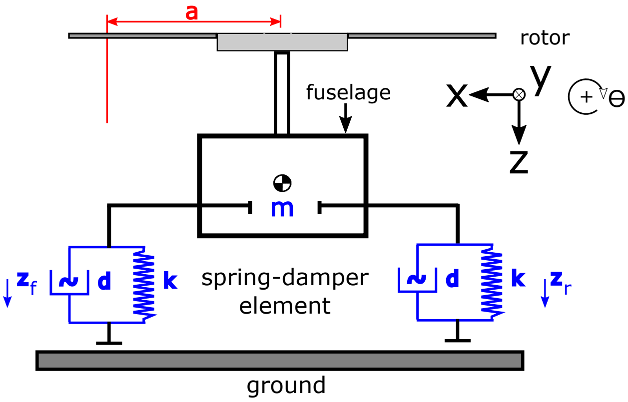

Figure 1: Setup of simplified ground resonance model

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. Additionally, two non-linear spring-damper elements are used to represent the landing gear. They are placed at the front (index f) and rear (index r) of the rigid airframe, allowing the helicopter to pitch in the longitudinal direction of the fuselage. Other movement directions are constrained.

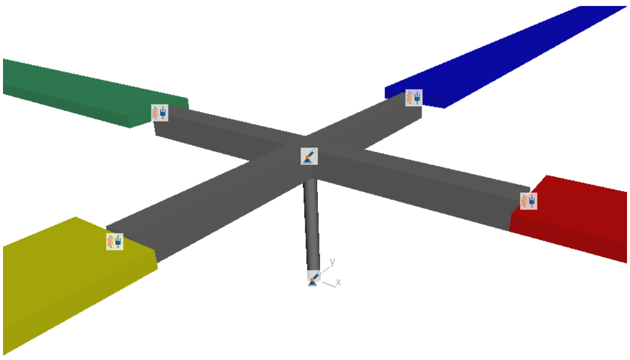

Figure 2: Rotor model with four rigid blades

The landing gear stiffness was choosen as $k = 370000\,kg/s^2$, the damper constant as $d = 1100000\,kg/s$ and the airframe mass as $m = 1906.4\,kg$ to resemble a Bo105 helicopter[7], leading to the simple model seen in Figure 3. The deflection at the front element is described by $z_f = z - a\Theta$, with a being the horizontal distance to the airframe centre of gravity and Θ as the pitch angle of the airframe relative to the ground. The rear deflection is given by $z_r = z + a\Theta$.

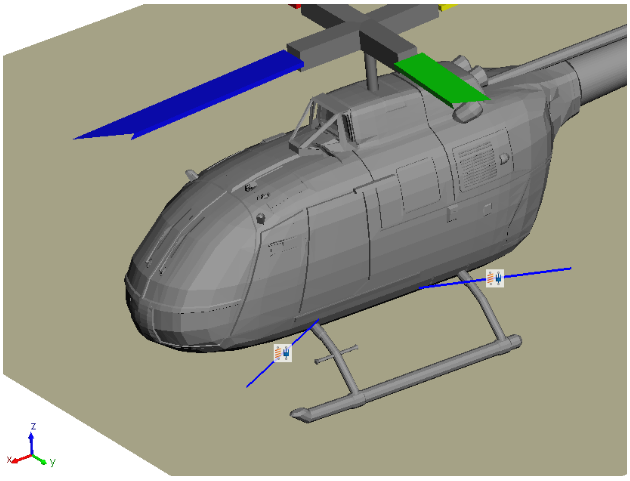

Figure 3: Simplified model in SIMPACK

The non-linear spring-damper forces are given by[8]

$$F_{f,r} = \frac{1}{2}k\left(z_{f,r} + \sqrt{z_{f,r}^2 + \epsilon^2}\right) \cdot (1 + b\dot{z}_{f,r})\,. \tag{1}$$

In Equation 1, the factor ϵ denotes a small parameter for smoothing of the damping curve. The parameter b describes the nonlinear damping behavior.

$$b = \frac{2d}{k\left(\frac{mg}{2k} + \sqrt{\frac{mg}{2k}^2 + \epsilon^2}\right)}\,. \tag{2}$$

Here g denotes gravitational acceleration of $9.81\,m/s^2$.
The model allows to verify the typical analysis method using multiblade coordinate transformation[9]. Additionally, the model was used to test the 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[7] with the multibody simulation tool SIMPACK. First structural analysis confirmed that the model shows non-linear behavior 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 behavior of the

helicopter model, as described by[7]. 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. A flexible landing gear model described in Section 3.2 is chosen for this task. It is attached to a rigid Bo105 fuselage.
The contact forces are modelled using SIMPACK force elements. Figure 4 depicts the contact configurations studied in this work. These conditions, originally defined by Donham[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 nonlinear effects due to partial contact or soft ground conditions. Therefore, the analysis method in this paper follows the approach given in[2]. To account for non-linear behavior, 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 contrains 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 repreated 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 ς_{reg}, which is shown in Figure 5.

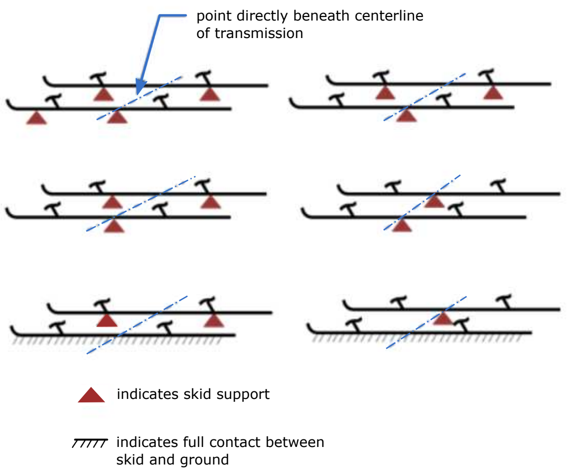

Figure 4: Donham contact cases[10]

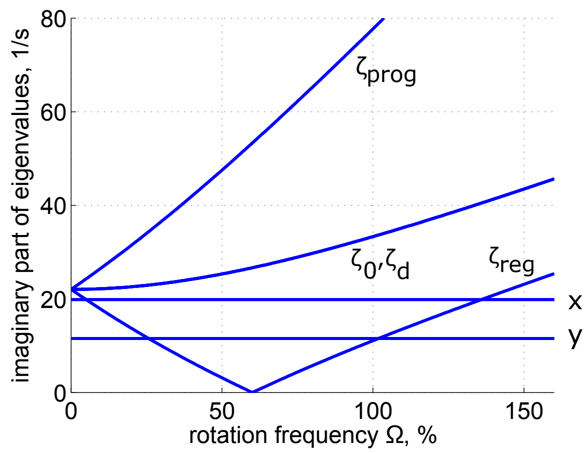

Figure 5: Eigenvalues in the nonrotating system dependent on the rotation frequency; collective and differential blade motion ζ_0 and ζ_d; regressive and progressive lead-lag motion ζ_{ref} and ζ_{prog}, hub motion in x and y direction

The eigenvalues in the nonrotating system are plotted over the rotation frequency. In addition to the collective and differential lead-lag motion ζ_0 and ζ_d, the progressive lead-lag motion ζ_{prog} and the regressive lead-lag motion ζ_{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.
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 behavior 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[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 resonance 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[12]. The model consist of rotor, airframe and landing gear as shown in Figure 6. The elasticity of

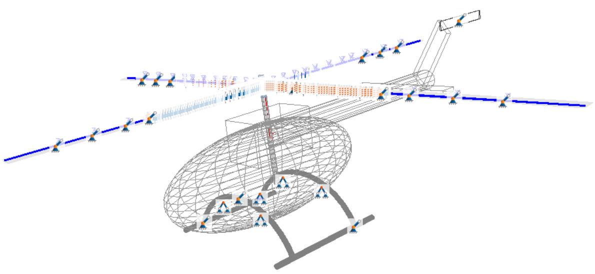

Figure 6: Helicopter model

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[7]. The connections points for the landing gear model are located at the same position as the real landing gear attachments.
The time simulation uses an adapted rigid blade rotor model. Spring elements at the blade-hub connection ensure a lead-lag frequency similar to real rotor blades. However, the damping properties and reference rotation velocity of the rotor model was modified, since the real Bo105 rotor is specifically designed to not be succeptible to ground resonance. The rotor model is used for all landing gear and ground contact models to simplifiy the post-processing.

3.2. Landing Gear Models

As a first step to study the influence of contact conditions on the ground resonance of helicopters, an elastic landing gear system as illustrated in Figure 7 was modelled. The landing gear represents

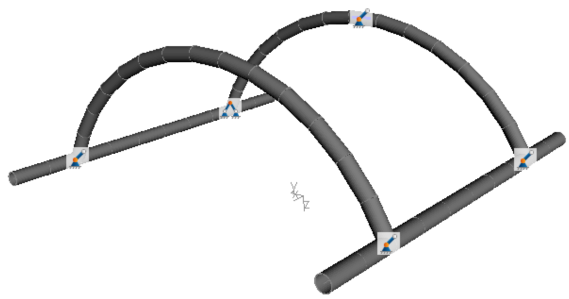

Figure 7: Elastic landing gear model

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 behavior 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 latteral is determined by a component mode synthesis (CMS) as described in[14]. The CMS reduces the system matrices to a smaller set of interface degrees of freedom and normal mode generalized coordinates. These information are provided by the finite element program ANSYS.

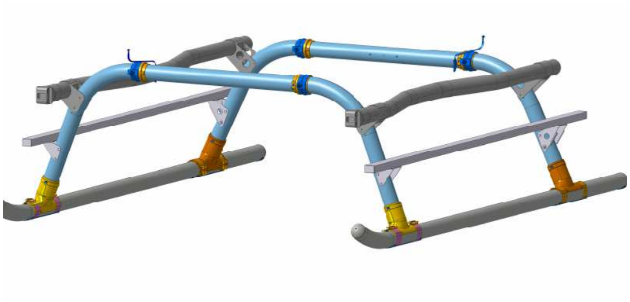

Figure 8: Original, fully detailed CAD model of the EC135 landing gear

Starting with the original CAD data of the FHS as given in Figure 8, the geometry complexity was reduced. The CAD was orignally 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.

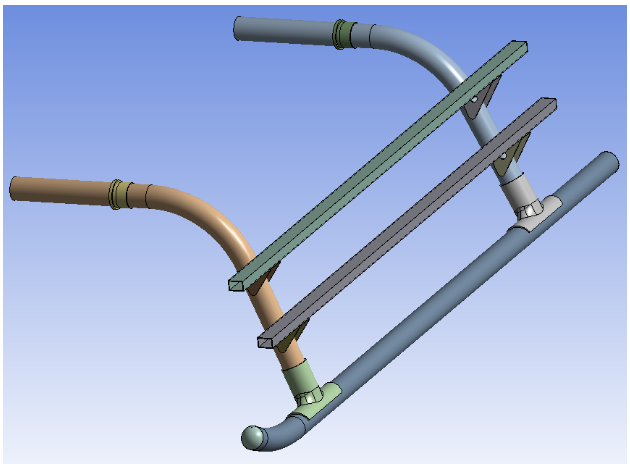

Figure 9: Simplified geometry

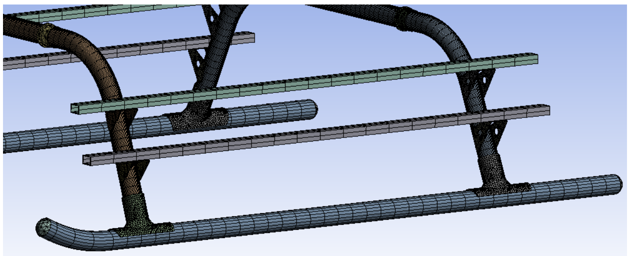

Figure 10: Mesh visualization

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. Moreover, it has to be ensured, that forces and moments acting on the bearing are correctly applied at the attachment marker. The corresponding ANSYS representation is shown in Figure 12.

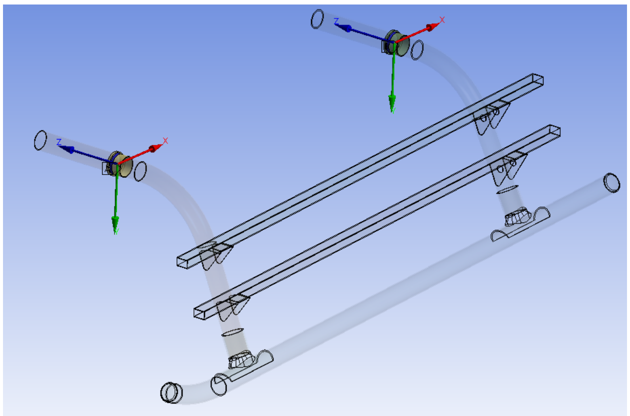

Figure 11: Landing gear interface for MBS

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 gen-

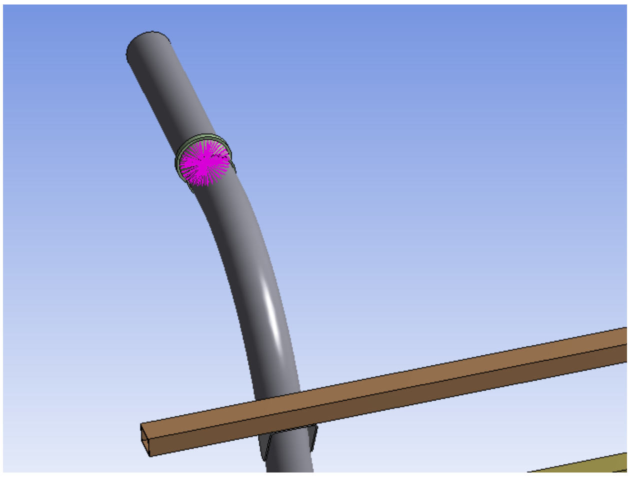

Figure 12: Bearing representation

erated.
The resulting model in SIMPACK, visualized in Figure 13 gives a detailed representation of the original flexible model. The predifined interface nodes allow to attach SIMPACK contact force elements like 3D contact element which depend on the exact geometrical defomation of the given model. It is therefore essential to include such a model in the study of operational contacts.

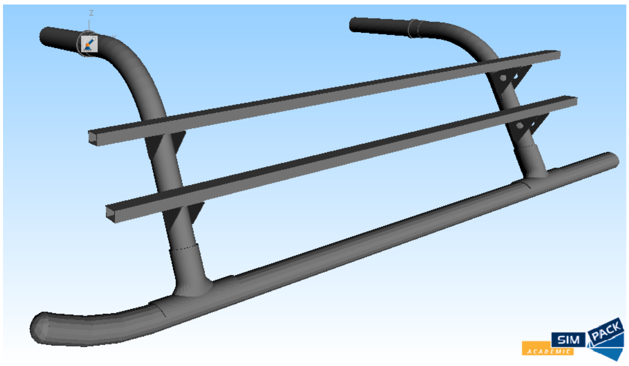

Figure 13: FHS landing gear in SIMPACK

3.3. Contact Simulation

3.3.1. Spring-damper elements

In previous works dedicated grids of the skids were clamped to the ground[2]. 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 used for the first 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 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. Using this contact type with flexible bodies one has to consider, that the contact definition itself allows to specify an elasticity. To avoid a series connection of the contact elasticity and the one of the landing gear model itself, the first one is set to zero. For the ground representation the material parameters of concrete were used, including the coefficient of friction. A representation of the model setup is shown in Figure 14.

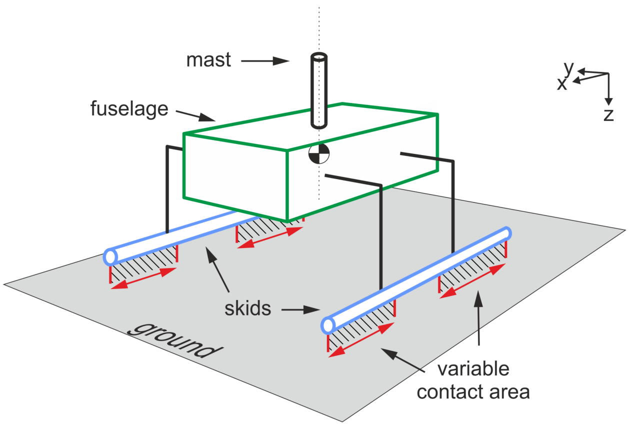

Figure 14: Visualization of principal of contact area variation

The model is connected to the ground via the landing gear skids and its variable hatched marked contact areas shown in Figure 14. 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 4. 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 14. In future studies asymmetrical configurations 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 15. Additional friction elements act directly on these force elements, which are in the foreground of Figure 15. The contact elements are only applied to those regions of the skid which have contact with the ground represented as the ocker, rectangular areas in Figure 15.

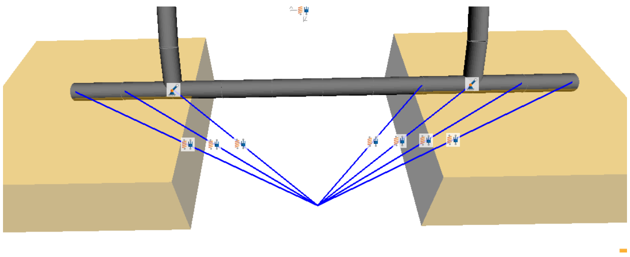

Figure 15: SIMPACK contact element applied to landing gear

3.3.2. PCM-contact elements

The polygonal contact elements (PCM-elements) in SIMPACK bases its body surfaces on polgygon meshes derived from the underlying FE-mesh or attached CAD-files. The contact force determination relies on the elastic foundation model. Thus, for usage in a simulation one needs the structural and geometrical representation. The usage of the PCM-elements allows multiple bordered contact patches and conforming contacts[15]. Moreover, this contact type was choosen due to its promised robustness for complex geometries as they can appear for uneven ground structures.

4. DISCUSSION OF 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 nonrotating system and an eigenvalue analysis is performed. Plotting the real part of the translational degrees of freedom in Figure 16 highlights the rotation frequencies where ground resonance occurs. In resonance condition the real parts which correlated to the system damping drastically decreases. The red dotted line shows the pure analyitical solution used as a reference, the black solid line shows the results of the Coleman-Feingold model.

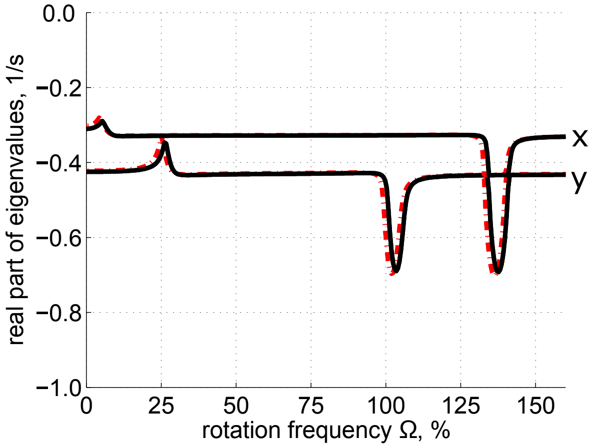

Figure 16: Hub motion eigenvalues in x- and y-direction

To test the approach described in Section 3, time simulations for the first SIMPACK model with two spring-damper elements as landing gear representations were performed. The filtered time signal of a sensor at the hub of this model is visualized in Figure 17. 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 64 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 with descreasing amplitude can be observed. However, after approximately 66 seconds a periodic time response with constant amplitude remains. These remaining non-subsiding oscillations are typical for non-linear systems. Thus, the non-linear dynamic behavior due to partial ground contact can be observed in the time signal of the simplified SIMPACK model, although, some signal processing is necessary. The results of this MBS model correlate with the results presented in[7].

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 choosen in a way to give similar frequencies as in the simplified Coleman model. The contact patches as illustrated in Figure 14 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

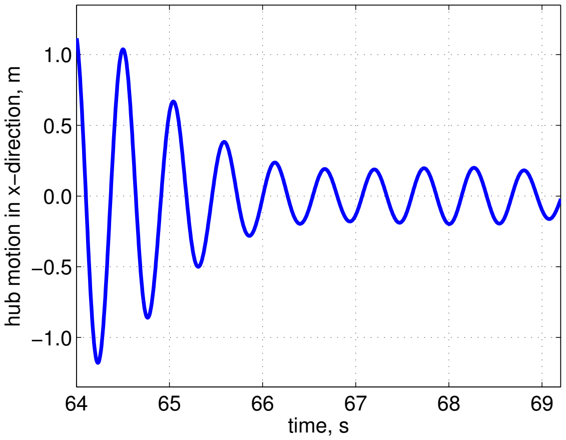

Figure 17: Filtered sensor measurement of longitudinal hub motion

the helicopter model should not get into resonance without artificial excitation at 62 seconds. A sudden excitation of $1000\ N$ in the chord direction of the first and thrid blade is applied as show in Figure 18. The excitation impulse is exemplary shown in Figure 19. 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 $14.2\ rad/s$ is presented. Figure 19 shows the filtered signal of the position marker at the hub in y-direction, correlating to the models roll movement.

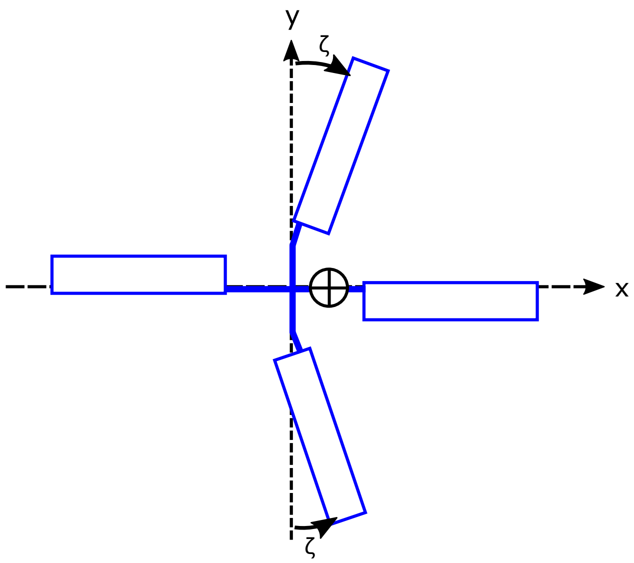

Figure 18: Excitation of rotor system

The signal is filtered using a Butterworh filter of fourth order as described above. The selected bandwidth is choosen in reference to the lowest landing gear eigenfrequencies eliminating higher frequency noise. From this filtered signal a subset

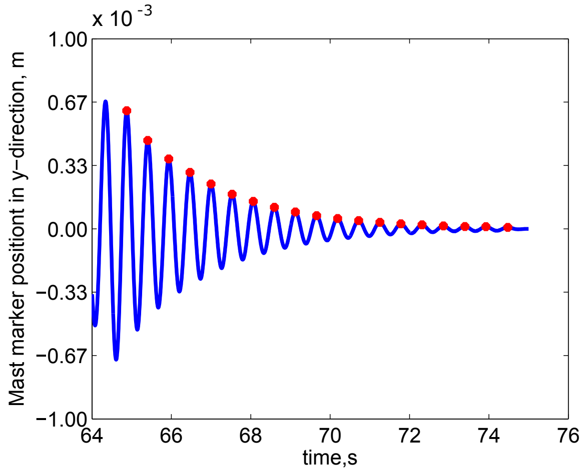

Figure 19: Filtered signal of hub motion in y-direction

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 20.

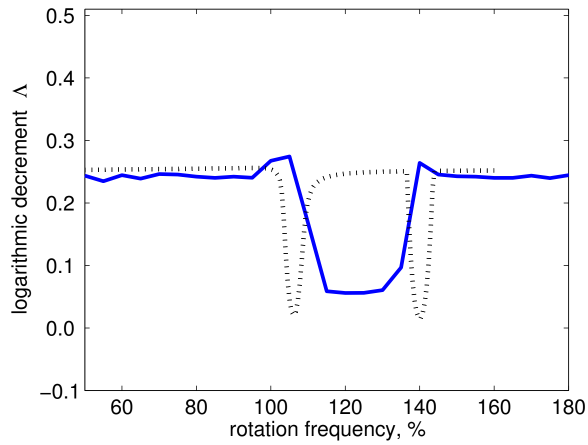

Figure 20: Visualization of aquivalent logarithmic decrement

For this contact configuration the presented approach delivers the results comparable to the analytic result. Figure 20 shows the calculation results as the solid blue line. A classical, analytical Coleman and Feingold model was used to calculate the reference results, which are shown as the dotted black line. The decrease at around $108\ \%$ of the reference frequency and the increase at around $142\ \%$ match the results of the classical model. The borders of the damping change fit the expectations. However, the results of the SIMPACK model show a continous course between 110 % to 130 % of the reference rotation frequency. This could be due to a insufficient number of calculation steps, leading to a low resolution of the results. The quality of the results has to be improved in the future to meet scientific standards. Therefore, additional tests are necessary.

4.1. Advanced models

Two advanced model variations were created in this study. Both models use PCM contact elements. Spring-damper elements only give punctual influence on the landing gear model. The models with PCM contact are:

- a modfied version of the Bo105 landing gear, as seen in Figure 22
- the EC-135 landing gear of the DLRs research helicopter FHS in Figure 23
- and a half model of the EC135 with landing gear

The PCM model is intended to determine a detailed 3d contact based on the geometry of the model and to calculate the contact forces based on the structural finite element model or modal reduced model data.
The contact is established between the grounds and landing gears geometry representation. The latter is connected to the rigid fuselage of a Bo105 and EC135, respectively. The contact is visualized in Figure 21. The rotor for both models is the same rigid four-bladed rotor as before to enable the comparison of results. This is important to narrow down modelling errors in this early stage of the study.

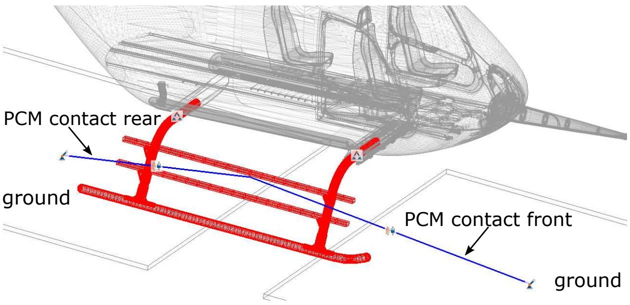

Figure 21: PCM contact of the EC135 landing gear

For simplicity and easier comparison of the results, the same rotor model is used for all landing gear variations. Since landing gears and rotor models are usually configured to avoid the occurence of ground resonance, the rotor system was modified. In Figure 24 the result of the MBS transformation over the rotational frequency of the standalone rotor is shown.

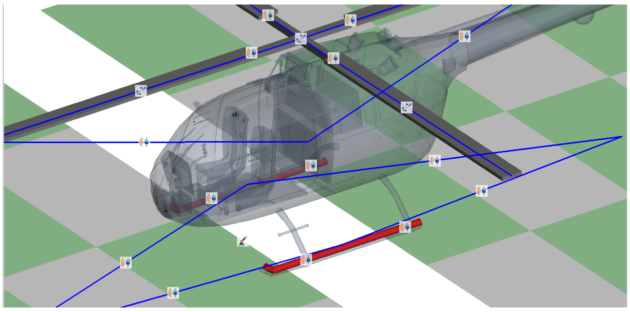

Figure 22: Bo105 high landing gear with 4-patch PCM contact

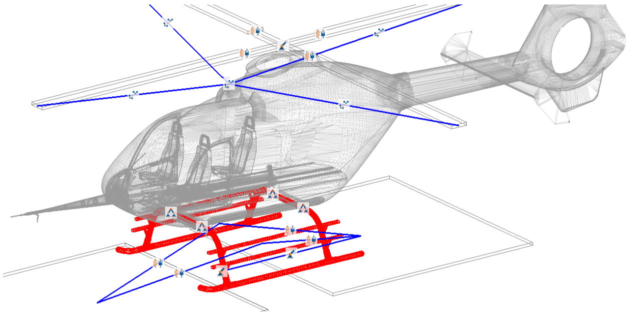

Figure 23: EC135 high landing gear with PCM contact

The red lines show the eigenfrequency of the standalone EC135 landing gear model attached to the fuselage for full contact. The crossing of the landing gear frequency and the regressive lead-lag eigenfrequency marks the region of interest for ground resonance.

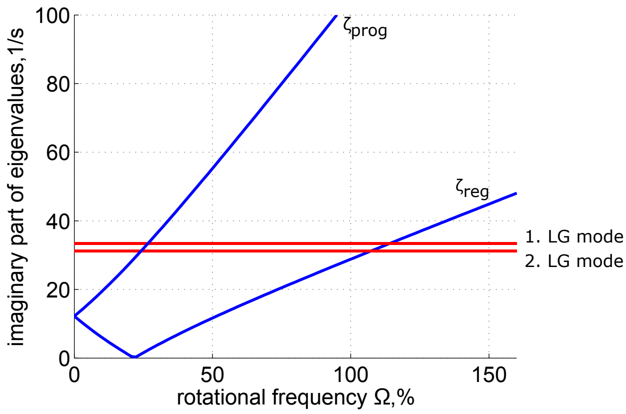

Figure 24: Progressive and regressive frequency of standalone rotor and first modes of standalone EC135-fuselage-landing-gear-model

4.2. Time signal analysis

The first results of the time signal calculations are shown for the EC135 landing gear. Two contact con-

figurations are choosen examplarily to elucidate the PCM contact. First, the 4-patch configuration as shown in Figure 22, simulating a landing in a pit and second, the same model in full contact.
The models were "set on the ground" and time integration continued till remaining vibrations due to the landing contact subsided. Then the helicopter model is excitated by sudden short force impulses at the first and third blade tip, deliberately causing an inbalance of the rotor. This excitation occurs at 20 seconds. Figure 25 shows the time signal of the

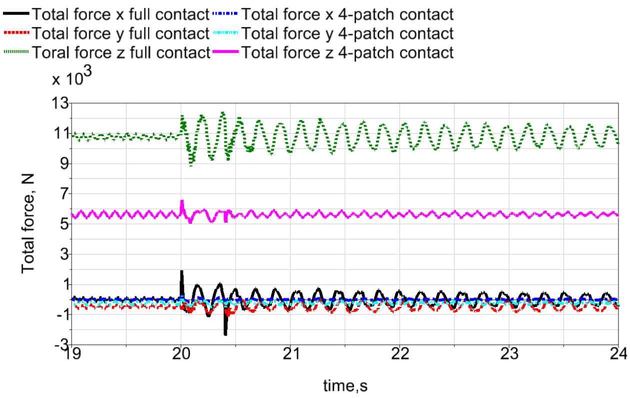

Figure 25: PCM contact forces for 4-patch and full contact

PCM contact at the left landing gear side for 19 s to 24 s. As can be seen, the contact captures the forces in x,y and z-direction. The small vibrations prior to the 20 s-excitation are caused by the main rotor angle. Whereas after 20 s the reaction due to the excitation is clearly visible. As expected, the 4-patch contact has a lower contact force in z-direction, but also shows smaller amplitudes after the excitation. If this is due to the choosen parameters or due to modelling choices is subject of ongoing efforts.
Figure 26 shows the maximum pressure contact for

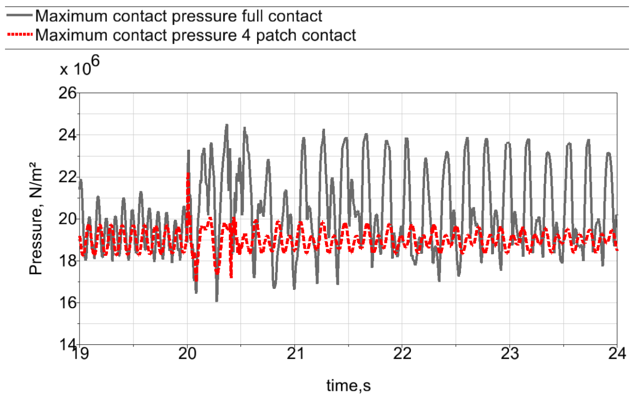

Figure 26: PCM maximum pressure contact for 4-patch and full contact

the different contact configurations. It is interesting to note, that the 4-patch contact does not change significantly after the excitation, although the excitation peak at 20 s is clearly visible. This behavior is unexpected and contradicts basic physical understanding, indicating the necessity of additional model tests. Nevertheless, the PCM contact offers the possibility to analyse such model effects in detail.
Both landing gears stay in a stable configuration, although some oscillations remain. In order to test how the PCM contact behaves for an instable configuration the main rotor was modified in a way which causes ground resonance. The reference rotor frequency was increased to 67 rad/s and the lead-lag damping was reduced to 20 % of its original value. The Bo105 high landing gear model with PCM contact was used. For the tests the rotation frequency was choosen to be in ground resonance conditions. The corresponding frequencies can be seen in Figure 27. It has to be mentioned, that the

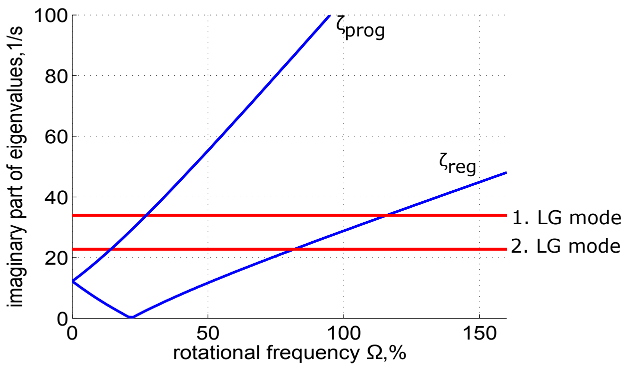

Figure 27: Progressive and regressive frequency of modified rotor and first modes of Bo105-fuselage-landing-gear-model

rotor model modifications used in these test cases was adapted based on the assumption of an isolated rotor. If the configuration with contact at the front and rear side of a skid is choosen, the simulation shows an instable behavior as can be seen in Figure 28.
It shows the helicopter in ground resonance two seconds after excitation. The typical blade position causing a displacement of rotation axis and center of gravity of the rotor are clearly visible. The times of ground contact can be seen in the time signal of the fuselage roll angle in Figure 29. The results confirmed, that the PCM contact is in principle usable for ground resonance studies.
The eigenfrequencies of the EC135 landing gear, shown in Figure 24, are much higher than anticipated. In order to review the generation of the flexible landing gear of the FHS and its usability in SIMPACK, the eigenfrequencies of the modal reduced

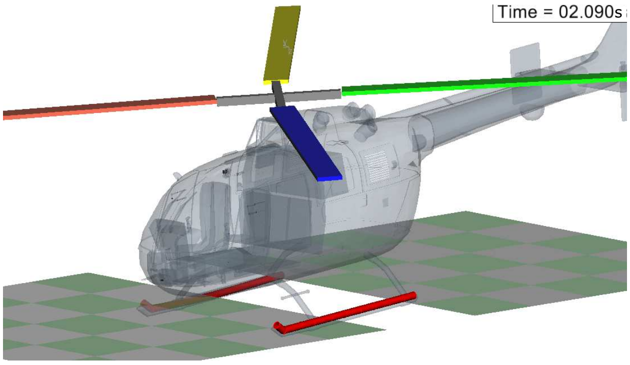

Figure 28: Ground resonance for landing in pit

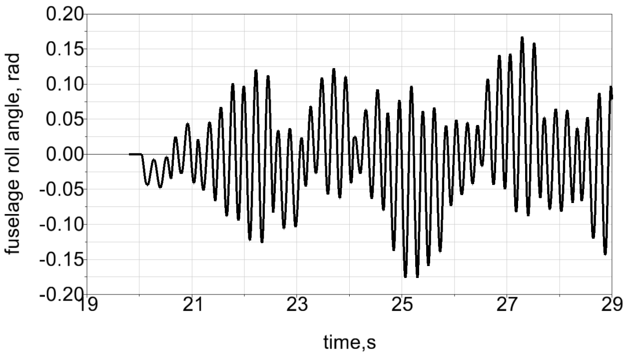

Figure 29: Roll angle of fuselage, PCM contact in ground resonance

model were compared to the one with an elastic bearing with a base stiffness of $3e08\ N/m^3$ 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 keept in mind for all simulation results.

Modes	Fixed attachment	Elastic attachment	Absolute difference	Relative difference
1	18.818 Hz	14.810 Hz	4.008 Hz	-0.213
2	31.171 Hz	24.201 Hz	6.970 Hz	-0.224
3	32.045 Hz	26.628 Hz	5.417 Hz	-0.169
4	33.860 Hz	53.819 Hz	19.959 Hz	+0.589
5	35.764 Hz	59.856 Hz	24.092 Hz	+0.674
6	58.480 Hz	60.714 Hz	2.234 Hz	+0.038
7	62.454 Hz	69.958 Hz	7.504 Hz	+0.120
8	70.166 Hz	74.136 Hz	3.970 Hz	+0.057
9	72.956 Hz	78.998 Hz	6.042 Hz	+0.083
10	75.561 Hz	82.237 Hz	6.676 Hz	+0.088

Table 1: Eigenfrequencies of FHS landing gear modes for fixed boundary conditions

5. CONCLUSION

This work represents the current status of the ongoing study on 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 nonlinear systems based on the measurement of time signals after sudden excitation are implemented. This includes signal post-processing like filtering of the time signals. First analysis are conducted delivering correct results for the classic Coleman and Feingold model and the simplified nonlinear 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 with spring-damper elements 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. PCM-elements in helicopter models can be applied for ground resonance studies and is usable for more exotic, that means operational based contact conditions. The models show the expected change in dynamic behavior for changes in these contact conditions.

The first, early test of advanced models in this paper show that the PCM contact can be used in principle for ground resonance analysis. The models created for this study are the basis for further investigation of this contact type and more sophisticated studies of ground resonance.

Based on the models presented in this work. An extensive parameter study for different ground stiffness and friction coefficients in combination with partial ground contact will be conducted. It will be examined if the existing analysis methods can be extended by a Lyapunov stability analysis using fractional elements[16]. Additionally, a model for the study of tailboom elasiticity will be implemented since it is confirmed to be the most significant contribution to the fuselage elasticity of low-frequency.

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