Numerical Simulation of Landing Gear Dynamics: State-of-the-art and Recent Developments

Dr. Wolf R. Krüger
DLR - German Aerospace Center
Institute of Aeroelasticity
Bunsenstr. 10
D - 37073 Göttingen
Wolf.Krueger@DLR.de

Marco Morandini
Politecnico Di Milano
Dipartimento di Ingegneria Aerospaziale
Via La Masa, 34
I - 20156 Milano
Morandini@aero.polimi.it

SUMMARY

Aircraft landing gears support the aircraft during ground operations, including take-off, landing impact, taxiing, gate handling and maintenance. Mostly for reasons of minimum mass and ground clearance, landing gears are slender structures which exhibit a considerable dynamic response to ground load excitiations. As the landing gear is one of the few systems on the aircraft without redundancies, the knowledge of landing gear dynamics is crucial for aircraft design and aircraft safety.

Simulation of landing gear dynamics is a cornerstone of aircraft loads analysis, as well for vertical loads resulting from touch-down as for longitudinal and lateral loads resulting from braking, steering and towing. Another important field of interest are landing gear vibrations like gear walk and shimmy. Those phenomena can be brake induced or result from tire spin up at touch-down or simply from a coupling of dynamics of the running tire and structural mechanics of the landing gear leg. All those effects strongly depend on a number of parameters such as aircraft speed, landing gear vertical deflection, tire pressure and wear of the parts. Many of those parameters can only be estimated and might change during the operation of the aircraft.

Numerical investigation is thus a challenging task. Analysis methods exist both in the frequency domain and in the time domain. As stability analysis is straight forward in frequency domain methods, this approach is still often used. However, in many cases non-linearities are dominant which lead to limit-cycle characteristics of the vibrations. Here, multibody modelling or a mixture of multibody and finite element modelling including time domain simulation is used.

In the paper, a general outline is given of how vibration problems in landing gears can be treated by numerical analysis methods. The paper will start with a classification of typical problems, give a short overview of classical papers, and explain typical approaches. In addition, alternative approaches for stability analysis and for the detection of LCOs as well as state-olf-the-art modelling approaches will be presented.

1.0 INTRODUCTION

1.1. Motivation and Background

The aircraft landing gear is one of the basic systems that have significant effects on aircraft performance. The tasks of the landing gear are complex and lead to a number of - sometimes contradictory - requirements. At landing, the landing gear absorbs the vertical energy of the aircraft via the shock absorber and the horizontal kinetic energy by means of brakes. At taxiing, the landing gear has to carry the aircraft over taxiways and runways of varying quality, a requirement that is mirrored in its British name, “undercarriage”.

The dynamics of the landing gear depend on the design of the gear structure and the attachment to the aircraft (e.g. strut design, attachment stiffness) as well as on the dynamics of the components which form a part of the system, i.e. the shock absorber, shimmy damper and, of course, the tire. Furthermore, most main landing gears on conventional aircraft are equipped with a brake (nose landing gears usually are not), and anti-skid systems are state-of-the-art since the 1950ies. Two important phenomena of landing gear oscillations can be seen in Figure 1. One important phenomenon is the so-called shimmy, i.e. self-induced oscillations which can occur under all taxiing conditions, as well as at starting and landing. "Shimmy" is a summarizing term for the lateral (torsional as well as side-bending) flutter phenomenon of vehicles, especially aircraft landing gears. The reasons for such unstable oscillations are found in the elasticity of the frame and tires (in combination with non-linear effects such as friction and free-play in the bearings of the king pin) which lead to limit cycle oscillations and uncomfortable vibrations causing mechanical wear and the danger of landing gear failures. Another phenomenon is the so-called gear walk, i.e. a fore/aft motion of the elastic gear structure induced either by the landing impact or from an application of the brake. In many cases, shimmy and gear walk can couple, i.e. a shimmy-type vibration can be induced by applying the brake. Thus, the dynamic properties of the gear structure and the brake have to be seen as a coupled, feed-back system.

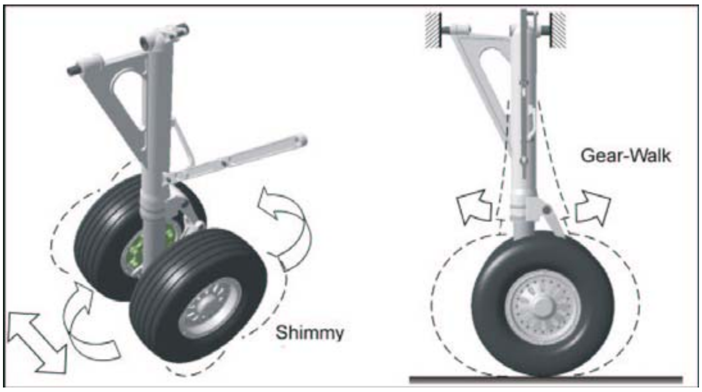


Figure 1: Shimmy and Gear Walk Phenomena [27]

1.2. Available Literature

There are a number of books and articles of landing gear design which must be mentioned here. The books of Conway [1], Currey [2], Pazmany [3], and Roskam [4] are standard textbooks which cover the whole standard landing gear design process from questions of landing gear location, suspension layout and the selection of tires. The “SAE Committee A-5 for Aerospace Landing Gear Systems” is an association of aerospace engineers who are engaged in landing gear design which was formed in the frame of the Society of Automotive Engineers (SAE). Thirty publications by members of this committee concerning questions of landing gear design have been selected by Tanner and published in [5]. A second volume of papers [6] has been published by the same editor. Further collections of articles have been published by the AGARD (Advisory Group for Aerospace Research and Development) in their conference proceedings CP-484 [7], “Landing Gear Design Loads”.

While all these publications are concerned with landing gear design in general, some specific publications exist with respect to the simulation of aircraft ground dynamics. An overview of computer simulation of aircraft and landing gear is published in another AGARD volume [8], which has its main emphasis on the simulation of shimmy. Two publications of the IAVSD (International Association for Vehicle System Dynamics), Hitch in 1981 [9] and Krüger et al. in 1997 [10] are state-of-the-art overviews of aircraft ground simulation, the latter article also discussing different modeling approaches and tools. Pritchard [11], 1999, is another overview of landing gear dynamics.

Some recent works on shimmy prediction and brake modeling include the publication of Denti and Fanteria [12] who discuss the effect of different tire models and brake on the longitudinal dynamics of aircraft landing gear. Khapane examines landing gear - brake interaction in [13]. Besselink very thoroughly investigates the influence of various parameters on shimmy prediction. His thesis also includes an almost complete list of references concerning the topic [14].

2.0 NUMERICAL ANALYSIS OF LANDING GEAR VIBRATIONS

2.1. Analysis Approaches

Classical Methods for shimmy analysis are **linearization and linear system analysis** and **time simulation**. The approaches will be shown at the example of a landing gear model reduced to the basic relations important in basic shimmy analysis, Figure 2, taken from [15] and [16].

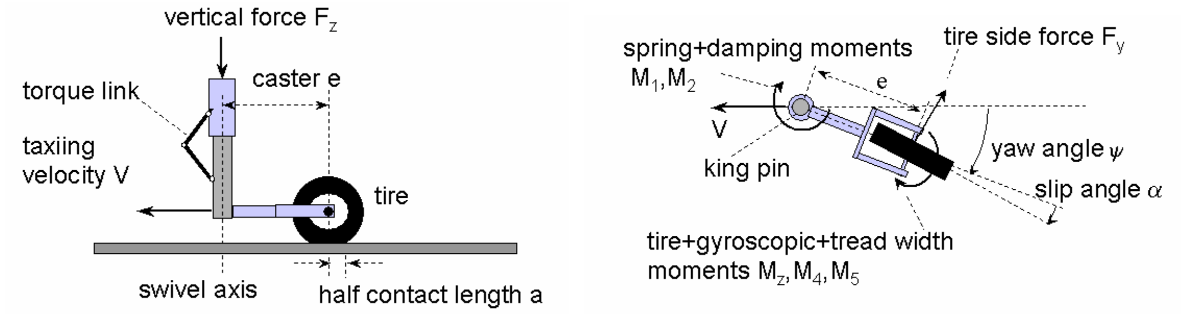


Figure 2: Basic parameters for shimmy analysis

2.2. Analysis of the Linearized System

For small amplitudes, the nonlinear dynamic system is Taylor linearized numerically. In parameter variation loops, one or two model parameters are changed systematically, and eigenvalues can be calculated, Figure 3, left. By checking the eigenvalues for critical stability, a linear stability chart can be drawn, Figure 3, right.

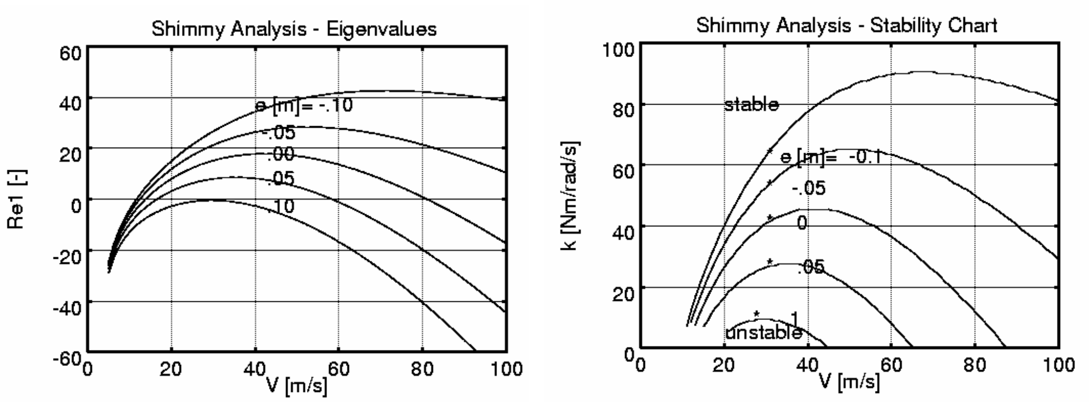


Figure 3: Landing gear eigenvalues and stability chart

2.3. Analysis of the System by Time Simulation

Another common method for analysis of landing gears is time simulation. This approach is able to capture arbitrary non-linearities, provided a suitable model is available. All solutions, stable, unstable and limit cycles can be obtained, see examples at Figure 4.

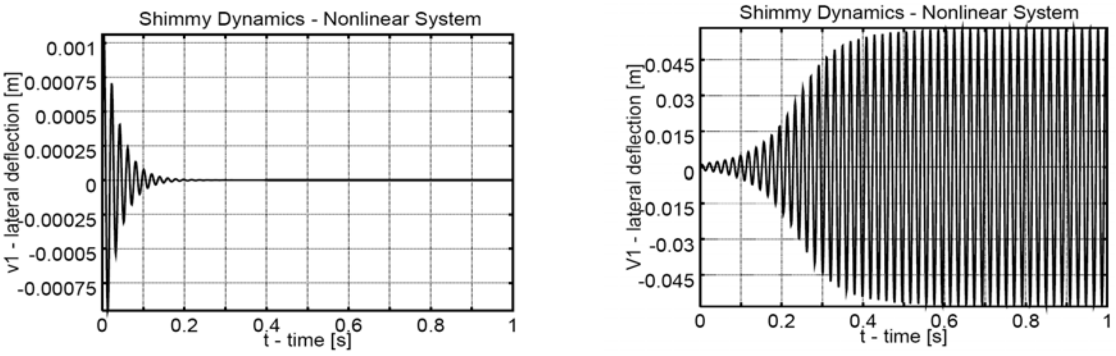


Figure 4: Time simulation, stable and initially unstable model displaying limit cycles

2.4. Quasi-Linear Analysis

The goal of this approach is to establish a numerical procedure for finding limit cycles, which is generally applicable to all dynamic systems (of ordinary, homogeneous differential equations) having several distinct nonlinearities of one variable. In landing gears, the predominant factors for limit cycle motion are non-linear tire behaviour, free-play and large angles of yaw rotation.

For large amplitudes a quasi-linear system is generated by determining the unknown amplitudes via eigenvectors (amplitude synchronization), then eigenvalues are calculated and a stability checking is performed. All these items are to be handled in an iterative loop because they are coupled, due to the amplitude dependency of the describing functions. To linearize the system, weak nonlinearities are linearized according to Taylor series, and for all other discrete nonlinearities (see examples) the quasi-linear approximation using describing functions is applied.

The approach is complicated by the fact that in the case of several nonlinearities with different input signals, the describing functions of these nonlinearities depend on different, unknown amplitudes of the input oscillations. The amplitudes have to be matched (the so-called “amplitude synchronization”); thus a nonlinear system of equations for the unknown amplitudes results. Using the fact that in a linear system the ratios of all amplitudes A and eigenvectors EV are constant for each eigenvalue, these equations can be set up. Provided that proper initial estimates and step sizes for the unknown amplitudes A are selected, the system of nonlinear EV/A-equations can be solved iteratively with a nonlinear solver software, see Figure 5, left.

By parameter variation of the selected basic amplitude (e.g. of the slip angle oscillation) and an interesting model parameter (e.g. velocity V), eigenvalues can be calculated and displayed in a 3-d graph, Figure 5, right.

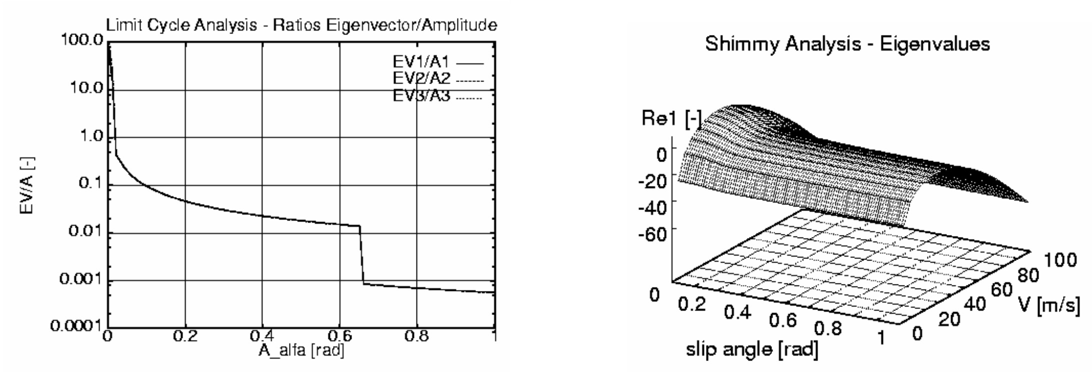


Figure 5: Amplitude synchronization and resulting eigenvalues

By checking the eigenvalues for critical stability (if any real part changes its sign) and by parameter variation with respect to a model parameter, conditions for amplitudes (of slip angle oscillation) are found, where limit cycles can occur. The results are best shown in a bifurcation diagram (see here for an explanation). It displays the regions in amplitude versus a model parameter, where stable and unstable behaviour occurs, separated by stable or unstable limit cycles, Figure 6, left. In addition, the frequencies of the limit cycle eigenvalue are recorded, Figure 6, right, [16].

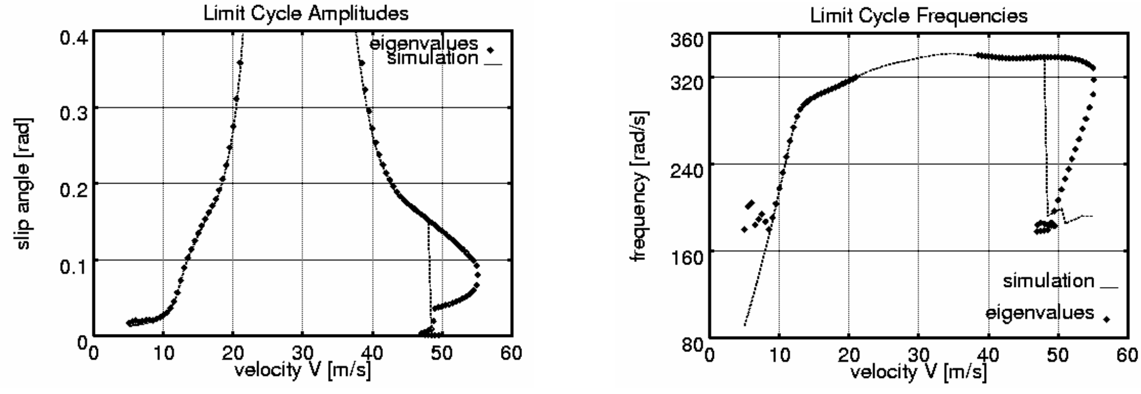


Figure 6: Bifucation diagrams: limit cycle amplitudes and frequencies from quasi-linear analysis

3.0 TOOLS AND MODELLING

3.1. Multibody Simulation

Multibody simulation (MBS) has shown to be a valuable software tool for virtual system design. In aeronautics, it is the state-of-the-art approach especially in the area of landing gear design, ground manoeuvres (take-off, landing, taxiing, ground handling) and the layout of high-lift systems as well as in helicopter and tilt rotor analysis. In addition, the medium level of complexity of typical multibody applications makes it a suitable tool for the application in aircraft preliminary design. Comprehensive simulation allows analysis and evaluation of performance, structural loading and dynamic behaviour of the system, as well as optimization of the design. It is becoming more and more important to perform these computations in complex, realistic scenarios. For that reason, modern multibody codes include a variety of interfaces to other tools from other engineering disciplines, for example to CAD, structural dynamics, control design tools and aerodynamic tools. Furthermore, the simulation environment can be included in a larger design loop [17].

Usually, forces between bodies can be represented by library elements or user-defined routines. Of prime interest for landing gear simulation is the integration of structural elasticity and of aerodynamics and flight mechanics. For the simulation of flexible bodies, the representation in modal form is state-of-the-art, leading to a combination of large rigid body motion and linear elastic deformations. The development of reliable aerodynamic models ranges from strip-theory and lifting-line-type models to interfaces with high end CFD tools, with applications for civil and military aircraft. A major advantage of using multibody dynamics for loads calculations is the straightforward introduction of flight mechanics into the aeroelastic simulation. The full advantage of using a complex multibody tool for that purpose becomes most evident for systems with large rotations like combined aircraft/landing gear analysis, including optimization, helicopters or tilt rotors, and for aircraft with large elastic deflections [18].

The multibody codes used in the application examples given below are SIMPACK and MBdyn. SIMPACK is a former DLR development now developed and distributed by INTEC [19]. SIMPACK is a commercial product which is used in the development of cars, trucks and railways, and is the standard multibody tool for aeroelastic applications at the DLR Institute of Aeroelasticity [20], [21]. MBDyn is a general-purpose multibody dynamics_analysis software, freely available as it is released under GNU license. The software has been developed at the Dipartimento di Ingegneria Aerospaziale of the University "Politecnico di Milano", Italy [22]. Other MBS tools frequently used in landing gear design and analysis are MSC.ADAMS [23] and LMS Virtual.Lab Motion [24].

3.2. Representation of Landing Gear Elasticity

The first step in building a multibody model is to account for the exact kinematics of the landing gear. This is easily accomplished using a rigid body, with the right mass properties, for each of the landing gear structural elements, and connecting them with ideal joints. A shock absorber model is then added to the system. A simple model like this is already able to correctly reproduce the vertical response of the landing gear. As soon as the interest shifts from vertical reaction forces to longitudinal and lateral forces, the model has to account for landing gear flexibility. As an example, a model without landing gear flexibility would not be able to predict any kind of spring back load.

The flexibility of the landing gear can be reproduced by replacing the rigid bodies with beams or with modal elements, and introducing deformable joints in place of the ideal ones. Please note that, as the landing gear compresses, the position of the contact points between main fitting and shock strut changes, thus continuously changing the resulting stiffness and, consequently, the natural frequency and mode shapes of the landing gear during compression, see Figure 7, [25]; see also the analyses in [26] and [27]. This effect might be very difficult to be correctly reproduced in MBS using a modal approach for the elastic landing gear components. The references cited above show alternative modelling approaches. Furthermore, many cases of interest for horizontal and lateral landing gear dynamics and can be analyzed assuming constant deflection.

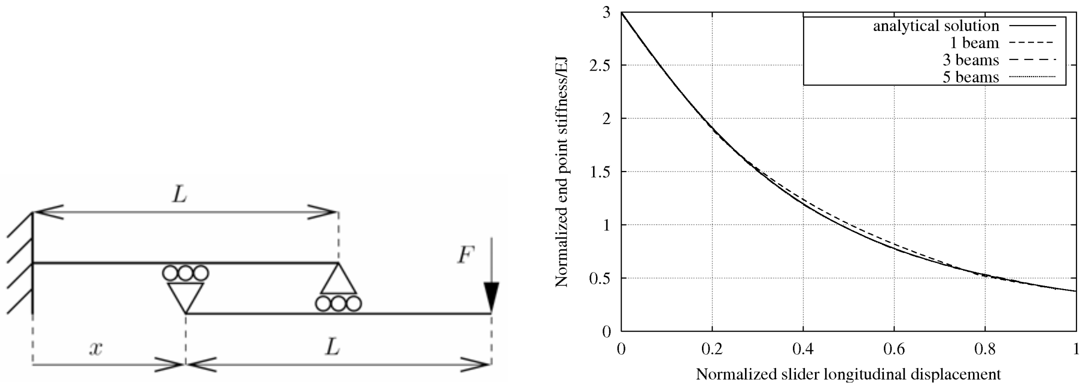


Figure 7: Sliding beams set-up

Fuselage dynamic can be accounted for using a modal approach as well, where the fuselage modes of vibration, extracted from a FEM model, are inserted in a floating frame of reference which accounts for average finite rotations of the body. This kind of model can be augmented with so called ”static modes“, allowing the recovery of relative displacements occurring due to local stationary elasticity, for example at the gear/fuselage attachment points. Of course, this last approach is feasible only if an enough detailed FEM model of the fuselage part where significant deformations are expected is available. An alternative approach is to add local attachment stiffness to the joints connecting the fuselage to the landing gear. Accounting for local elasticity can be necessary in order to reliably predict the onset of instabilities. For example, Figure 8 shows the simulation results of two models during a braking manoeuvre with the intervention of an anti-skid system. The dotted line is the braking torque time history predicted for a landing gear deformable model that do not account for the elasticity of the landing gear/fuselage attachment; the continuous line, showing the occurrence of a so-called “gear-walk” instability, is the result obtained with the same model, but with landing gear/fuselage attachments stiffness.

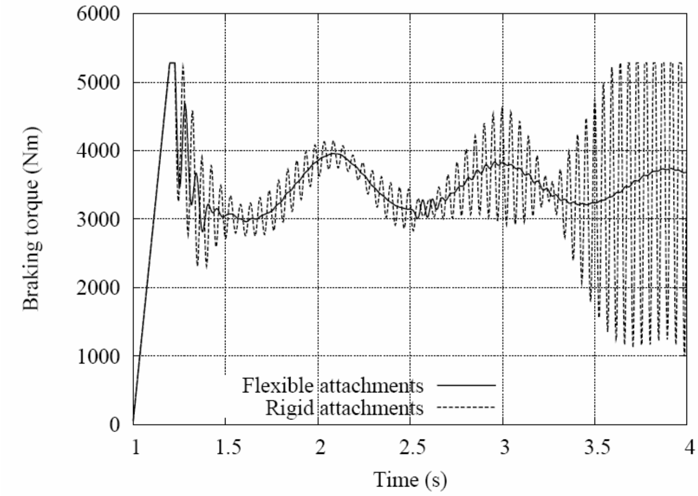


Figure 8: Influence of attachment stiffness on gear walk simulation

3.3. Shock absorber

One of the central elements of landing gear design is the shock absorber. For the simulation of the longitudinal lateral dynamics, this element is often neglected, assuming a fixed landing gear stroke. For simulations of the gear dynamics during landing, however, the introduction of the shock absorber is crucial. Furthermore, a number of landing gears are equipped with so-called shimmy dampers, which often use the same damping principle as the one described below.

For transport aircraft, the main task of vertical energy dissipation is almost exclusively taken over by an oleo-pneumatic shock absorber, often just called the “oleo”. This device combines gas spring with oil damping. Damping force is provided by oil flow forced through an orifice by vertical strut motion. Often the oil flow is controlled by means of a metering pin. The gas spring is represented by a law of polytropic expansion,

$$F_f = F_0\left(1-\left(\frac{s}{s_m}\right)\right)^{-n\cdot c_k}$$

with spring force F_f, pre-stress force F_0, oleo stroke s, oleo gas length s_m, polytropic coefficient n ($1\leq n\leq k$), and a correction factor c_k, typically between 0.9 and 1.1. The properties of the damper are determined by the laws describing the laws of viscous fluid, e.g. oil, through an orifice,

$$F_d = \pm|\dot{s}|\cdot d\cdot \dot{s}^2$$

Typical force curves are given in Figure 9. Furthermore, friction in the oleo seals can play a significant part, but exact modeling is difficult and often done on the basis of experience and proprietary approximation formulae.

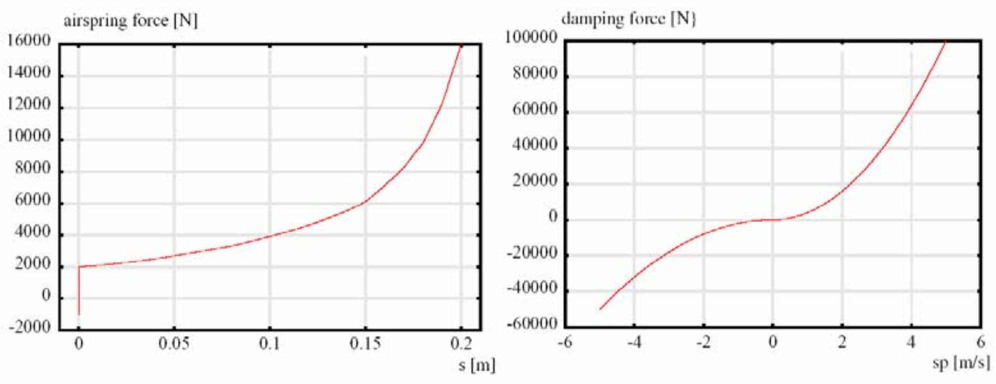


Figure 9: Typical air spring and oil damper force curves for a light aircraft

3.4. Free Play

Free-play is typical inside joints connecting moving mechanical parts, e.g. the members of the landing gear legs. The presence of free-play might considerably change the stability margins and be the responsible effect for limit cycle motion. Free-play is modelled as non-linear springs (see Figure 10). Some deflection is possible before a force develops, and if the amplitude remains inside the free-play band, the force will remain zero. For linear approximations, free-play migth be treated as a spring with equivalent stiffness, the values can be taken from harmonic balance. Grossmann [28] suggests two formulae to determine equvalent linear stiffness for motion outside the free-play band ($a_m > a_{fp}$):

$$c_{eq} = c \cdot \left(1 - \frac{a_{fp}}{a_m}\right)$$

$$c_{eq} = c \cdot \left(1 - \left(\frac{a_{fp}}{a_m}\right)^2\right)$$

with a_m the amplitude of the motion and a_{fp} half of the free-play. Obviously the stiffness has become a function of the amplitude of the motion and will increase with the amplitude of the motion. Besselink [14] suggests that the first equation gives better correspondance with non-linear simulations than the second, and that the equivelent stiffness might be even lower.

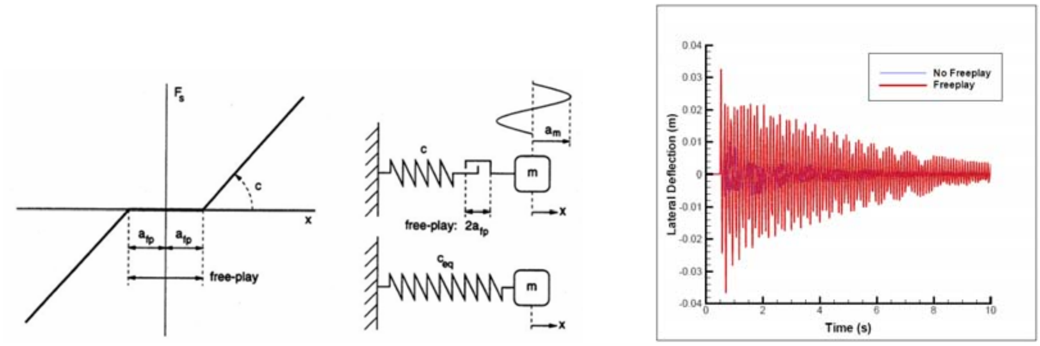


Figure 10: Representation of free-play and typical effect on landing gear dynamics

3.5. Tires

In the field of aircraft landing performance evaluation, the nonlinear effects at the tire-ground interface play a very important role. Different models have been developed for the simulation of tire longitudinal behaviour, ranging from simple, static slip ratio to friction force maps to completely nonlinear finite element-like models [29]. A good compromise between the model complexity and its ability to reproduce the actual tire behaviors is given be the combination of so-called rigid ring models, such as the one used by Zegelaar [30], [31] with dynamical models of the frictional interaction between tire and runaway. A rigid ring model (Figure 11) is built connecting two masses with and elastic component, so that the average deformation dynamic between the rim and the belt can be accounted for. The forces exchanged between the tire and the runaway are computed by an element that represents the tire contact patch. At least two different approaches are available for the longitudinal force component; the first one, built using a simple bush-like model, is widely used in multibody codes [32]; the second one is built averaging over the contact patch the friction coefficient, computed using a dynamical model such as the LuGre's one (cf. Section 3.6), and is more used by control system analysts [33]. Both models are available in MBDyn, and, if their parameters are tuned appropriately, both can reproduce experimental results with a good precision.

Lateral tire dynamics are crucial for shimmy analysis, the first models being based on a single contact point approach. In 1941, von Schlippe introduced the concept of a stretched string with a finite contact length to describe the mechanics of the rolling tire [14]. For a detailed discussion of the stretched string models see the work of Pacejka [32]. One popular model is the Moreland tire model, first published in 1954 [34]. One major point is the correct representation of phase lag for lateral motion.

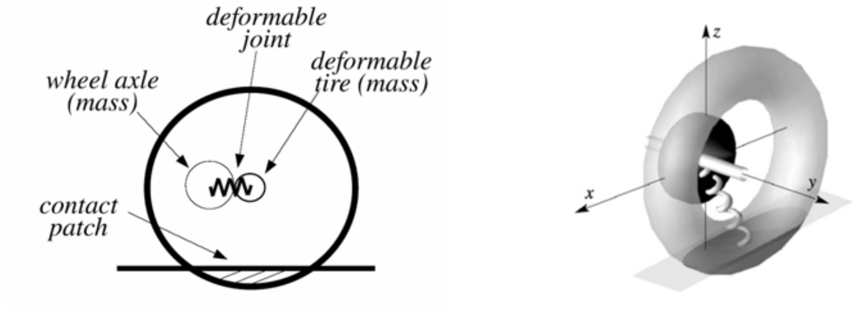


Figure 11: Rigid ring tire model; schematic and MBS representation

3.6. Friction

Different friction models can be used in order to introduce friction in joints, to model the longitudinal forces exchanged between the tire and the runaway, and to predict the behavior of brakes. A detailed review of friction models can be found in [35]. Among all the friction model the most widely used is the Coulomb friction model. Unfortunately, this friction model is not only very difficult to implement in a dynamic multibody code, but can also lead to ill-posed problems [36]. A wide range of techniques were adopted in the past in order to regularize the Coulomb friction model, but none proves to be completely satisfactory. A good alternative to the Coulomb friction model is given by dynamic friction models, and, one of the more successful among them is the well-known LuGre friction law. This friction formulation [37], [38] considers a single state model which decomposes the rigid body displacement x at the contact point into its elastic (reversible) and plastic (irreversible) components, ξ and x-ξ, respectively, and reads:

$$\begin{aligned} f &= \sigma_0\xi + \sigma_1\dot{\xi} + \sigma_2\dot{x} \qquad\qquad \sigma_0, \sigma_1, \sigma_2 > 0 \\ \dot{\xi} &= \dot{x}\left(1 - \frac{\sigma_0}{|f_{ss}(\dot{x})|)}\mathrm{sign}(\dot{x})\xi\right), \end{aligned}$$

where f is the friction coefficient. This approach accounts for the elastic pre-sliding relative displacement (with σ_0), for viscous friction (with σ_1), for rising static friction and for frictional memory during slip (with σ_2). The Stribeck effect can also be accounted for using the steady-state friction curve $f_{ss}(\dot{x})$ (also known as the Stribeck curve).

Friction models deal with so-called ”conform“ contacts, where the vertical reaction, and the horizontal frictional force, are uniform. When dealing with friction in joints one has to consider the actual distribution of contact forces in the joint. For example, the actual distribution of normal forces in a cylindrical joint can lead to a correction to the resulting frictional moment that can be as high as 30 % [39].

3.7. Braking

When dealing with brake performance and braking stability the model have to be enhanced with a brake model. The simplest one is a simple, linear relation between an applied braking force F_b and the braking moment M. This simple model can be enhanced, adding dynamic friction effects, so that the applied braking force is no more in phase with the braking torque. This can be accomplished, for example, considering an average brake disk radius R_d, and computing the average friction coefficient f as a function of the average relative velocity between the disk and the brake pads. The braking moment is then

$$M = F_b \, f \, R_d$$

Thermal effects can be significant for carbon/carbon disks, for which the static friction coefficient is a known function of temperature. For this kind of brakes the model should be enhanced not only with a dynamic friction law, but with thermal conduction equations as well, in order to predict the disks and pads temperature. The simplest mode, taking in account only the conduction trough disks and pads thickness leads to the results like that of Figure 12, where the temperature of a small size business aircraft carbon-carbon disks is shown as a function of time and position thought the thickness.

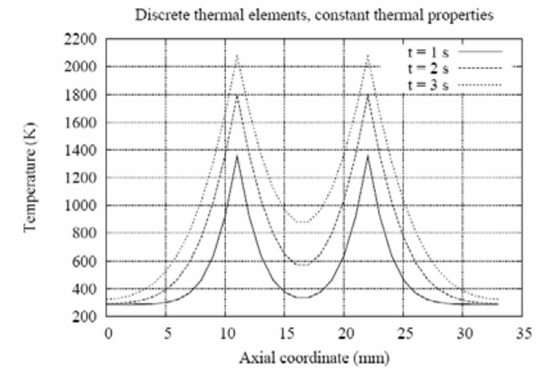


Figure 12: Brake temperature

3.8. Control Systems

Both SIMPACK and MBDyn can simulate the dynamic of control systems using state-space realizations of their transfer functions. Moreover, both codes can interact, during the simulation, with an external SIMULINK model, which can be used in order to build controllers of arbitrary complexity. The anti-skid system shown in Figure 13 was used for the example presented in Section 4.2 and implemented in MBDyn. A similar layout has been used for reference analyses and implemented using the integrated control loop functionality of SIMPACK by Khapane [13].

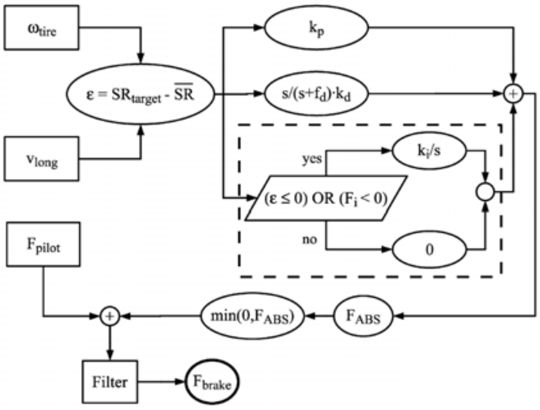
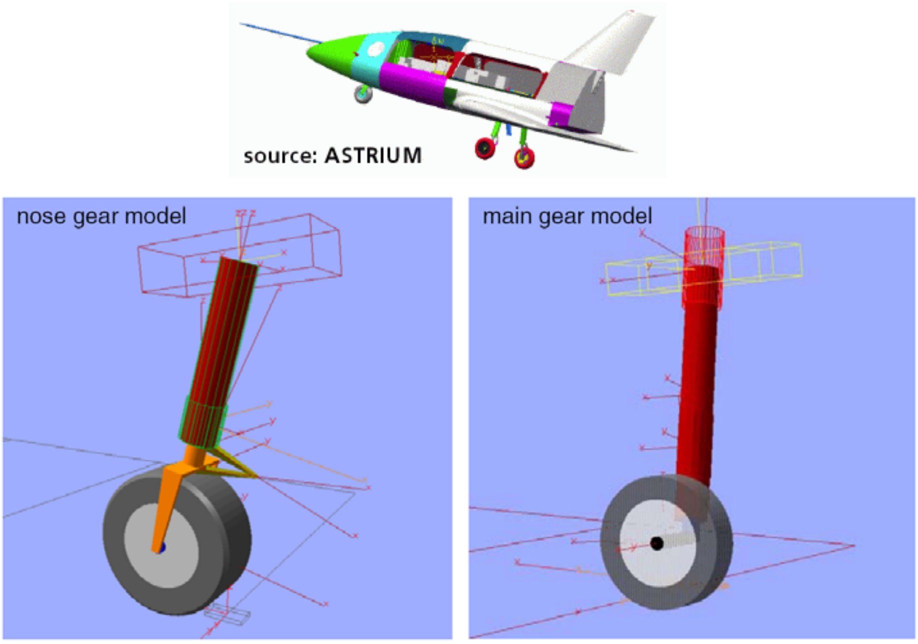


Figure 13: Brake scheme with anti-skid logic (used in example, see Section 4.2)

4.0 APPLICATION EXAMPLES

4.1. Shimmy Analysis of a Scaled, Unmanned Re-entry Vehicle

The PHOENIX vehicle was a one-seventh scale model of the future space transport vehicle HOPPER, developed by ASTRIUM [40]. The vehicle particularly served for acquiring real flight and landing attitude data that cannot be simulated. The flight demonstrator had a wing span of 3.90 metres and an aluminium structure with a weight of about 1,000 kg. The vehicle was successfully flight tested in an autonomous flight after being dropped from a helicopter from an altitude of 2400 m. The test took place place at the test airport of Vidsel in northern Sweden in 2004. PHOENIX was equipped with one nose landing gear (NLG) and two main landing gears (MLG), see Figure 14. Due to the high speeds at landing, shimmy was a concern. DLR performed a preliminary stability analysis based on data from the landing gear design.


source: ASTRIUM

nose gear model

main gear model

Figure 14: PHOENIX test vehicle with nose and main landing gear simulation models

The analysis followed the established approaches of a frequency domain analysis for all gears at pure rolling condition for fixed strokes, and a study of the transition from fully extended gears to static closure position of the gears, performed for three weight configurations. The analysis has been performed using the MBS code SIMPACK (Section 3.1).

For normal rolling conditions at static load, no critical points could be found neither for the nose nor for the main landing gear. However, when investigating the landing, the main landing gear was analysed for several aircraft attitude angles and landing gear strokes. One configuration was found which displayed a potential instability, for an attitude angle which the aircraft would transition through at derotation.

Figure 15 shows the example of a stability analysis in the frequency and the time domain for this configuration. For the frequency analysis, the model was linearized for various forward speeds. Free-play in the joints had no influence for this model, as the main landing gear wheel, due to its installation at an angle to the fuselage, is subject to a constant force in y-direction, putting a pre-stress in the relevant bearings. The values for natural damping vs. speed are plotted in Figure 15, left. The damping decreases for increasing speed, and crosses the the zero-boundary approximately at 60 m/s. In Figure 15, right, a non-linear time integration of the model is shown, indicating a return to the equilbrium position after a disturbance for a speed of 50 m/s, while for 70 m/s the system is unstable. Such time analyses have been performed for several speeds and configurations to support the results of the linear analysis.

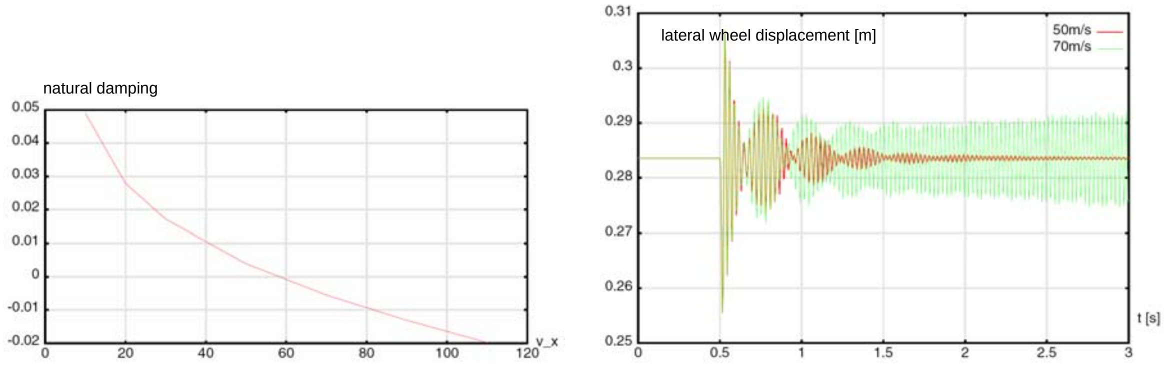


Figure 15: PHOENIX main landing gear stability analysis

It was understood that the found instability was only valid for a point which the aircraft would transition through very quickly. A set of non-linear time simulation has thus been performed to evaluate the system behaviour for the complete landing phase. Figure 16 shows results for three different weight configurations. While the landing impact and wheel spin-up is clearly visible, no indication for an instable behaviour is seen. It is clearly a help that the unmanned aircraft settles very quickly onto static position.

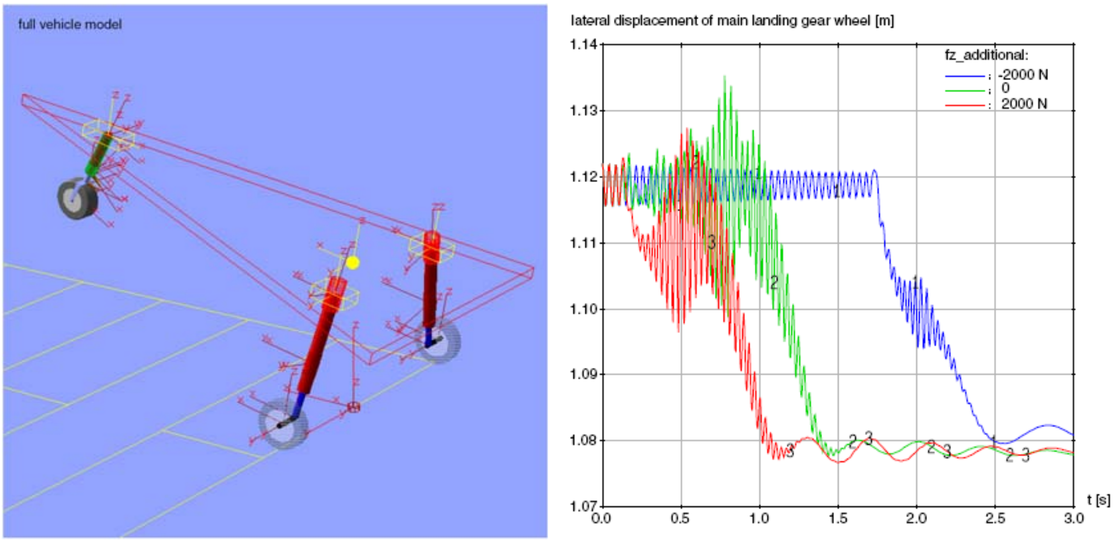


Figure 16: PHOENIX main landing gear stability analysis, complete vehicle simulation

4.2. Investigation of Anti-skid Induced Landing Gear Instability

In [41], the phenomenon known as gear-walk is investigated as an example of multidisciplinary modelling and simulation. The focus is on the fore-and-aft oscillation of the main landing gear due to the coupling of the landing gear deflection with the brake anti-skid control systems characteristics. The objective of the work is the development of a modelling approach that can be used as a design tool for the anti-skid controller in order to avoid malfunctioning during the braking manoeuvre. A comprehensive multibody model of an aircraft with a tripod main landing gear is developed and used, together with a simple anti-skid model, to predict the onset of the instability.

The multibody model used in this work is implemented in the MBDyn code (see Section 3.1). Particular attention has been dedicated to the development of nonlinear models: tires, shock absorbers, brakes and the anti-skid control system. In the frame of virtual testing, special elements simulating translational accelerometers have been introduced to monitor the accelerations without having to resort to a posteriori derivations. The case study presented regards an aircraft with a tripod-type main landing gear (MLG) which is known to suffer from gear walk in normal braking conditions. A tripod LG is peculiar from a kinematic and dynamic standpoint, as it increases the gear track during compression, see Figure 17. A symmetrical approach is adopted under the assumption that the time scale of the aircraft yaw dynamics radically differs from that of the deformable LG longitudinal dynamics. A multibody semi-model of the aircraft is fitted with a single tripod MLG and a telescopic nose landing gear (NLG). Although the gear walk phenomenon actually involves only the MLG, the NLG is needed to capture the pitch oscillations that arise during braking due to the longitudinal aircraft dynamics and LG deflection. The deceleration applied, in fact, induces a pitch in the aircraft attitude, causing a vertical load transfer between the MLG and the NLG. Although occurring at relatively low frequencies, the vertical load variation can influence the behaviour of the anti-skid control system.

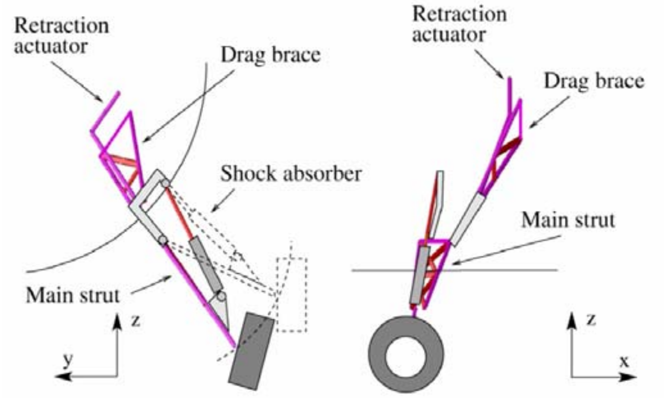


Figure 17: Detailed landing gear analysis model

Preliminary studies lead to the conclusion that the MLG model and its fuselage attachment need a certain degree of detail to fulfill gear walk instability simulation requirements. The NLG, on the other hand, is of interest only to guarantee the correct dynamic and static behaviour of the aircraft semi-model; it has thus been modeled without introducing structural flexibility. The MLG multibody model includes leg deformability and fuselage attachment flexibility: the main strut, the drag brace and the retraction actuator are modelled using flexible beam and rod elements, reproducing the web-like structures, Figure 17, whilst the connecting elements, the wheel axle and the wheel are rigid. The local MLG-fuselage attachment deformability, computed using an available FE model, has been introduced in the model using flexible joint elements. The mass and inertial characteristics, including those of the brakes mounted on the MLG, have been lumped at the structural element nodes using the available manufacturer mass breakdown data sheets and assembly drawings. Internal friction has been added to all the relevant joint elements, using a realistic friction model combined with a Herzian contact force distribution model in order to estimate joint friction. The metal-on-metal friction coefficient has been chosen referring to the literature, as no experimental data was available. Free-play has not been taken into account at this stage. The multibody semi-model of the aircraft comprises 429 degrees of freedom. During the simulation, the model is run through a complete landing manoeuvre with brake application after a brief ground roll.

Examining the available manufacturer documentation, it is possible to hypothesize that the anti-skid control gains were tuned taking in account at most the landing gear structural flexibility, completely disregarding the gear–fuselage attachments. For this reason, the authors have tuned (using the Ziegler–Nichols method) a set of control parameters using the multibody model without the flexible gear–fuselage attachment. This parameter set, referred to in the following as “NoFlex”, leads to an unstable system when applied to the complete multibody model, which includes the gear–fuselage flexibility. This last model was also used in order to tune a second set of control parameters, indicated as “Flex” in the following, that leads to a stable system. Figure 18 shows the effects of the two different parameter sets on the behaviour of the complete simulation model, which includes the gear–fuselage flexibility.

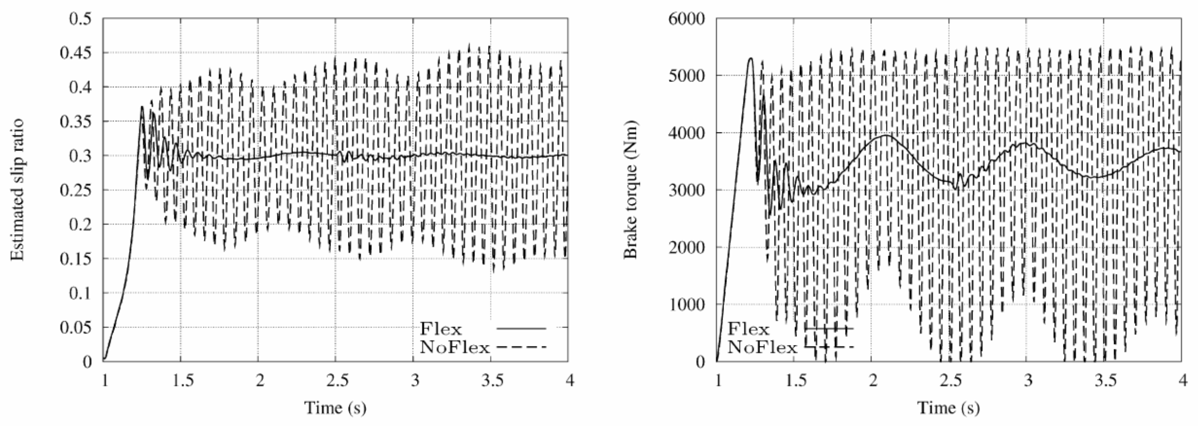


Figure 18: Comparison of various controller designs

The work showed that difficulties are encountered in the definition of an adequate dynamic model for the simulation of landing and braking manoeuvres. The approach adopted is initially time-consuming, for the fact that the single elements composing the landing gears need to be tuned referring to the available experimental data. Once the model has been assembled, however, its versatility is undoubtedly an asset in the anti-skid controller design phase. It in fact allows to explore the system behaviour in a wide range of operational conditions, also in terms of aircraft payload distribution (an aspect for which results are not presented here) and in terms of runway surface characteristics. In its present form, the effects of brake heating, tire inflation pressure and wear have not been taken into account: this will be the object of future research.

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