International Forum on Aeroelasticity and Structural Dynamics
IFASD 2019
9-13 June 2019, Savannah, Georgia, USA

A HYBRID APPROACH FOR THE ANALYSIS OF AIRCRAFT GROUND LOADS

Wolf R. Krüger[1] and Sunpeth Cumnuantip[1]

Wolf.Krueger@DLR.de

[1]Institute of Aeroelasticity, German Aerospace Center (DLR)
Göttingen, Germany

Keywords: Dynamic Landing Loads, Multibody Simulation, Direct Transient Response, Finite Element Analysis

Abstract: This work presents a new process for the detailed assessment of the impact of aircraft ground maneuvers on local structural loads. The process is comprised of two core elements, a multibody simulation analysis and a subsequent direct transient response finite element analysis. The multibody simulation is used for the simulation of aircraft landing loads. These loads are then applied to an aircraft finite element model, via a direct transient response, for a more detailed analysis of the aircraft dynamic behavior at the desired points of interest. The process has been developed using landing simulations with three different finite element models of a 150-passenger aircraft. The objective of the current activities is to study the effect of major simulation and modelling parameters on the detailed aircraft dynamic response. In the paper, the process and detailed results will be presented.

1 INTRODUCTION

The determination of landing loads is an important part of the loads analysis process. Generally, the landing impact is simulated using multibody analysis (MBS) approaches, either custom-coded or in the form of standard software. The structural dynamics of the airframe can be represented by including reduced models of the structural elasticity, very often in the form of modal models derived from more detailed finite element models of the aircraft. In MBS, resulting dynamic forces between components – i.e. defined in discrete points - can readily be determined. An example of the application of MBS with the reduced models of the structural elasticity for the analysis of aircraft dynamic behaviors due to the landing impact can be found in [1] and [2]. However, the determination of local, transient dynamic loads over the aircraft structure, usually defined in a detailed finite element model, from those models is not straight forward.

This work proposes a new process with the objective to improve the limitations described above. The core of this process is the combination of a multibody simulation analysis for the determination of aircraft landing loads, and the subsequent application of a direct transient response finite element analysis, for a detailed analysis of the aircraft dynamic behavior.

Multibody simulation provides a numerical representation of the equations of motion of interconnected rigid or elastic bodies. The motion of these bodies is influenced by the realistic representation of applied forces and kinematical constraints to the bodies. MBS with its physics-based force routines such as non-linear shock absorber forces and tire forces has been well-proven for a dynamic analysis of aircraft during landing and ground manoeuvres. However, MBS has a limitation in the size of the elastic representation which can be imported from a finite element model. MBS models are usually several orders of magnitude smaller than detailed finite element models, FEM, used in aircraft loads analysis. These models have generally to be reduced, e.g. by a Guyan reduction or by a generalized dynamic reduction [3], in a pre-processing step, before they can be imported into an MBS model. As the result, global structural behavior can be well represented, but the representation of a detailed dynamic response, such as e.g. the acceleration of structural components between two fuselage frames, can usually not be obtained from an MBS analysis.

Finite element analysis, on the other hand, is the standard approach for structural analysis, i.e. for static analysis and for dynamic loads and stress analysis. Very large elastic models are possible; the structural models are in the majority of cases linear, non-linear models are also possible. Most FEM analyses are based on static solutions and frequency domain approaches. However, time domain solutions can be applied. The transient response analysis is a method to compute the dynamic response of a structure subjected to a time-varying excitation. These excitations can be given in the form of applied forces or enforced motions. The important results obtained from a transient analysis are typically displacements, velocities, and accelerations of grid points, as well as forces and stresses in elements [4].

Based on the characteristics of the two simulations methods described above, the so-called 'Hybrid Multibody / Full Finite Element Simulation Approach' has been developed. In the approach, the aircraft landing gear attachment loads are determined via MBS, using a reduced finite element model for the aircraft structure. These loads are then used as the input for a direct transient response finite element analysis of the full aircraft finite element model. As the result of the combination of these two analyses, a structural dynamic response can be obtained for all details represented in the finite element model.

The following section of this paper focuses on the description of the new process. The process flow and the interface between the two analyses are explained. Important interface and modelling parameters are also addressed in the section, and the objective of the parameter studies is described. Afterwards, the simulation and analysis models for the validation of the new process are presented. Details of the MBS models and the finite element models for the transient analysis of the two references aircraft are explained, as well as simulation scenarios. The final section discusses the result of those simulations, the major focus being on the effect of the interface parameter settings as well as of finite element modelling issues on the results of the aircraft dynamic responses.

2 THE HYBRID MULTIBODY / FULL FINITE ELEMENT APPROACH

As mentioned previously, this work introduces a 'Hybrid Multibody / Full Finite Element Approach' for an improved determination of the dynamic response of the aircraft structure due to landing gear loads. Figure 1 shows the diagram of the process. The MBS tool implemented in the process is the commercial software SIMPACK [5]. The finite element software used is MSC NASTRAN [4].

A finite element model of the aircraft structure forms the starting point of the process. This model has to be pre-processed to be used in the MBS analysis. Due to its typical range of application in vehicle dynamics, there is a sensible limit of the size of an elastic model which can be included in an MBS simulation. Thus, the full and detailed aircraft finite element has to be reduced. This is done via a generalized dynamic reduction in NASTRAN. The reduced finite element model with the mass and stiffness information at the condensed nodes is then imported to the MBS. Evidently, nodes acting as interface nodes for the connection of MBS forces to the elastic structure have to be provided. SIMPACK then performs a modal analysis on the elastic model. The number of modes representing the structure to be used in the analysis can be selected.

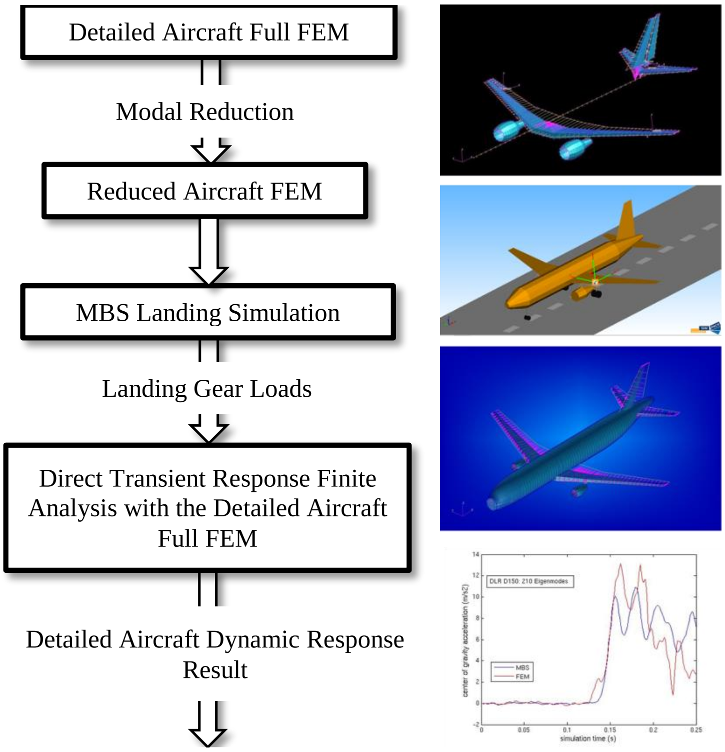

Figure 1: A hybrid multibody / full finite element process for the assessment of dynamic landing loads

In SIMPACK, the models of the landing gears are built up and connected to the airframe at the landing gear attachment points, i.e. the respective interface nodes. The initial conditions are defined, consisting of forward and vertical landing speed, as well as the scenario, e.g. three point landing or two point landing. Afterwards, a time domain landing simulation in MBS is performed. The landing gear attachment loads are obtained in the time domain.

The loads are transferred into the appropriate format of the FEM tool and are applied to the full detailed finite element method for the transient analysis. The method which is implemented in this process is the direct transient analysis method of MSC NASTRAN, the so-called SOL109. The result from the transient analysis can be element stress, element force and nodal dynamic response such as velocity and acceleration. For the assessment of the process described in the paper, the main focus is on the comparison of nodal accelerations.

Two key elements play an important role in the determination of the aircraft dynamic response. The first key element is the realistic determination of the landing gear attachment loads in the MBS simulation. For an elastic aircraft, there is a dependence of the landing loads on the representation of the elastic airframe in the MBS model. A parameter that significantly effects this representation is the number of selected eigenmodes during the MBS preprocessing. The selected eigenmodes shall cover all of the relevant mode shapes and eigenfrequencies that are concerned with the aircraft structural part of interest.

The second key element is the proper transfer of the ground loads from the attachment points into the aircraft structure. These transfer elements shall represent the actual load path from the landing gear to the real aircraft structure. A realistic modelling of the transfer elements to the actual load path structures will finally lead to a correct result of the dynamic response.

In this paper, two studies are described. The first study is a parameter study on the number of eigenmodes of the reduced finite element model to be selected for the use in MBS analysis. In the study, the dynamic response from the MBS analysis will be correlated with the dynamic response from the FEM transient analysis. The second study is an investigation of different modelling approaches for the transfer of landing gear loads into the airframe. The objective of both studies is to find a proper set-up of the MBS model and of the transient analysis model parameters. The obtained knowledge from both studies is the basis for the implementation of the new process using a detailed aircraft model which is presented in this paper as the final step of the process development.

The following section presents in more detail the modelling of the MBS and the transient analysis models which are used in this paper. Furthermore, the problem definition of the studies mentioned above is given.

3 MBS AND FINITE ELEMENT TRANSIENT ANALYSIS MODELS

3.1 Reference Aircraft

Three aircraft models are used for the development of the new process. The reference aircraft is a 150-passenger mid-range aircraft, the so-called DLR-D150. The DLR-D150 aircraft is a low-wing civil transport aircraft of the 150 passenger class. The maximum take-off weight of the DLR-D150 is 72.5 t. The wing span is 33.9 m. The aircraft has a twin nose landing gear and two twin main landing gears. This configuration has been created and used in several DLR internal projects. A detailed description of the definition of this aircraft can be found in [6]. Figure 2 shows a view of the DLR-D150 aircraft, taken from [7].

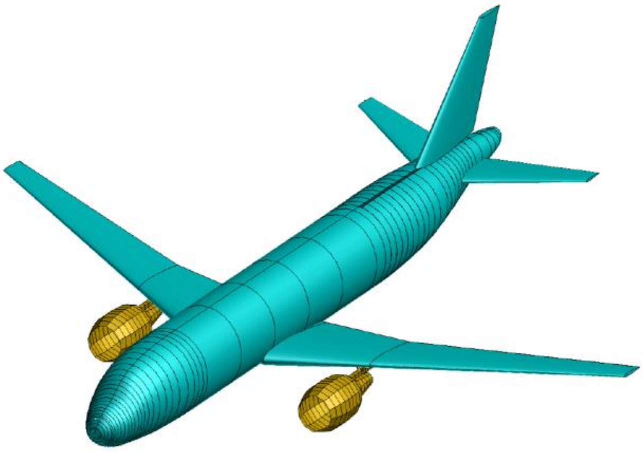

Figure 2: The DLR-D150 aircraft

For the studies presented in this paper, the aircraft is represented by three finite element models with different levels of complexity. The first developments of the process have been made with a simplified, conceptual model, in the following called “**DLR-D150-CON**”. The simulation process has been further developed using a finite element model with a preliminary design level of detail, with a shell model of wings and fuselage, and the fuselage represented as a beam. This model will be called “**DLR-D150-PRE**”. Finally, investigations have been performed with a full finite element model of the aircraft, representing wings and fuselage with a higher level of detail. Consequently, the model will be called “**DLR-D150-FULL**”. The following paragraphs describe the three aircraft configurations more closely.

3.1.1 The Conceptual 150 Passenger Aircraft

The first assessment of the new approach begins with a functionality test of the process and a test of the interfaces between the two core analyses. The reference aircraft for this task is a conceptual model of the D150. The airframe is described by a small finite element model only representing global elastic properties. Figure 2 shows the finite element model of the aircraft.

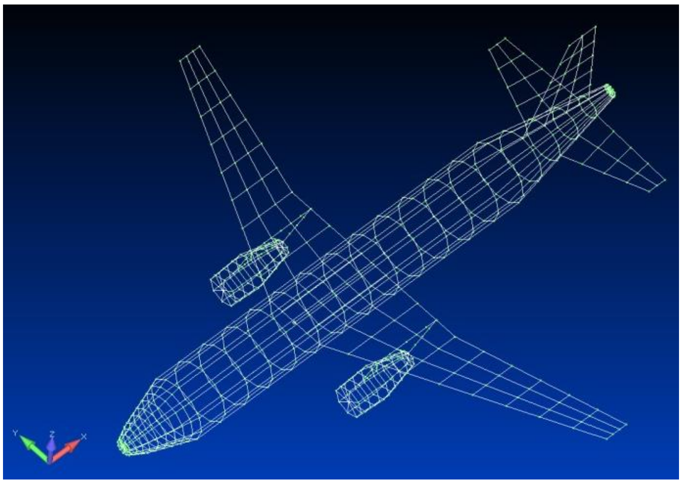

Figure 3: Finite element model of the Conceptual Level (“DLR-D150-CON”)

3.1.2 The Preliminary Level DLR-D150 Passenger Aircraft

The second reference aircraft model is used to study the effect of the number of selected eigenmodes on the results of the multibody simulation. It has also been used to investigate the effect of the topology of the landing gear attachment structure on the final aircraft dynamic results. For this purpose, a more detailed finite element model has been used, see Figure 4. In the following sections, this aircraft will be called the “DLR-D150-PRE” model.

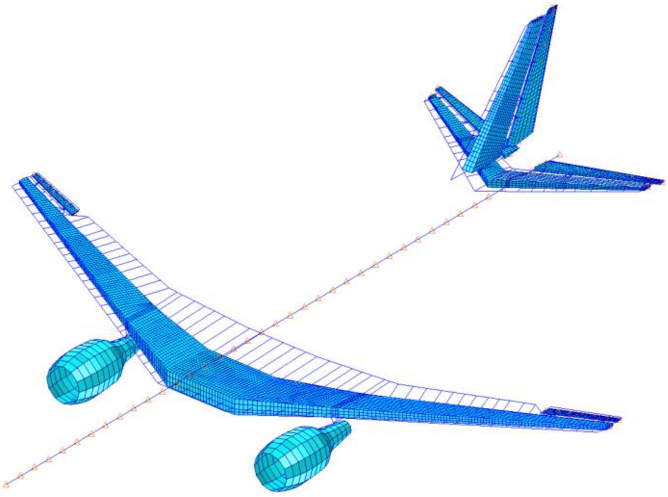

Figure 4: Finite element model of the Preliminary Level aircraft (“DLR-D150-PRE”)

3.1.3 The Detailed Level DLR-D150 Passenger Aircraft

The third reference aircraft model represents the most detailed level of the DLR-D150 aircraft model. The difference to the preliminary level model is primarily the representation of the fuselage, which is modelled as a shell model including all structural components typical for the fuselage, see Figure 9, Section 3.3.3, for a detailed picture of the finite element model. This third reference aircraft model is used first to show the ability of the new process to work with complex structural models. Furthermore, the investigation of the ground loads on fuselage dynamics is of special interest for the hybrid approach presented here. In the following sections, the detailed design level aircraft will be called the “DLR-D150-FULL” aircraft. Section 3.3.3 will give a more detailed explanation of the difference between the DLR-D150-PRE and the DLR-D150-FULL models.

3.2 MBS Models

3.2.1 MBS Models for Aircraft Landing Simulation

In principle, an MBS system is comprised of various ‘bodies’ that are connected via different ‘joints’, and the force between each body is represented by a ‘force element’. In the case of an aircraft landing simulation, the MBS system is comprised of the following components:

- The aircraft as the reference body,
- The nose landing gear substructure,
- The main landing gear substructures,
- The force elements within the landing gear substructures.

Figure 4, top, shows an MBS schematic for an aircraft landing simulation of an aircraft with a twin nose landing gear and two twin main landing gears, the aircraft landing gear configuration of both reference aircraft in this paper.

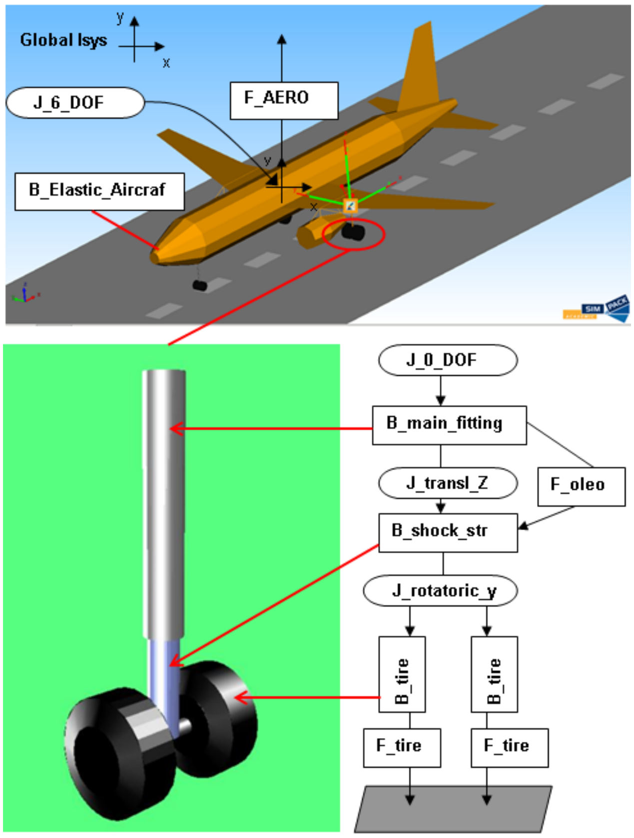

Figure 5: MBS simulation model of aircraft and landing gear

The aircraft is connected to the global reference coordinate system via a 6 degree-of-freedom joint, see Figure 5, top. The landing gear substructures are connected to this reference body via a rigid joint. Each of the landing gear substructures, see Figure 5, bottom, is comprised of various bodies, joints and force elements. Main fitting, shock strut, bogie, axle and wheels are modeled as rigid bodies. The shock absorber force element acts between main fitting and shock strut. The attachments to the airframe are assumed to be rigid. Note that for the simulation of the landing impact, the aerodynamic forces are not explicitly calculated but are assumed to exactly counter the gravitational force. This approach is justified for very short simulation durations where only the peak load of the impact is of interest.

The landing gear modelling approach described above is simplified, but remains complex enough to represent the dynamical behavior of the actual landing gear during the conceptual and preliminary design phase. An example of the use of this modelling approach is the assessment of semi-active landing gear [1], and the optimization of landing gear positioning [8].

The three following major force elements are sufficient to represent the characteristics of the landing gear shock absorber.

Oleo Force (gas spring): The gas spring is represented by the law of polytropic expansion [1],

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

with spring force F_f, pre-stress force, F_0, oleo stroke, s, oleo gas length, s_m, polytropic coefficient n, and a correction factor, c_k. The value of $n*c_k$ is assumed to be 1.4, which is a common value for a commercial aircraft of this passenger class. The oleo stroke, s, is measured internally in SIMPACK. Finally, the force element is applied between the main fitting body and the shock strut body as shown in Figure 5.

Oleo Force (passive damper): The properties of the passive damper are determined by the laws describing the flow of hydraulic oil through an orifice. Bernoulli's equation solves for the force on the oleo piston yields,

$$F_d = \ \mathrm{sgn}\ (\dot{s}) \cdot \mathrm{d} \cdot \dot{s}^2 \tag{2}$$

with oleo stroke velocity $\dot{s}$, oleo damping force F_d and damping coefficient d. The damping coefficient can be adjusted for touchdown or for rolling of the aircraft. The oleo stroke velocity is measured internally in SIMPACK. Similar to the oleo spring force, the damper force is also applied between the main fitting body and the shock strut body.

Tire forces: The tire connects the wheel to the runway when the aircraft is on the ground. The simulation force element measures the height of the wheel axis with respect to the excitation. This rolling radius, r_r, is subtracted from the nominal tire radius r_{nom} to determine the tire deflection d_z:

$$d_z = dr_{nom} - r_r \tag{3}$$

The wheel is modeled as a separate body with a rotational degree of freedom. The longitudinal motion of the body with respect to the runway is used to calculate tire slip and torque on the wheel. The major tire force, vertical force F_z, is calculated using the tire deflection from Equation 4 as follows

$$F_z = c_1 d_z - F_{zN} - d_t v_z \tag{4}$$

The parameter c_1 [N/m] is the tire vertical stiffness. The force F_{zN} [N] is the norminal vertical force (negative values are acting upwards on the tire). The parameter d_t [Ns/m] is the tire damping coefficient. The variable v_z [m/s] is the tire vertical velocity.

For longitudinal forces, the slip calculated in the main tire element is used. It is defined as the ratio of the horizontal velocity of the wheel contact point and the axle forward velocity, v_x, as

$$\mathrm{slip} = \frac{v_x - r_r\ \omega}{v_x} \tag{5}$$

Using the obtained slip, the runway friction coefficient μ_{RW} can be determined as a function of the slip. Finally, the longitudinal force F_x which is a function of vertical force F_z and μ_{RW} can be evaluated as

$$F_x = \mu_{RW} \cdot F_z \tag{6}$$

The vertical and longitudinal forces described above are sufficient in this work which is restricted to straight aircraft motion without turning load cases.

The landing gears are modelled as rigid bodies. This is sufficient for the dynamic response study which has a major focus on the aircraft structure rather than the landing gear structure itself. The airframe, however, must be modelled as an elastic body. All data for landing gear mass, gas spring and oleo damper parameters, as well as the tire vertical stiffness and tire damping coefficient have been taken from the DLR internal database.

3.2.2 MBS Pre-Processing: Integration of the Finite Element Model

Figure 6 shows the pre-processing flow diagram of SIMPACK for the import of the elastic (airframe) body into the MBS system. The pre-processing begins with a model reduction of the full finite element model of the aircraft structure. The finite element models are built up in MSC NASTRAN. The method for the model reduction is the generalized dynamic reduction method. The details of this method can be found in [3]. A very important task of the model reduction is the proper set-up of the superelement interface nodes. These nodes are the nodes where the stiffness and the mass information of the full model are condensed to.

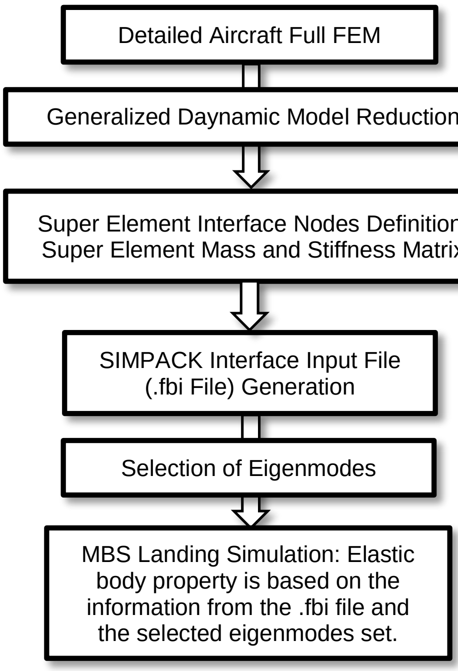

Figure 6: Pre-processing diagram - import of elastic airframe body into MBS landing simulation

After the model reduction, a SIMAPCK interface input file (the so-called .fbi file), is created. The file contains the information of interface nodes definition, the super element mass and the super element stiffness matrix of the aircraft structure. When the MBS aircraft model is set up, the aircraft body is defined to be elastic. The elastic properties of the aircraft body are obtained from the .fbi file. In SIMPACK, the number of relevant eigenmodes for an elastic body to be used in the simulation is then selected.

3.3 Finite Element Models of the DLR-D150

As introduced in Section 3.1, three finite element models of the DLR-D150 have been used for the investigations. While the smallest model, the DLR-D150-CON, has been set up manually, both the finite element models of DLR-D150-PRE and DLR-D150-FULL have been created by the implementation of the DLR parametric modelling process CPACS-MONA [13], [14].

3.3.1 The DLR-D150-CON Model

As mentioned above, the definition of the superelement interface nodes and the selection of relevant eigenmodes play a major in the realistic representation of the aircraft structure during the MBS landing simulation. The finite element model of the DLR-D150-CON model (Figure 3) only has in total 614 element nodes, thus all of the nodes are set to be the superelement nodes.

3.3.2 The DLR-D150-PRE Model

In the case of the DLR-D150-PRE model, the structure of the wing and the empennage is modelled in more detail. Wing, tails and control surfaces finite element models are modelled as 2-D shell elements. The fuselage is modelled as beam elements. The 2-D shell elements center wing box is connected to the fuselage beam elements via a rigid body element. Figure 7, left, shows the complete FEM of the DLR-D150-PRE aircraft. Figure 7, right, shows the topology of the connection element between the center wing box and the fuselage. The complete DLR-D150-PRE finite element model contains 13,790 nodes, which is over the limitation of the dynamic degrees of freedom that can be handled in the MBS-based landing simulation. The SIMPACK User Guide suggests a maximum of approximately 3000 DOFs [5]. Thus, the DLR-D150-PRE superelement interface nodes are defined at the load reference axis of the aircraft. In total, 261 superelement interface nodes defined are which are illustrated in Figure 8.

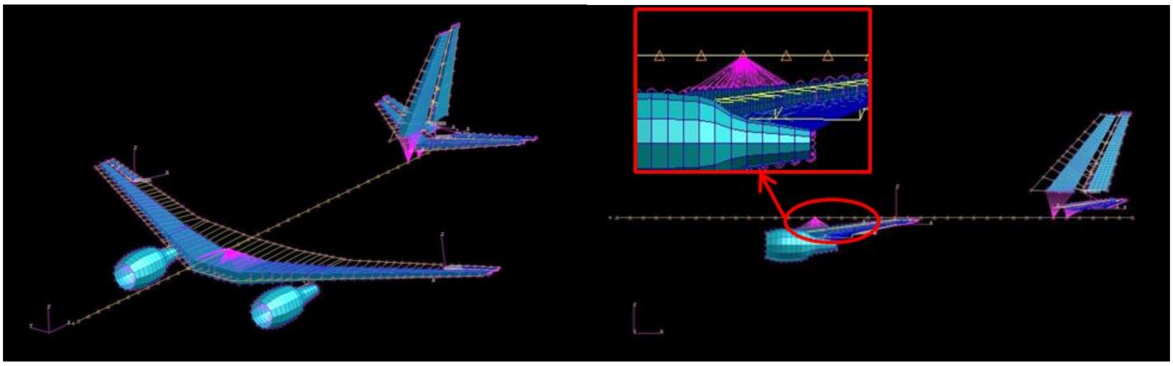

Figure 7: The DLR-D150 aircraft complete FEM and the topology of the wing fuselage connection elements

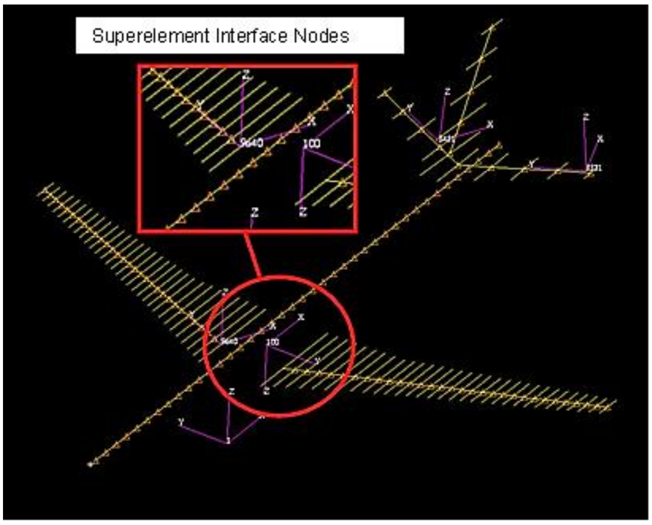

Figure 8: Superelement interface nodes at the load reference axis of the DLR-D150 FEM

3.3.3 The DLR-D150-FULL Model

For the most complex model, the DLR-D150-FULL model, the structure of the fuselage, wing, tails and control surfaces are modelled in more detail than the DLR-D150-PRE aircraft structure. All of the structural components are modelled as 2-D shell elements. The level of detail of this aircraft model is comparable to one used in industrial applications detailed global aircraft loads and structural dynamic analysis. The DLR-D150-FULL contains a center wing box model with 2-D shell elements which are connected to the 2-D shell elements making up the fuselage including fuselage keel beam, passenger floor and front landing gear bay pressure bulk head. Figure 9, left, shows the complete FEM of the DLR-D150-FULL aircraft. Figure 9, right, shows detail of the connection between the center wing box and the fuselage of the DLR-D150-FULL FEM. The DLR-D150-FULL complete finite element model contains 34,268 nodes and 44,535 elements. The DLR-D150-FULL superelement interface nodes are also defined at the load reference axis of the aircraft. A total of 261 superelement interface nodes ar defined. The positions of these nodes are the same as the ones for the finite element model of the DLR-D150-PRE which have been illustrated in Figure 8.

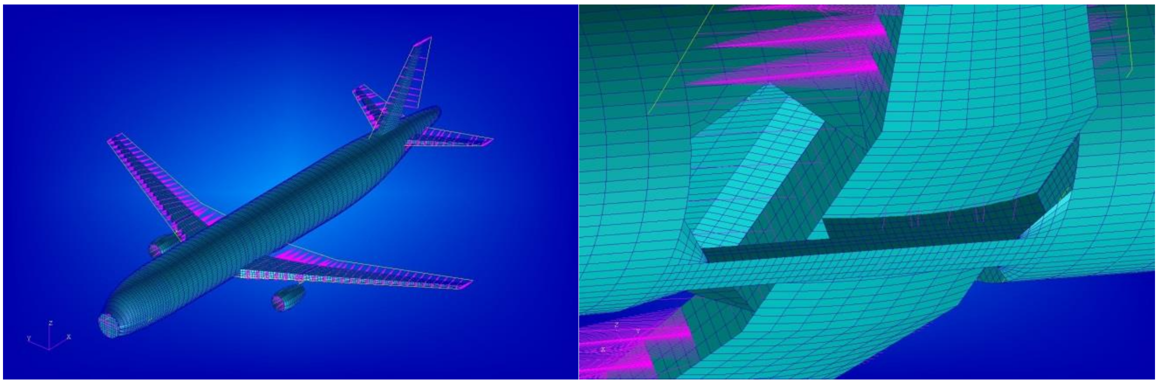

Figure 9: The DLR-D150-Full aircraft complete FEM and the detail of the wing fuselage connection

The selection of the eigenmodes used in the MBS simulations is part of the parameter study problem definition and will be discussed in more detail in Section 3.4.

3.3.4 MBS Landing Simulation Scenarios

The initial conditions will be selected in order to cover representative examples of possible touch-down scenarios. As this work has the main focus on the functionality study of the process, a level landing (a so-called Three-Point Touchdown) has been chosen for the study in this work. The scenario is based on an authority requirement according to JAR-25 [9], where main landing gear and nose landing gear tires touch the runway at the same instant (pitch angle = 0.0°, yaw angle = 0.0°, roll angle = 0.0°). The landing is performed at a maximum descent velocity of 6 ft/s. The aircraft is landed with the maximum take-off weight.

3.4 Finite Element Transient Analysis Model

The purpose of a transient response analysis is to compute the behavior of a structure subjected to time-varying excitation. The transient excitation is explicitly defined in the time domain. Depending upon the structure and the nature of the loading, two different numerical methods can be used for a transient response analysis: direct and modal. This work implements the direct method. The direct method performs a numerical integration of the complete coupled equations of motion as described in the following equation, [3], [4].

$$[M]\{\ddot{u}(t)\} + [B]\{\dot{u}(t)\} + [K]\{u(t)\} = \{P(t)\} \tag{7}$$

The matrices [M], [B] and [K] are the aircraft full finite element system mass matrix, damping matrix and stiffness matrix, respectively. P(t) is the applied landing gear loads vector from the MBS analysis. The vectors $\ddot{u}(t)$, $\dot{u}(t)$ and $u(t)$ are the system acceleration, velocity and displacement vector respectively. The details of the numerical method of the solution of Equation 7 can be found in [3]. The important results obtained from a transient analysis are typically displacements, velocities, and accelerations of grid points, and forces and stresses in elements.

The important aspect of the transient response analysis implementation in order to obtained a correct dynamic response result is the correct application of the time dependent external force, P(t), to the structure system of interest. In this paper, the effect of different landing gear attachment finite elements topologies on the aircraft dynamic structural response is investigated. Section 3.4 explains this study in more detail.

3.5 Functional Test and Parameter Study: Definition

The following paragraphs describe the functional test of the new process and a process parameter study which have been performed in this work.

3.5.1 Functional Test of the New Process

The first study in this work is on the functionality of the new process itself. The functionality of the process is tested by the landing simulation of the DLR-D150-CON aircraft. The MBS simulation scenario and the MBS model have been set up according to the description in Section 3.2. Due to the purpose of this simulation, the functionality test of the process, only the first elastic eigenmode is imported to the MBS for the modelling of the aircraft elastic body. The landing gear forces resulting from the MBS simulation are applied to the full FEM for the direct transient analysis via rigid body elements. Figure 10 shows the position of the rigid body elements which connect the landing gear shock absorber attachment point to the nearby wing and fuselage structure nodes. The result of interest for the process functional test is the comparison of the vertical acceleration result of the tail cone from the MBS analysis and from the direct transient analysis. The result will be discussed in Section 4.

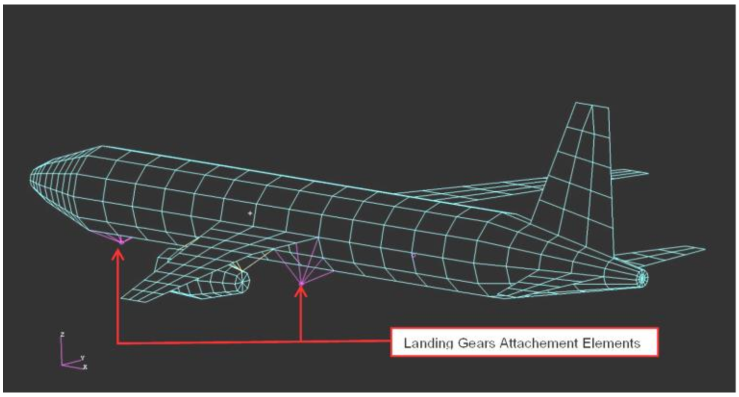

Figure 10: The FEM of the DLR-D150-CON with rigid body elements for landing gear attachment

3.5.2 Effect of the Number of Selected Eigenmodes

The result of the functionality test has shown the capability of the process to determine the aircraft dynamic response. Thus, in order to successfully implement the new process with a more detailed aircraft FEM, additional knowledge concerning the simulation model is required. As stated previously, in the case of a complex FEM, the full model must be reduced before the MBS analysis can be performed. The question is now how far a model can be reduced to still deliver good results.

The DLR-D150-PRE aircraft FEM is a model with the complexity level that can represent the global dynamic behavior of the real aircraft structure. Three sets of the number of the selected eigenmodes have been investigated: 19 modes (all of the modes with eigenfrequency less than 10 Hz), 73 modes (all of the modes with eigenfrequency less than 50 Hz), and 210 modes (all of the modes with eigenfrequency less than 150 Hz). The result of interest of the study is the effect of the number of the selected eigenmodes on the vertical acceleration of the aircraft structure at selected positions. Four locations have been chosen to be the monitoring positions: the aircraft nose, the aircraft center of gravity, the aircraft tail tip, and the aircraft wing tip. Figure 11 shows the four positions. The result of this study will be discussed in detail in Section 4.

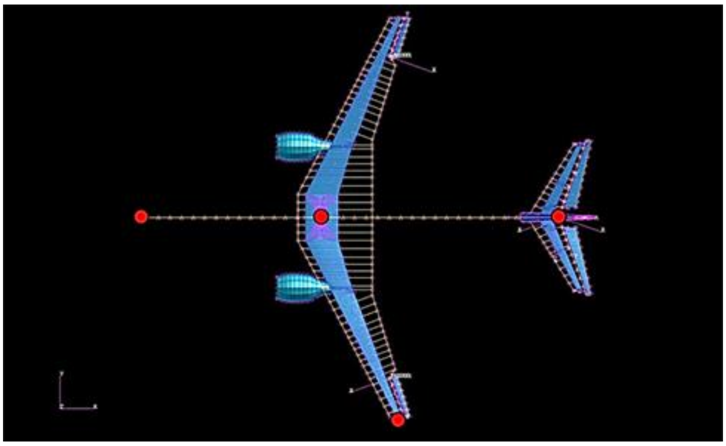

Figure 11: Monitoring positions on the DLR-D150-PRE FEM

3.5.3 Effect of the Landing Gear Attachment Structure Topology

Two configurations of the topology of the landing gear attachment structure in the finite element model are investigated using the DLR-D150-PRE model. Figure 12shows the first configuration, where the landing gears are attached directly and only to the center wing box.

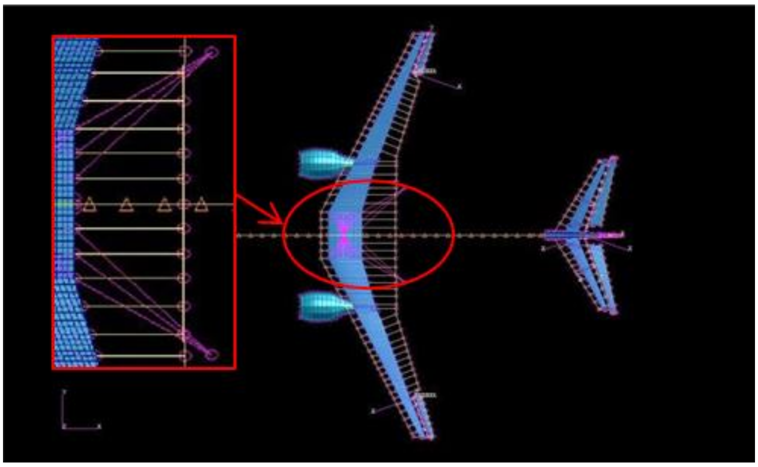

Figure 12: Landing gear attachment topology, configuration 1

Figure 13 illustrates the second attachment structure finite element topology. In contrast to the first configuration, the landing gear loads of the second configuration are distributed both to the rear spar of the center wing box and to the rear spar of the inner wing.

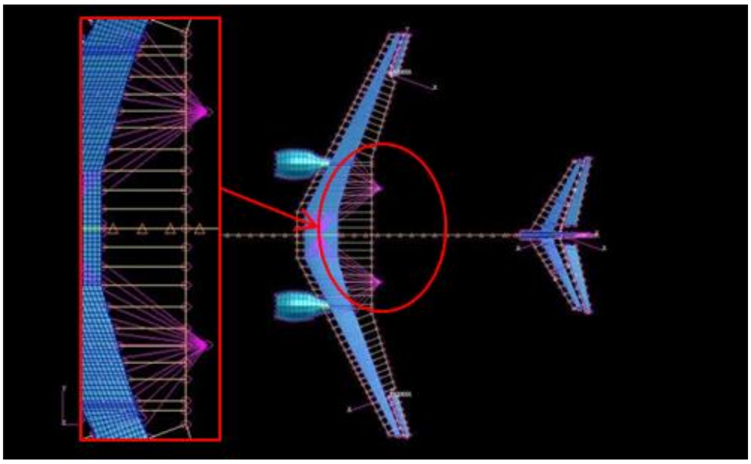

Figure 13: Landing gear attachment topology, configuration 2

4 FUNCTIONAL TEST AND PARAMETER STUDY: RESULTS AND DISCUSSION

4.1 Functional Test of the New Process

Figure 14 shows the vertical acceleration result at the tail tip position of the conceptual 150 passenger aircraft. The blue line is the result from the MBS analysis and the red line is the result from the direct transient analysis.

It can be observed that the vertical acceleration at the aircraft tail tip resulting from the MBS has the same trend as the result from the direct transient finite element analysis. This proves the functional of the new process. Note that the curves cannot be on top of each other, as elastic modes are excited in the FEM which have not been used in the MBS analysis.

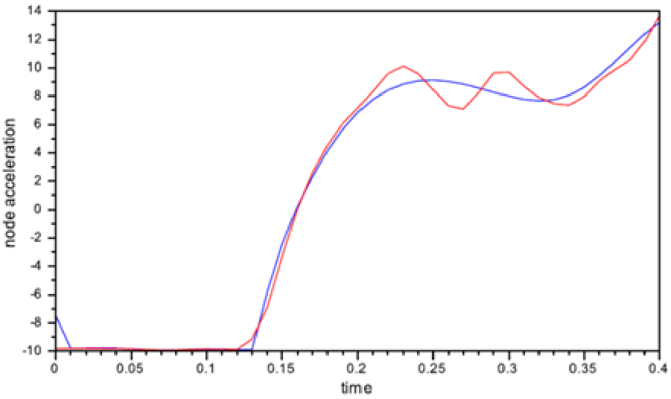

Figure 14: The vertical acceleration result at the tail tip position of the DLR-150-CON aircraft

4.2 Parameter Study: Effect of the Number of Selected Eigenmodes

The process parameter study begins with the investigation of the effect of the number of selected eigenmodes for the MBS set-up on the aircraft dynamic response. Landing simulations of the DLR-D150-PRE with two different numbers of selected eigenmodes of the aircraft elastic body are performed for this investigation. The first simulation uses 19 modes, i.e. all of the modes with eigenfrequency less than 10 Hz, the second simulation uses 73 modes, i.e. all of the modes with eigenfrequency less than 50 Hz. The landing gear attachment structure is configuration 1, Figure 12, for both simulations. Figure 15 shows the vertical acceleration result at the nose tip from the simulation with 19 considered eigenmodes (Figure 15, left) compared to the result from the simulation with 73 considered eigenmodes (Figure 15, right).

The blue line is the result from the MBS analysis and the red line is the result from the FEM direct transient analysis. Figure 16 shows the vertical acceleration result at the tail tip for the same simulation cases.

According to the results shown in Figure 15 and 16, the consideration of 19 eigenmodes for the DLR-D150 elastic body in the MBS is not sufficient to predict the trend of the direct transient finite element analysis. On the other hand, the consideration of 73 modes in the MBS gives a better trend in the MBS simulation. These observations are valid for both monitoring positions on the airframe. It can be noticed that even with the higher number of considered eigenmodes there is still difference between the result from the MBS and the direct transient analysis.

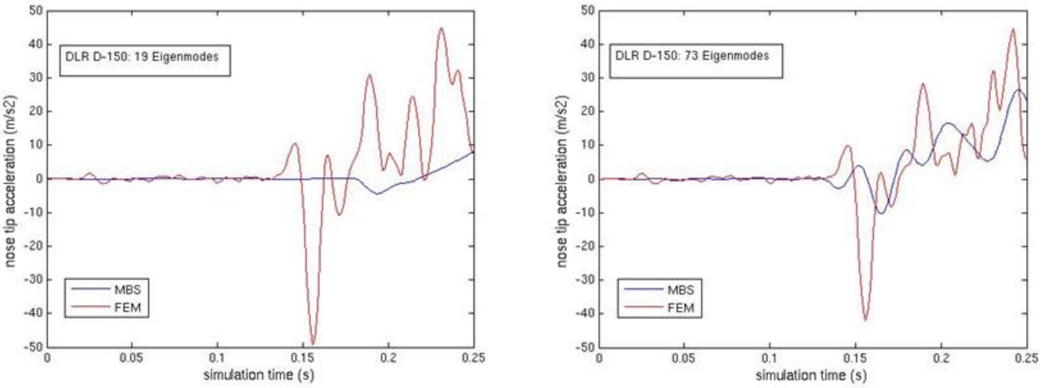

Figure 15: Vertical acceleration at nose tip, simulations with 19 and 73 considered eigenmodes for the DLR-D150 elastic body

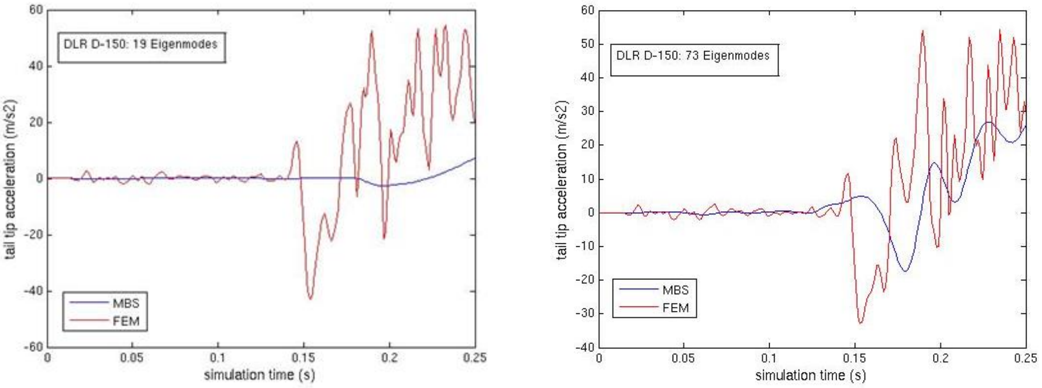

Figure 16: Vertical acceleration at tail tip, simulations with 19 and 73 considered eigenmodes for the elastic body of the DLR-D150-PRE model

4.3 Parameter Study: Effect of the Landing Gear Attachment Structure Topology

The second parameter study of the new process is the study of the effect of the finite element topology of the landing gear attachment structure. Two landing simulations with two different landing gear attachment topologies are performed for this study. The first simulation has the finite element topology which transfers the loads from the landing gear only to the center wing box as shown in Figure 12. The topology which distributes the landing gear loads both to the center wing box and the inner wing section as shown in Figure 13 is used for the second simulation.

In both cases, the DLR-D150 elastic body is represented by 73 eigenmodes. Figure 17 shows the vertical acceleration result at the aircraft center of gravity from the simulation with the landing gear attachment structure finite element topology configuration 1 (Figure 17, left) and configuration 2 (Figure 17, right). The blue line is the result from the MBS analysis and the red line is the result from the direct transient analysis. Figure 18 shows the vertical acceleration result at the aircraft wing tip from the simulation with the landing gear attachment structure finite element topology configuration 1 and configuration 2. The blue line is the result from the MBS analysis and the red line is the result from the direct transient analysis.

Based on the result shown in Figure 17 and 18 it can be clearly observed that for the landing gear finite element topology configuration 2 results from the MBS are closer to the result from the direct transient finite element analysis. This applies for both monitoring positions.

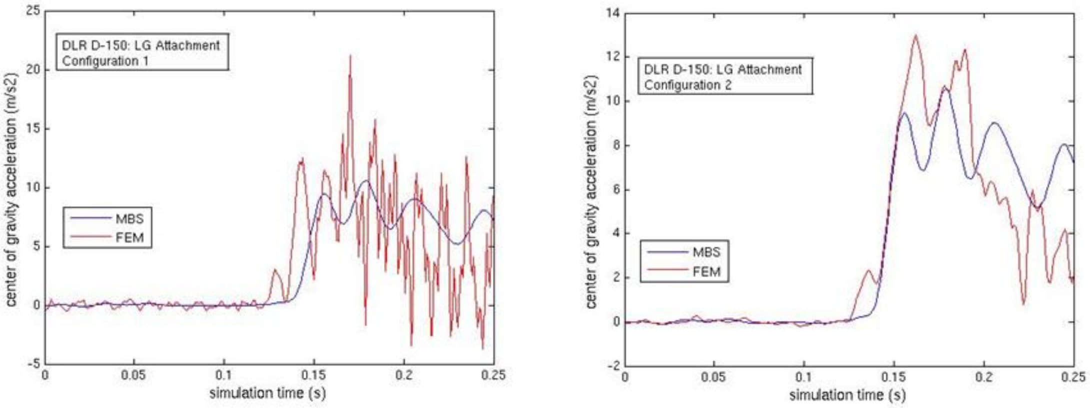

Figure 17: Vertical acceleration at aircraft center of gravity, simulations with landing gear attachment structure topology configuration 1 and configuration 2

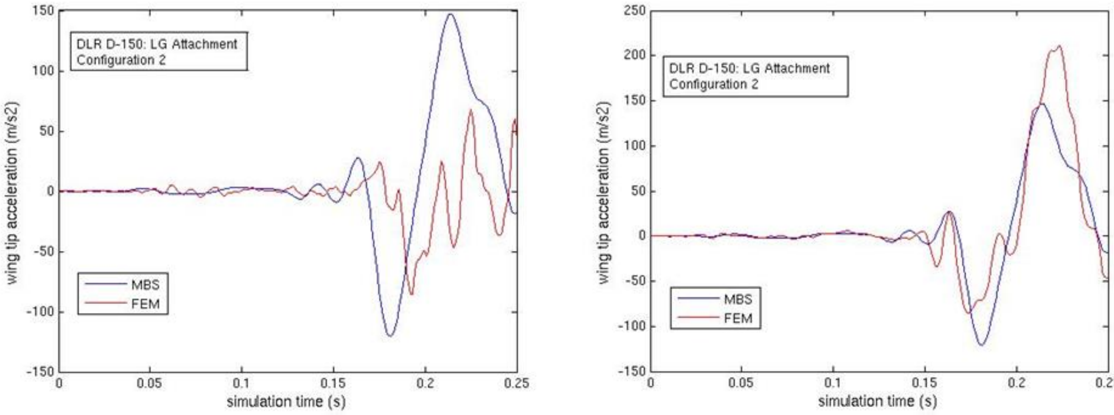

Figure 18: Vertical acceleration at aircraft wing tip, simulation with landing gear attachment structure topology configuration 1 and configuration 2

According to the result shown in Figure 15 through Figure 18 it can be deducted that a higher number of considered eigenmodes and the better distribution of the landing gear loads lead to a closer prediction of the result trends from the MBS and the direct transient finite element analysis.

Based on this information, it has been attempted to bring the result from the MBS even closer to the result from the direct transient finite element analysis. This has been performed by the consideration of more eigenmodes (210 modes up to 150 Hz) and the distribution of the landing gear loads via the landing gear finite element topology configuration 2. Figure 19 shows the vertical acceleration results at the aircraft center of gravity from the simulation with 73 considered eigenmodes of the DLR-D150 elastic body compared to the result from the simulation with 210 considered eigenmodes. The blue line is the result from the MBS analysis and the red line is the result from the direct transient analysis. Figure 20 shows the results for the vertical acceleration at the aircraft wing tip for the same simulations.

According to the results shown in Figure 19 and 20, the higher number of 210 considered eigenmodes, unlike the expectation, does not lead to a significant closer trend between the result from the MBS and from the direct transient finite element analysis.

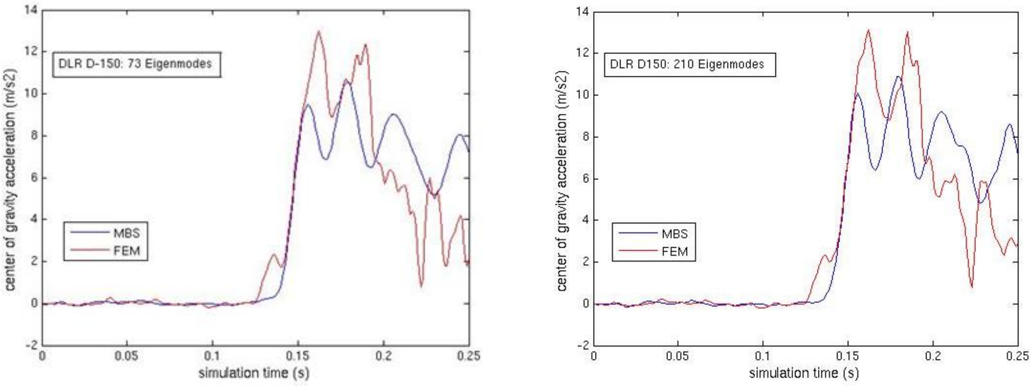

Figure 19: Vertical acceleration at aircraft center of gravity, simulations with 73 and with 210 considered eigenmodes of DLR-D150 elastic body

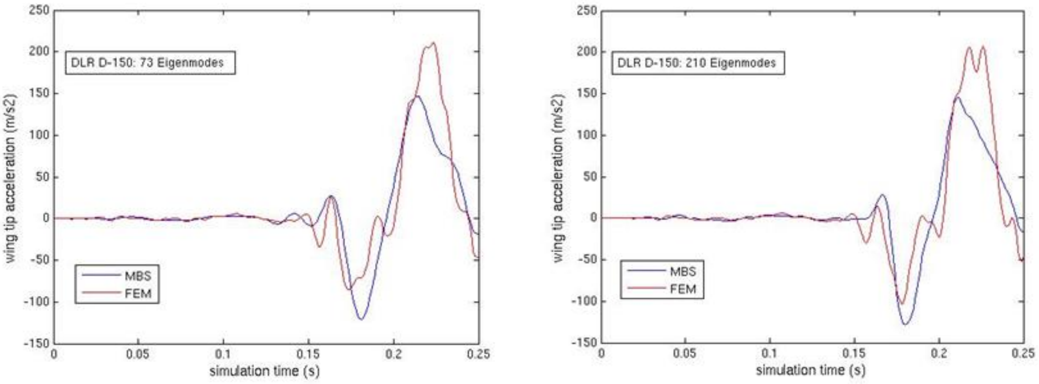

Figure 20: Vertical acceleration at aircraft wing tip, simulations with 73 and with 210 considered eigenmodes of DLR-D150 elastic body

4.4 Functional Test and Parameter Studies: Discussion of Results

The results which have been described in the sections above have proven the capabilities of the new process to determine the aircraft dynamic response due to landing gear loads. Studies have shown the importance of selecting an appropriate number of eigenmodes during the MBS set-up and of modelling a representative finite element topology of the landing gear attachment on the aircraft dynamic response.

Concerning the effect of the number of selected eigenmodes, it can be noticed that with only 19 considered eigenmodes for the elastic body of the DLR-D150 the model cannot represent the complete global dynamic character of the aircraft. Considering modes up to an eigenfrequency of 10 Hz are not suitable for the landing impact simulation. Consideration of more eigenmodes up to 50 Hz leads to a better correlation of the MBS result with FEM and implies a proper representation of the actual aircraft structure in the MBS landing simulation. The attempt to import more eigenmodes of up to 150 Hz for the structural model did not improve the results further for the DLR-D150-PRE model.

In the case of the effect of the landing gear attachment finite element topology, it is evidenced that the simulation with the topology which distributes the landing gear loads both to the inner wing section and to the center wing box has a better correlation of the results. This can be expected, due to the fact that in current civil transport aircraft of that class the landing gear loads are transferred both to the inner wing section and the center wing box.

Based on the information from the result discussion above, the new process has been implemented to the DLR-D150-FULL aircraft in order to show the capability of the process to use models for the analysis of aircraft ground loads beyond an academic level of detail.

5 APPLICATION OF THE NEW PROCESS TO A FULL AIRCRAFT FEM

In order to illustrate the capability of the new process with a complex aircraft model, the process has been implemented for landing simulation and landing dynamic behavior analysis of the DLR-D150-FULL aircraft.

As has been mentioned in Section 3.2.2, the DLR-D150-FULL aircraft is the most detailed of the DLR-D150 aircraft models. Instead of the fuselage beam elements of the DLR-D150-PRE aircraft, the fuselage of the DLR-D150-FULL aircraft is modelled with more physical representative elements. The fuselage skin panels are modelled as 2-D shell elements. The fuselage frames are modelled as beam elements. The fuselage passenger and cargo floors are modelled as 2-D shell and beam elements. The landing gear fuselage pressure bulk heads are modelled as 2-D shell and bar elements. In addition, instead of a straight forward rigid body connection of the wing and fuselage beam elements of the DLR-D150 aircraft, the wing and fuselage of the DLR-D150-Full aircraft model are connected with a proper connection between the 2-D shell elements of the fuselage at the keel beam, passenger floor and front landing gear bay pressure bulk head to the 2-D shell elements of the center wing box, see Figure 9 above. Figure 21 shows in more detail the FEM at the wing and fuselage connection area of the DLR-D150-FULL aircraft.

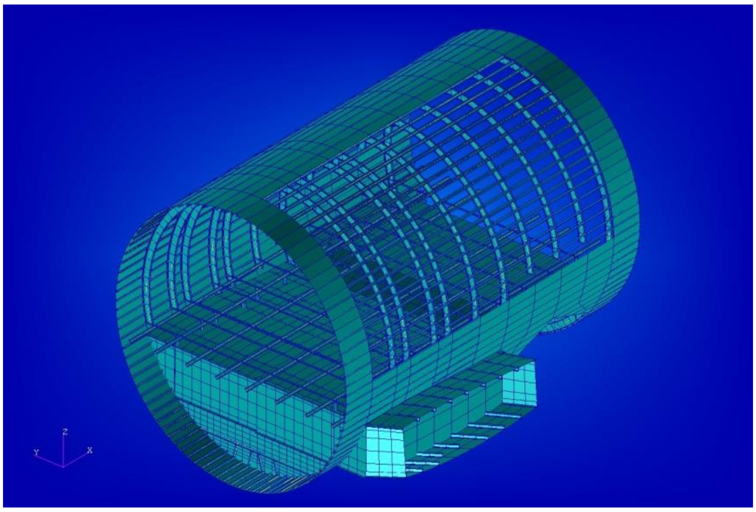

Figure 21: The DLR-D150-FULL aircraft detailed FEM at the wing fuselage connection

For the ground loads assessment of the DLR-D150-FULL aircraft, the landing simulation scenario and the MBS model set up are the same as those presented in Section 3.2.

Based on the discussion of result from Section 4 concerning the landing gear attachment structure topology, the landing gear of the DLR D-150-FULL aircraft is attached to the rear wing spar elements via a distributed rigid body element as shown in Figure 22. This topology represents the same principal as the attachment configuration 2 of the DLR D-150-PRE aircraft which is explained in Section 3.4.3 and Section 4. This topology distributes the loads better along the rear wing spar which finally leads to a better correlation of the acceleration results.

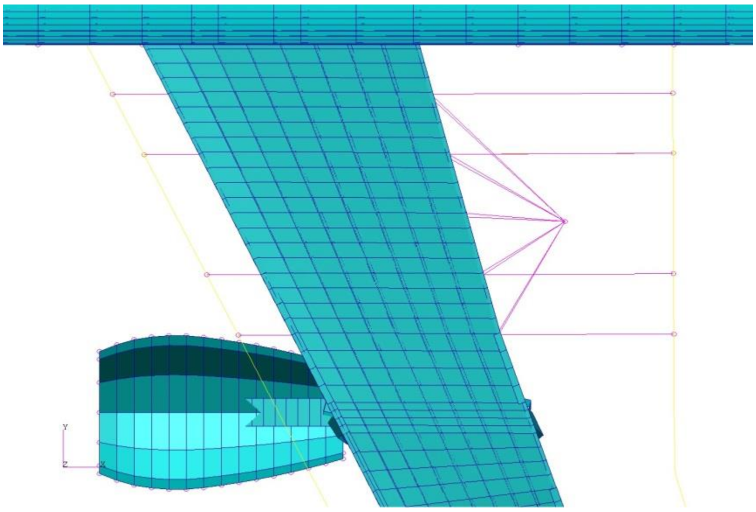

Figure 22: Landing gear attachment topology of the DLR-D150-FULL FEM

According to the discussion of result in Section 4, the number of selected eigenmodes effects the correlation of the acceleration results. As the result, the landing simulation of the DLR-D150-FULL aircraft is performed with five different numbers of selected eigenmodes of the aircraft elastic body. The following list summarizes these five different numbers of selected eigenmodes:

- Rigid body landing simulation
- Elastic body landing simulation with 38 considered eigenmodes, i.e. all of the modes with eigenfrequency less than 25 Hz
- Elastic body landing simulation with 95 considered eigenmodes, i.e. all of the modes with eigenfrequency less than 50 Hz
- Elastic body landing simulation with 192 considered eigenmodes, i.e. all of the modes with eigenfrequency less than 100 Hz
- Elastic body landing simulation with 270 considered eigenmodes, i.e. all of the modes with eigenfrequency less than 150 Hz

The result of interest of the simulation is the vertical acceleration of the aircraft structure at selected positions. Two locations have been chosen to be the monitoring positions: the aircraft center of gravity and the aircraft wing tip. The result of the simulation will be discussed in the following section.

5.1 DLR-D150-FULL Aircraft Landing Simulation Results

Figure 23 shows the vertical acceleration results at the center of gravity of the DLR-D150-FULL model from the simulations with rigid body, with elastic body with 38 considered eigenmodes, elastic body with 95 considered eigenmodes, with an elastic body with 192 considered eigenmodes and with an elastic body with 270 considered eigenmodes, respectively (from the top to the bottom of the figure). The blue line is the result from the MBS analysis and the red line is the result from the direct transient analysis.

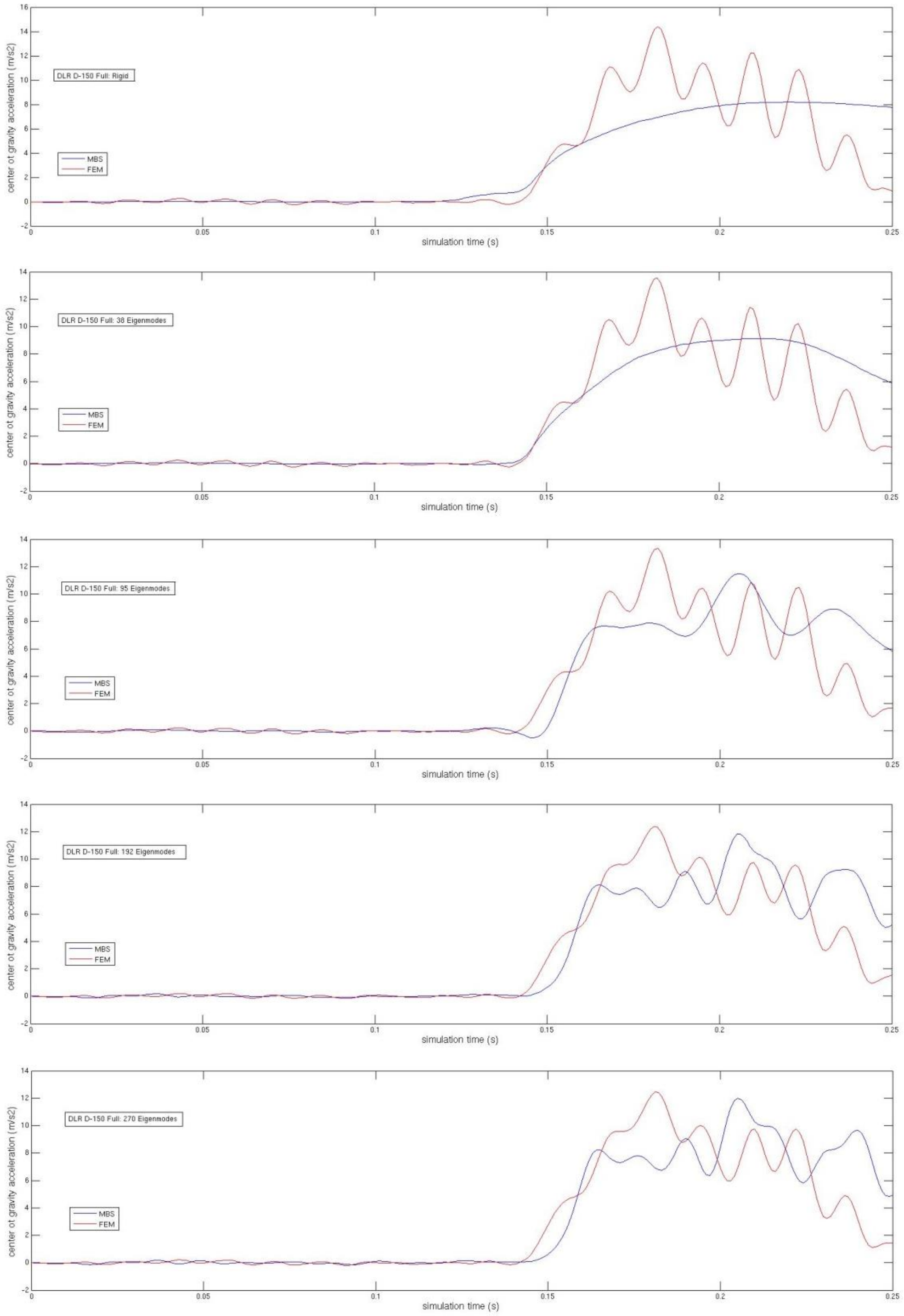

Figure 23: Vertical acceleration at the center of gravity of the DLR-D150-FULL model, simulations with rigid body, with 38, with 95, with 192 and with 210 considered eigenmodes of DLR-D150-FULL MBS body

Figure 24 shows the vertical acceleration result at the wing tip of the DLR-D150-FULL FEM from the simulation with rigid body, with elastic body with 38 considered eigenmodes, elastic body with 95 considered eigenmodes, with elastic body with 192 considered eigenmodes and with elastic body with 270 considered eigenmodes respectively (from the top to the bottom of the figure). The blue line is the result from the MBS analysis and the red line is the result from the direct transient analysis.

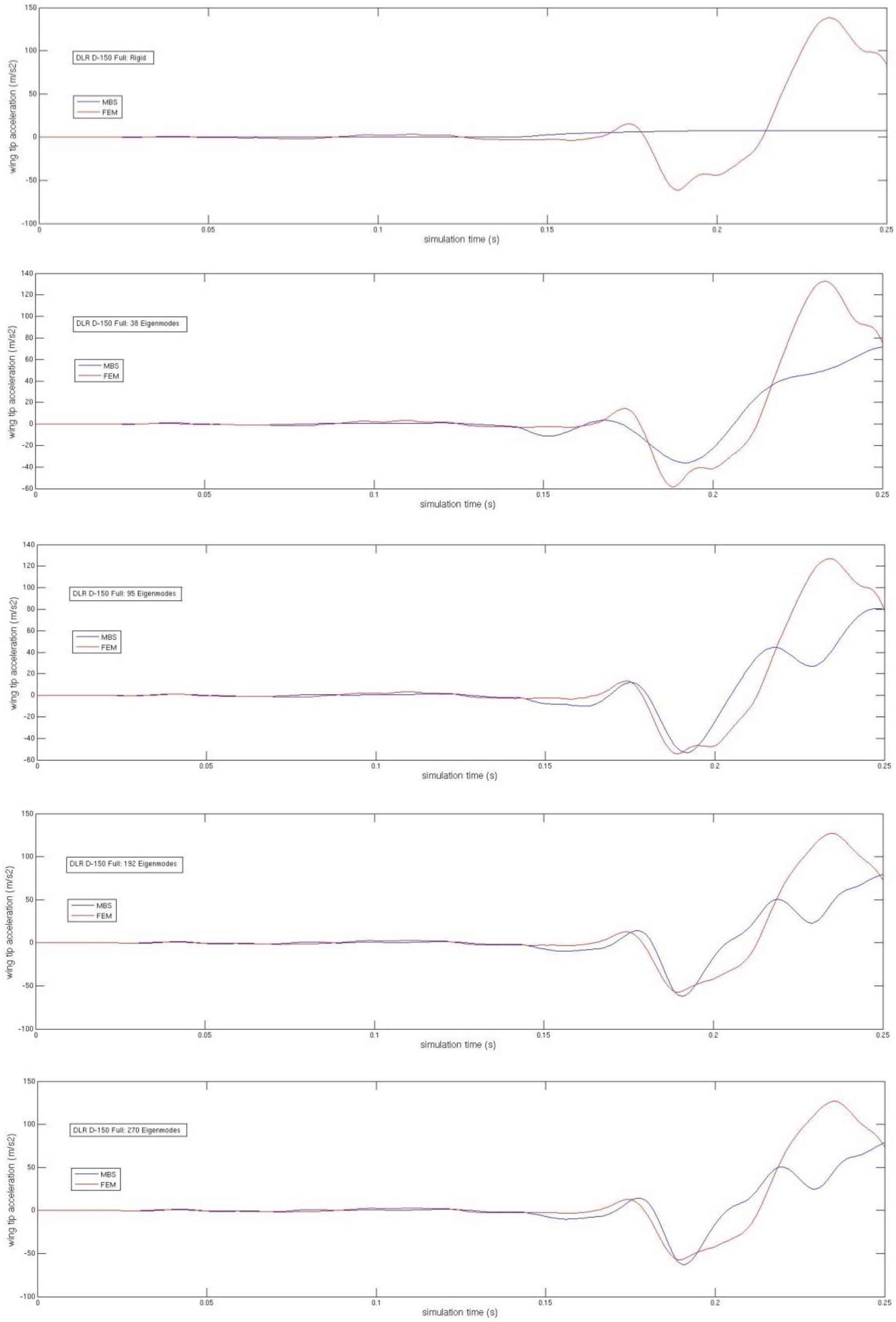

Figure 24: Vertical acceleration at the wing tip of the DLR-D150-FULL model, simulations with rigid body, with 38, with 95, with 192 and with 210 considered eigenmodes of DLR-D150-FULL MBS body

5.2 DLR-D150-FULL Aircraft Landing Simulations: Discussion of Results

The results from the DLR-D150-FULL aircraft landing simulation and analysis above have proven the capabilities of the new process to determine the aircraft dynamic response due to landing gear loads for an industry levelled aircraft model. As same as the DLR-D150-PRE aircraft results, the DLR-D150-FULL aircraft landing analysis results have shown the importance of selecting an appropriate number of eigenmodes during the MBS set-up on the aircraft dynamic response.

It can be noticed that the rigid body consideration and the elastic body with only 38 considered eigenmodes for the elastic body of the DLR-D150 the model cannot represent the complete global dynamic character of the aircraft. This is evidence especially in the case of the vertical acceleration result of the center of gravity. As mentioned previously in the discussion in section 4.4, it can be emphasized again that the rule of thumb to consider modes up to an eigenfrequency of 10 Hz, which is, according to the authors’ knowledge, applied by various studies of global aircraft dynamics, may not be suitable for the landing impact simulation. Consideration of more eigenmodes up to 50 Hz leads to a better correlation of the MBS result with FEM and implies a proper representation of the actual aircraft structure in the MBS landing simulation. The attempt to import more eigenmodes of up to 150 Hz for the structural model did not improve the results further.

6 CONCLUSION

This paper has described the new proposed process for the assessment of the aircraft dynamic response due to landing gear loads. The process has two core elements, the multibody simulation for the determination of landing gear loads, and the direct finite element analysis for the determination of the dynamic response of the airframe. In this work, a functionality test of the process has been performed which confirms that the process is capable of determining detailed aircraft dynamic response due to landing gear loads. A parameter study of the effect of two major process parameters, the number of selected eigenmodes during the MBS preprocessing and the topology of the landing gear attachment finite element layout have been performed using an aircraft simulation model with the preliminary design level. Finally the new proposed process has been implemented for the ground loads and dynamic behavior analysis of the aircraft with a detailed full FEM simulation model.

The parameter study results and the results of the simulation with the detail model suggest to perform an evaluation of the aircraft FEM eigenmodes as a pre-processing step in order to determine and use the modeshapes which are relevant for the landing impact characteristics of the aircraft. The results have also shown the significant effect of the landing gear attachment finite element topology. It is recommended that the topology should as closely as possible represent the actual landing gear attachment structure.

7 REFERENCES

[1] Krüger, W.R.: Integrated Design Process of the Development of Semi-Active Landing Gear for Transport Aircraft. DLR Forschungsbericht 2001-27, Deutsches Zentrum für Luft- und Raumfahrt, Germany, 2000.
[2] Spieck, M.: Ground dynamics of flexible aircraft in consideration of aerodynamic effects. Hochschulschrift Technische University München, Germany, 2004.
[3] MSC Software Corporation: MSC Nastran – Advanced Dynamic Analysis User’s Guide, MSC, Nastran Version 70.
[4] MSC Software Corporation: MSC Nastran –Dynamic Analysis User’s Guide, 2018.
[5] SIMPACK 9.7 User’s Guide. Dassault Systemes Company, Gilching, Germany.

[6] Zill, T., Ciampa P., Nagel, B.: Multidisciplinary Design Optimization in a Collaborative Distributed Aircraft Design Systems. Proceedings of 50th AIAA Aerospace Sciences Meeting including the New Horizons Forum and Aerospace Exposition, 2012.

[7] Klimmek, T.: Statische aeroelastische Anforderungen beim multidisziplinären Strukturentwurf von Verkehrsflugzeugflügeln. DLR Forschungsbericht 2016-34, Deutsches Zentrum für Luft- und Raumfahrt, Germany, 2016.

[8] Cumnuantip, S.: Landing Gear Positioning and Structural Mass Optimization for a Large Blended Wing Body Aircraft. PhD Thesis. Technical University of Munich, Germany, 2014; DLR Forschungsbericht 2014-20.

[9] Joint Aviation Authorities Committee (publ.): Joint Aviation Requirement JAR-25, Large Aeroplanes, Change 13, 1989.

[10] Cumnuantip, S., Kier, T., Risse, K., Chiozzotto, G. P.: Methods for the Quantification of Aircraft Loads in DLR-Project iLOADS. In: Proceedings of Deutscher Luft- und Raumfahrtkongress 2016, 13-15 September 2016, Braunschweig, Germany.

[11] Liepelt, R., Handojo, V., Klimmek, T.: Aeroelastic Analysis Modelling Process to Predict the Critical Loads in an MDO Environment. In: Proceedings of International Forum on Aeroelasticity and Structural Dynamics (IFASD) 2015, 28 June - 02 July 2015, Saint Petersburg, Russia.

[12] Klimmek, T., Schulze, M., Abu-Zurayk, M. and Illic, M.: CPACS-MONA – An Independent and in High-Fidelity Based MDO Tasks Integrates Process for the Structural and Aeroelastic Design of Aircraft Configurations. In: Proceedings of International Forum on Aeroelasticity and Structural Dynamics (IFASD) 2019, 9 - 13 June 2019, Savannah, Georgia, USA.

COPYRIGHT STATEMENT