SIMULATION OF LANDING GEAR DYNAMICS USING FLEXIBLE MULTI-BODY METHODS

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Abstract

The predominant task of an airplane is no doubt to fly with the best performance achievable. It must not be forgotten, however, that it will spend a good part of its life on the ground. Landing gear dynamics, especially shimmy and brake-induced vibrations, is one of the problems faced today by the aircraft community. Though they are not catastrophic, can lead to fatal accidents due to excessive wear. It can also shorten the gear life and cause discomfort to the pilot and passengers. Although equations for representing various parts of a landing gear are well established, solving the problems manually with mathematical programs can be slow and laborious. Simplifications made to reduce problem size may introduce inaccuracies such that a design modification to correct a problem in one area causes unforeseen vibration in other parts of the structure. In many cases, vibration problems may not be uncovered until physical prototypes are built and tested, adding considerable time and expense to the product development cycle. However, many commercially available computer-aided engineering tools have made it possible to test some of the problems in the design phase by simulating the landing gear impact and rolling. An adequate modeling of tire and brake dynamics is an important issue for the analysis of the behavior of an aircraft during ground maneuvers as potentially unstable phenomenon such as gear walk and shimmy may occur in these phases. At the German Aerospace Center (DLR), simulation of such an unstable and complex phenomenon [14, 15] during aircraft ground maneuvers is done to detect vibrations in aircraft landing gear and study the effect of brake dynamics and other important parameters that my affect the stability and comfort.

Symbols

Hz	Hertz
V	Aircraft Forward Velocity
$\mathbf{L_{pipe}}, \mathbf{D_{pipe}}$	Length and Diameter of Hydraulic Pipe
P	Pressure in Hydraulic Pipe
$\mathbf{D_{1,2}}$	Beam Diameter
$\mathbf{L_{1,2}}$	Beam Length
$\mathbf{E_{1,2}}$	Elasticity Modulus
$\rho_{1,2}$	Mass Density
R_e	Reynolds number
v	Flow Velocity
e	Trail Length

1 Introduction

The term landing gear indicates one of the main functions of the gear, namely the containment of the landing impact but it fails to describe the other main functions, namely the provision of means for the aircraft to maneuver on the ground, taxi and take off [5]. The predominant task of an airplane is no doubt to fly with the best performance achievable. It must not be forgotten, however, that it will spend a good part of its life on the ground. Landing gear dynamics, especially shimmy and brake-induced vibrations, is one of the problems faced today by the aircraft community. Though they are not catastrophic, can lead to fatal accidents due to excessive wear. It can also shorten the gear life and cause discomfort to the pilot and passengers. Structures of modern aircraft become increasingly flexible. The main reasons are slender fuselages that frequently arise from the stretching of existing aircraft, see [16], and the use of new, light-weight structures and materials that influence the vibrational properties of fuselage and wings. Not only unsuitable combination of structural stiffness, damping, and pneumatic tire characteristics but also an unlucky combination of brake system design with the tire physics can produce a serious vibration problem [20].

Although equations for representing various parts of a landing gear are well established, solving the problems manually with mathematical programs can be slow and laborious. Simplifications made to reduce problem size may introduce inaccuracies such that a design modification to correct a problem in one area causes unforeseen vibration in other parts of the structure. In many cases, vibration problems may not be uncovered until physical prototypes are built and tested, adding considerable time and expense to the product development cycle.

However, many commercially available computer-aided engineering tools have made it possible to test some of the problems in the design phase by simulating the landing gear impact and rolling. An adequate modeling of tire and brake dynamics is an important issue for the analysis of the behavior of an aircraft during ground maneuvers as potentially unstable phenomenon such as gear walk and shimmy may occur in these phases. At the German Aerospace Center (DLR), simulation of such an unstable and complex phenomenon during aircraft ground maneuvers is done to detect vibrations in aircraft landing gear. A commercial MBS (multi-body simulation) tool SIMPACK is used for this purpose. It allows the import of external models from other codes such as Nastran. Landing gear parts modeled in Nastran are used to represent the vibration modes accurately. The goal of this project is to study brake and gear interaction and the related vibration phenomena including low frequency gear walk, and shimmy.

1.1 State of the Art

Both civil and military organizations have put great effort into optimization of the landing gear and its components. There exist some specific publications in the area of landing gear dynamics and simulation. This can be divided into three broad modules, namely modeling and simulation related to *landing gear structure*, *tire*, and *brake dynamics*.

An early overview of computer simulation of aircraft and landing gear is given by Doyle [7]. Shepherd, Catt, and Cowling [4] describe a program funded by British Aerospace for the analysis of aircraft-landing gear interaction with a high level of detail, including brakes and anti-skid, steering control, to simulate standard hardware rig test (dynamo-meter and drop tests) as well as flight tests involving ground contact. Barnes and Yager [2] discuss the use of simulators for aircraft research and development. Two publications of the IAVSD (International Association for Vehicle System Dynamics), Hitch [12] in 1981 and Krüger et al [18] in 1997 and one at NASA Langley Research Center by Pritchard [25] are state-of-the-art overviews of aircraft landing gear dynamics.

Modeling tires is a science for itself: In 1941, von Schlippe and Dietrich [27], analyzed the shimmy motion of an aircraft tire and described the interaction of tire and landing gear leg stiffness with tire forces analytically. Pacjeka [24] used a similar tire model based on the stretched string concept and developed simple derivatives representing first order lag with a relaxation length and a gyroscopic couple coefficient as parameters. For the description of steady state slip characteristics empirical formula have been developed by Bakker and Pacjeka [1], using trigonometric functions, this model is known as Magic Formula.

The performance of braking system is an important consideration in the design of landing gear system. Luber et al [20] have shown in their experimental work that adjustable control of brake torque is a sensible way to improve aircraft ground handling and performance. Krüger et al [18] also mention the need of a good model of the anti-lock braking system dynamics. Yager et al [32] under the FAA/NASA friction program discuss the evaluation of friction measurements for different runway surfaces. General requirements of a good anti-skid brake system are described in an SAE (Society of Automotive Engineering) paper [29]. Unfortunately there is not much work published related to the brake dynamics and it's effect on landing gear dynamics and aircraft in general. Although the know-how exists the brake manufacturers are not eager to share it. Since aircraft spends a good amount of time on the ground and related issues play an important part in modern aircraft design it is necessary to study the aircraft ground dynamics and the brake-gear interaction.

One of the early investigations on brake-induced vibrations was reported by Edman [8]. The report contains both experimental and theoretical studies explaining the basic phenomena and pointing out the importance of design considerations. Only linear solutions were considered in this report, however, it was recommended that non-linear friction characteristics be included in future theoretical studies. The dynamo-meter tests revealed a connection between the chatter frequencies and the wheel rotation. Theoretically, decrease in chatter amplitudes were noticed for increase in strut damping, rolling radius, and total mass. Biehl [3] during the development of a digital program to simulate the DC-9 aircraft main landing gear found out that brake torque was the primary contributor to chatter and squeal vibrations. J. Enright [10] discusses a simplified technique for laboratory dynamo-meter simulation of landing gear-brake dynamics which enable it to be used as a matter of routine to study brake dynamics accurately. Hamzeh et al [11] discuss the friction induced instabilities in a simplified aircraft brake model. Denti and Fanteria [6] in their work discuss the effects of different tire models and brake on the longitudinal dynamics of aircraft landing gear. As far as simulation of landing gear dynamics is concerned two reports from the BF Goodrich Aerospace by Rook et al [26] and H. Vinayak et al [30] are state of the art.

Fig. 1 Shimmy and Gear Walk [19]

2 Landing Gear Vibrations

The aircraft landing gear, a complex multi-degree-of-freedom dynamic system may encounter vibration modes which can be influenced by brake frictional characteristics and design features [10]. As airplane gross weights are increased, the braking performance requirements have become more severe. The performance requirements include normal landing/refused take-off braking distance limits, thermal requirements on the landing gear components, durability of friction material and overall weight considerations. Due to superior performance of carbon, increasing numbers of airplanes are using carbon brakes [22]. Although carbon has a higher specific heat capacity, a higher friction coefficient, is lighter in weight and has a better wear rate compared to steel, it is more prone to vibrations. Brake friction acts in the pitch-plane of the landing gear system, and so affects the stability of three pitch-plane modes of vibration as shown in Fig. 2.

Gear Walk is defined as the cyclic fore and aft motion of the landing gear strut assembly about a normally static vertical strut center line.

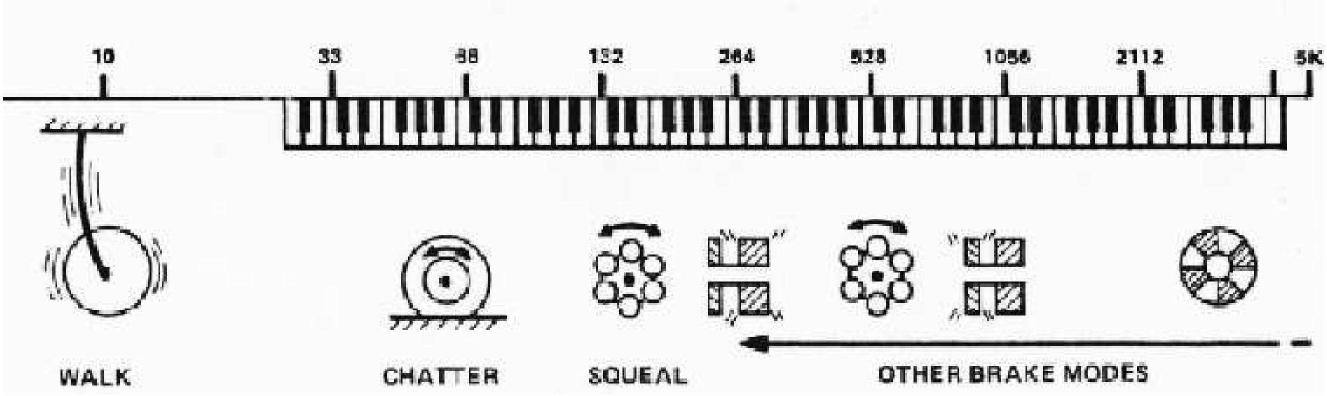

Fig. 2 Vibration Modes of a Landing Gear [10]

This motion is caused by tire-runway interface friction loads which deflect the landing gear. It may be sometimes induced by the anti-skid system and could cause passenger discomfort.

Brake Chatter is defined as the torsional motion of the rotating parts of the brake-wheel-tire assembly about the axle and against the elastic restraint of the tire. It is typically above 50 Hz and coupled with the squeal mode.

Brake Squeal can be defined as torsional vibrations of non-rotating components about the axle in the frequency range of 100-1000 Hz. The root cause of this mode is largely unknown, however, the erratic vibration phenomenon from flight test suggest that this mode is caused by the friction characteristics of brake material. it produces very high oscillatory loads on the landing gear/brake structure and can sometimes cause failure.

Shimmy Since the introduction of pneumatic tires, automobiles and aircraft have suffered from unstable oscillatory swivel motions. The oscillations exhibited by the steerable wheels is popularly known as "shimmy". Shimmy is also the term used to describe the self-induced swiveling motion of the gear of an airplane. Pneumatic tires are used for obtaining better road-holding and comfort. The vertical and lateral elasticity of the tire introduce additional degrees of freedom of motion, which are coupled with the angular motions of the wheel about the swivel axis [23]. Such a coupling may lead to the occurrence of an oscillatory instability of the stationary rectilinear motion. In case of aircraft landing gear this may be caused by the landing gear structure and interaction of the brake and gear. These vibrations are usually in range of 10 to 30 Hz, and may assume grave proportions and cause failure of mechanical components or result in loss of control of the vehicle.

3 Modeling Landing Gear

Modeling of landing gear as a rigid MBS system in SIMPACK is explained in details in the earlier work published. Please refer to [13, 14, 15, 16, 17, 18] if you need some detailed information.

3.1 Modeling Flexible Bodies in SIMPACK

SIMPACK has been designed as an open system which accepts various kinds of inputs from external standard software products. Interfaces have been established which allow links and transfers of various depth to and from other tools.

Two major options are available to analyze flexible mechanical systems: the finite element method (FEM) and the multi-body system approach. A simulation based on finite element models is, despite of the labor for setting up the model data, straightforward, the corresponding codes are well developed, and include linear and nonlinear theory of elasticity. Unfortunately, dynamic analysis with FEM-codes is very time consuming. In many applications one is confronted with system models, in which the deformations of the flexible bodies are small but superimposed of a large reference or 'rigid body motion'. In multi-body systems one exploits this fact to reduce the computational burden for such applications by linearizing the equations of motion assuming small deflections. Using relative variables to represent the reference motion and applying *O(N)*-formalisms [28], MBS-codes provide an efficient alternative for system analysis. In this work multibody system approach has been prefered.

Elastic bodies are transferred into SIMPACK using the modal approach. An elastic body is set up in a FEA tool and subject to an eigen value/eigen vector analysis. Mode shapes and nodes are transferred into the MBS model. The resulting deformation is a linear superposition of the mode shapes, see Fig. 3. For further details about the FEA interface in SIMPACK, please refer to [15, 31].

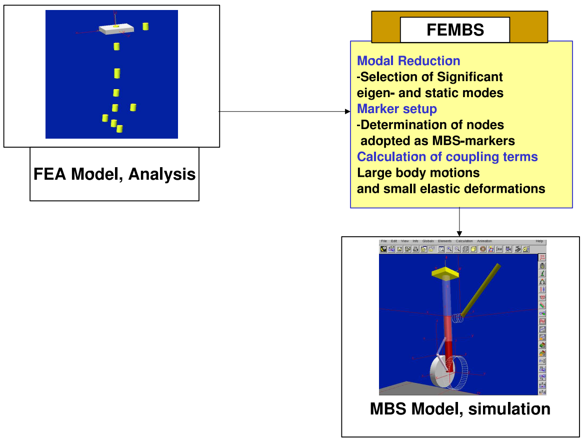

Fig. 3 How FEMBS work in SIMPACK [17, 31]

3.2 Modeling Flexible Main Landing Gear for Embraer Regional Aircraft

A valid landing gear simulation is one having the same dynamic response to brake torque as the actual gear. This means that the simulated gear must be designed to have the same equation of motion in its walk mode under the action of speed-dependent braking friction [10]. The traditional way to simulate the gear has been to use alternate structure, a dynamo-meter fixture such that one of its fundamental modes duplicates the dynamic characteristics of the gear walk mode of interest. In this paper, the flexible multi-body dynamics methods are used for the simulation of such an unstable and complex phenomenon during aircraft ground maneuvers to detect friction-induced vibrations in aircraft landing gear.

The landing gear model is prepared in Nastran as a beam model with the help of data exchanged with the industry partner Liebherr for a newly developed regional aircraft. The landing gear is modeled for different strokes and the results of the modal analysis are compared to the model received from the Liebherr and fine tuned to get similar eigen shapes and eigen frequencies. To create the model in Nastran following data given in Table 1 is used. The wheel axle is attached with the rotational degree of freedom around the y-axis at the end of beam number two. The wheels are represented by condensed masses. The nastran model is then imported in SIMPACK as explained in the Section 3.

After the touch down one can safely assume the shock strut travel (stroke value) inside the main-fitting remain constant. The model prepared in Nastran is based on the assumption that the stroke value is 0.478 m which is obtained from the flight-test data. The eigen frequencies and mode shapes after the analysis are shown in Table 2.

Parameter	Beam1	Beam2
$D_{1,2}$	0.15 m	0.13 m
$L_{1,2}$	1.469 m	1.188 m
$t_{1,2}$	0.005 m	0.004 m
$E_{1,2}$	2.1E+11	2.1E+11
$\rho_{1,2}$	7895 Kg/m^3	7895 Kg/m^3

Table 1 Data used for the Two Beam Landing Gear Model in Nastran.

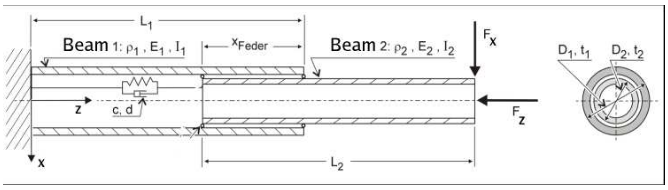

Fig. 4 Two Beam Landing Gear Model in Nastran [19]

Mode Number	**Frequency** Hz	**Mode Shape**
1	10.10	Torsion, Lateral
2	11.22	Fore-aft, Side stay tangential
3	13.25	Torsion, Side stay radial
4	45.69	Second Lateral
5	62.31	Vertical mode of the wheels

Table 2 Results of modal analysis in Nastran

4 Braking Algorithm

Stopping of the aircraft being their primary task, brakes are also used to control speed while taxiing, to steer the aircraft through differential action, and to hold the aircraft stationary when parked and during engine run-up. They are generally fixed to the main gears only and add substantial weight to them. Most airplanes use disk brakes in conjunction with an advanced anti-skid control system.

In this work various braking algorithms have been implemented and tested for simulation cases. *Dynamic Braking* - which is negative torque acting at the wheel axle and the *Anti-lock Braking System* (ABS) where slip is optimized in order to avoid locking, are explained in details in the earlier work [15]. The new sophisticated braking algorithm works as follows.

4.1 Sophisticated Braking using Hydraulic-dynamics

A simplified control diagram for this new algorithm is shown in Fig. 5. The brake control module receives inputs from the aircraft system, which includes desired velocity profile for different ground maneuvers, optimal slip values based on the runway and atmospheric conditions (rainy, icy etc.) as well as feedback from the brake system, which includes actual velocity and slip values, and also information about the malfunction of the system or part of it. The pedal transducer input is also given to the brake control module which works on the principle of LVDT (Linear Variable Displacement Transducer). This actually gives out initial brake pressure input to the ABS valve which adjusts the brake pressure by means of optimizing the slip as explained in the earlier work [15]. The brake pressure is then given as input to the brake system through hydraulic fuse. It uses hydraulic pipes to transmit this pressure.

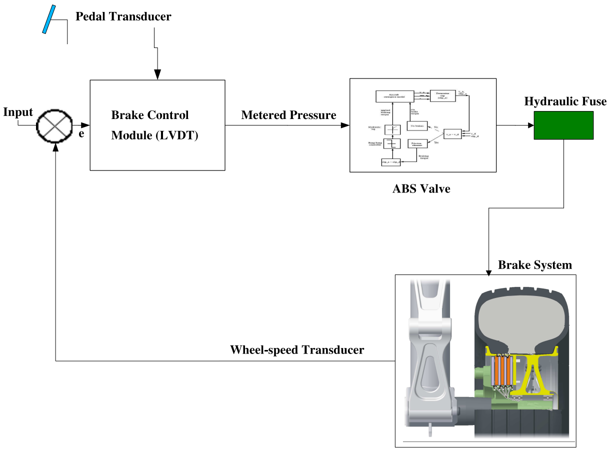

Fig. 5 Brake Control System Architecture for Sophisticated Braking

4.2 Role of Hydraulics

The results of the simulations based on the simple ’slip-optimized’ braking showed that it is necessary to sophisticate the braking algorithm. This is done by means of hydraulic lag and modeling 'real-life' like braking algorithm instead of simple braking based on 'slip-optimization' principle. The dynamics of the hydraulics is taken into the consideration as a part of the sophisticated braking algorithm in order to study the effects of changes in the geometrical parameters such as thickness and length of the hydraulic lines [15].

The pressure drop in the landing gear hydraulic lines is based on the assumption that the fluid flow state inside the pipe line will be either laminar or turbulent. A switch based on the Reynolds number is used in the calculation. The pressure drop equation is given as [21, 33]

$$\mathbf{P}_{in} - \mathbf{P}_{out} = \begin{cases} \frac{64}{R_e} \frac{L_{pipe}}{D_{pipe}} \frac{v^2}{2} & \text{if } R_e \leq 2000, \\ \frac{0.3164}{R_e^{1/4}} \frac{L_{pipe}}{D_{pipe}} \frac{v^2}{2} & \text{if } R_e \geq 2000. \end{cases} \quad (1)$$

5 Simulation Cases and Results

In this work, a ground handling scheme has been examined and has been evaluated by means of various important ground maneuvers. Different modeling tasks included development of a tire model with lateral dynamics to calculate the cornering forces during a curved run, braking system with an ABS algorithm and its effect on the aircraft performance in terms of stopping distance and passenger comfort. The goal of the work was also to study landing gear and brake interaction and the related friction induced vibrations such as gear walk and shimmy. A flexible landing gear was also modeled for that purpose. The results presented in this work are for a two mass model main landing gear of the Embraer regional aircraft. The simulations case were designed to study the landing gear vibrations, its interaction with the brake dynamics, and various parameters affecting landing gear shimmy. For the simulation of rolling and braking maneuvers it is safe assume that the aircraft is level on the ground.

Although the earlier braking algorithm showed improvements in terms of stopping distance and passenger comfort it was necessary to sophisticate this algorithm, See Section 4.2. The new braking algorithm showed vast improvements in the stability, See Fig. 6.

The oscillations exhibited by the steerable wheels is popularly known as "shimmy". Shimmy is also the term used to describe the self-induced swiveling motion of the gear of an airplane. One of the most important task of these MBS simulations was to be able to detect the shimmy oscillations along with the vibrations in the longitudinal directions known as gear walk. Flexible landing gear of a two-mass model was prepared, as explained in Section 3.2, for this purpose.

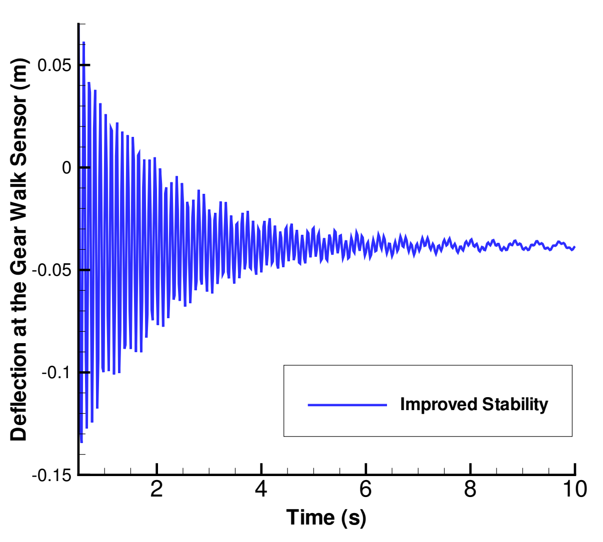

Fig. 6 Improved Stability with Sophisticated Braking Algorithm

It is known that for fixed parameters, the gear may become unstable and subsequently develop shimmy as the aircraft taxiing velocity is increased beyond a critical point [15]. Fig. 7 shows a plot of maximum real part of the eigenvalue against the taxiing velocity. As seen, at $V = 115.2\ m/s$ the real part becomes zero, above which system becomes unstable, See Fig. 8.

It was one of objectives of these simulations to study the effect of various parameters, tire mass, trail length etc, on the gear vibrations. Effect of important geometrical parameters of hydraulic line is already covered in earlier work [15]. Important parameters were changed by 25% to see if it has any effect on the stability.

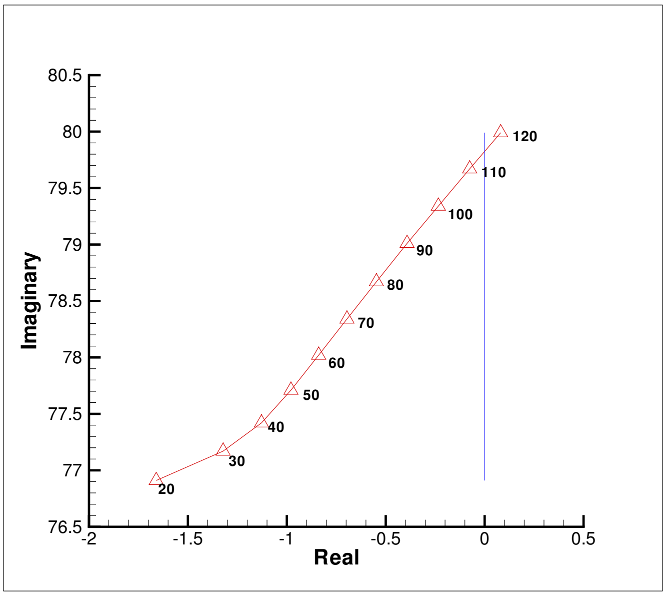

Fig. 7 Argand Diagram for Different Rolling Speeds

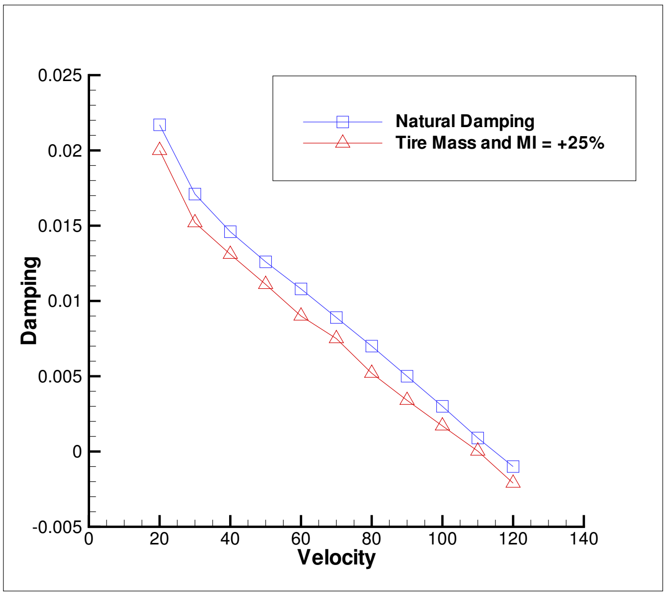

Fig. 9 Effect of Heavier Wheel on Stability

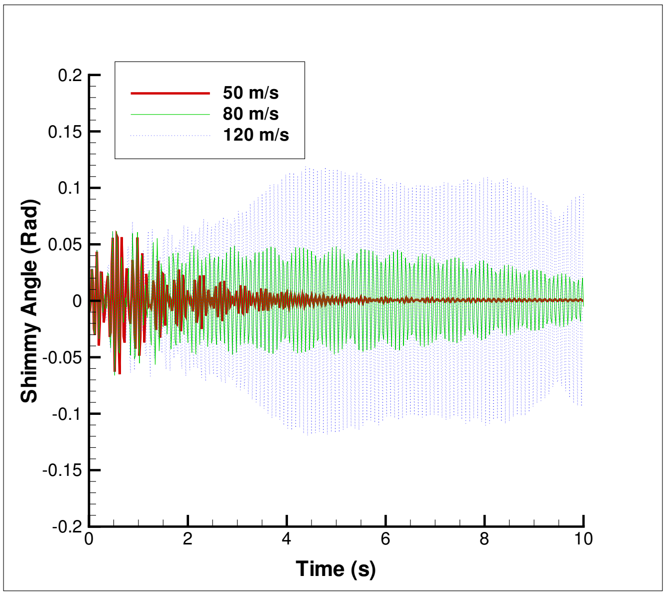

Fig. 8 Shimmy at Different Rolling Speeds

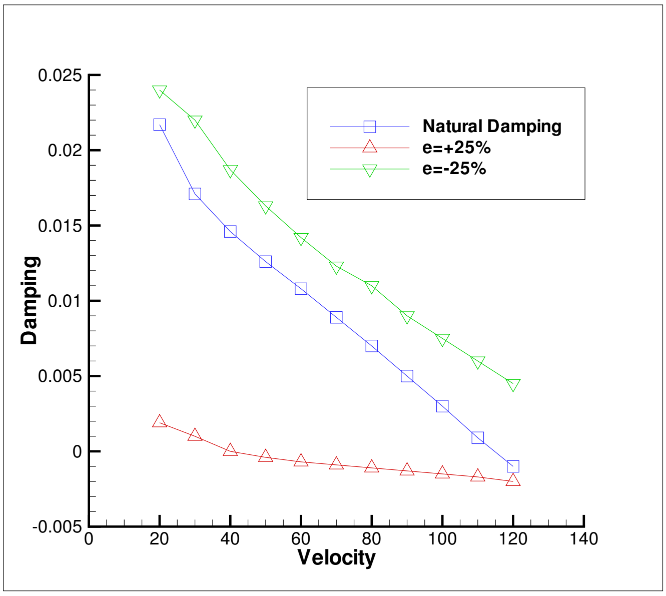

Fig. 10 Effect of Trail Length of Inertia on Stability

Fig. 9 show the effect of wheel size and mass, it was found that a larger and heavier wheel is undesirable. When wheel mass was increased by 25% the resulting system is less stable.

One of the factors playing an important role in stability is the trail length, *e*. Stability boundaries were plotted for three different trail lengths. If the system can provide more damping than the critical value, then it can be said to be stable. From Fig. 10, it is clear that for smaller trail length the system is more stable whereas when trail length is increased the system becomes less stable.

Fig. 11 show the effect of increasing the wheel span and cant angle of the gear in forward direction. It is seen that when the wheel

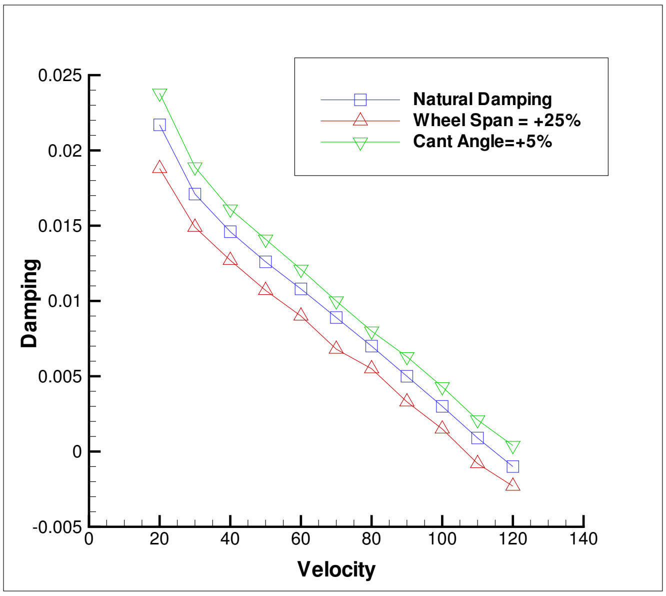

Fig. 11 Effect of Larger Wheel Span and Cant Angle Inertia on Stability

span is increased by 25% of the default value, the natural damping of the system is reduced. Thus the resulting system is less stable. Whereas the increase in cant angle of the gear improves the stability of the system which is in agreement with [5, 9]

6 Conclusions and Outlook

A flexible landing gear model was developed in order to study the friction-induced vibrations in the landing gear. In order to simulate important aircraft ground maneuvers and brake-gear interaction different modules such as a tire model with lateral dynamics effects, sophisticated brake control system were implemented in the commercial multi-body simulation code SIMPACK. The simulations and comparisons show that the new braking algorithm is more effective in terms passenger comfort, the gear vibrations, and the stability, it showed vast improvements compared to the simpler ABS algorithm based on the slip-optimization principle. It was also possible to detect the potentially unstable phenomenon such as gear walk and shimmy. With the help of the modules and simulation case effect of various parameters affecting the stability of the gear was also studied.

As a next step, thermal effect on the stability of the gear may be studied. A complex landing gear may also be modeled including non-T type structures.

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