

# ASSESSMENT OF DYNAMIC LANDING LOADS BY A HYBRID MULTIBODY / FULL FINITE ELEMENT SIMULATION APPROACH

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## Abstract

This paper describes a new process for the detailed assessment of the impact of aircraft ground manoeuvres 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 of two reference aircraft with their corresponding finite element models. 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 the results of the parameter studies 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 paper introduces 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].

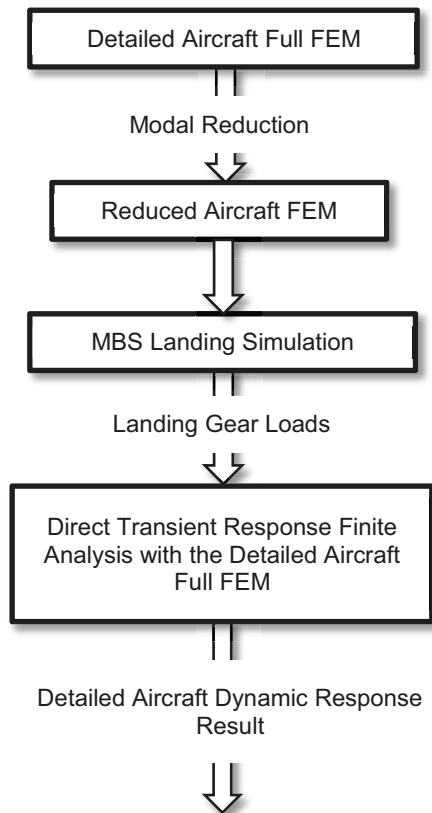
Based on the characteristics of the two simulations methods described above, the so-called 'Hybrid Multibody / Full Finite Element Simulation Approach' has been developed. In the approach, the aircraft landing gear attachment loads are determined via MBS, using a reduced finite element model for the 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. ASSESMENT OF DYNAMIC LANDING LOADS BY A 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].



**Figure 1:** A Hybrid Multibody / Full Finite Element Process for an Assessment of Dynamic Landing Loads

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.

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 pre-processing. 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.

Section 3 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 TRANSIENT ANALYSIS MODELS

#### 3.1. Reference Aircraft

Two reference aircraft configurations are used for the development of the new process. The first aircraft is a simplified, conceptual model of a 150 passenger aircraft configuration. The second aircraft is the DLR-D150 configuration, a transport aircraft modelled with a preliminary design level of detail. The following paragraphs describe the two aircraft configurations more closely.

##### 3.1.1. 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 150 passenger aircraft. It is a low-wing configuration with a mass of 72.6 t. The wing span is 34.0 m. The aircraft is equipped with a twin nose landing gear and two twin main landing gears. The airframe is described by a small finite element model only representing global elastic properties. Figure 2 shows a sketch of the aircraft.

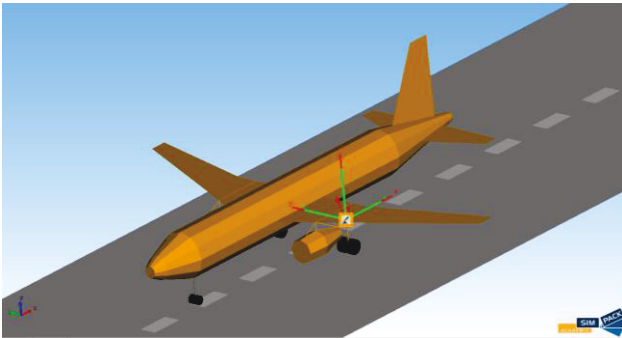


Figure 2: Conceptual 150 passenger aircraft

##### 3.1.2. DLR-D150 Aircraft

The second reference aircraft model is the DLR-D150 configuration, for which a more detailed finite element model is available. This aircraft has been created and used in several DLR internal projects. 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 also has a twin nose landing gear and two twin main landing gears. A detailed description of the generation of this aircraft can be found in [6]. Figure 3 shows a view of the DLR-D150 aircraft, taken from [7].

The structural model of the DLR-D150 offers an opportunity 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.

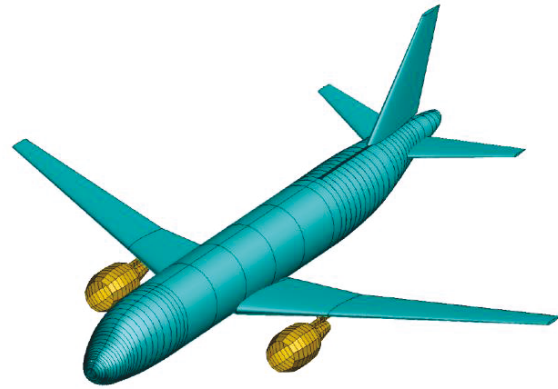


Figure 3: DLR-D150 Aircraft

#### 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:

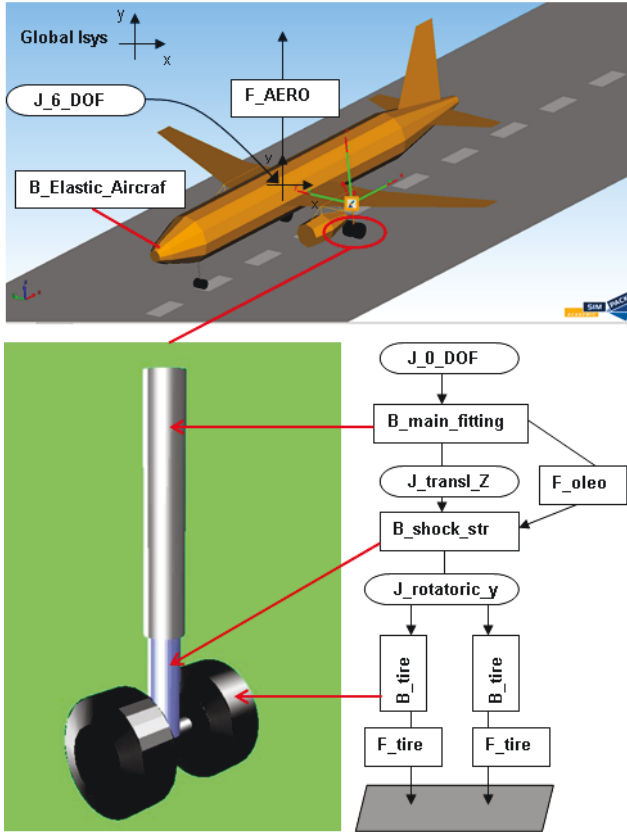
- The aircraft as the reference body,
- The nose landing gear substructure,
- The main landing gear substructures,
- The force elements within the landing gear substructures.

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.

The aircraft is connected to the 'global' reference coordinate system via a 6 degree-of-freedom joint, see Figure 4, top. The landing gear substructures are connected to this reference body via a rigid joint.

Each of the landing gear substructures, see Figure 4, 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 [11].



**Figure 4:** MBS topology diagram for a Conceptual 150 Passenger model

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

#### Oleo: Gas spring

The gas spring is represented by the law of polytropic expansion [1],

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

with spring force  $F_f$ , pre-stress force,  $F_0$ , oleo stroke,  $s$ , oleo gas length,  $s_m$ , polytropic coefficient  $n$ , and a correction factor,  $c_k$ . The value of  $n \cdot c_k$  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 expressed in Figure 4.

#### 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,

$$(2) \quad F_d = \text{sgn}(\dot{s}) \cdot d \cdot \dot{s}^2$$

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  $d_z$ :

$$(3) \quad d_z = dr_{nom} - r_r$$

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

$$(4) \quad F_z = c_1 d_z - F_{zN} - d_t v_z$$

The parameter  $c_1$  [N/m] is the tire vertical stiffness. The force  $F_{zN}$  [N] is the nominal 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

$$(5) \quad \text{slip} = \frac{v_x - r_r \omega}{v_x}$$

Using the obtained slip, the runway friction coefficient  $\mu_{RW}$  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  $\mu_{RW}$  can be evaluated as

$$(6) \quad F_x = \mu_{RW} \cdot F_z$$

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

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.

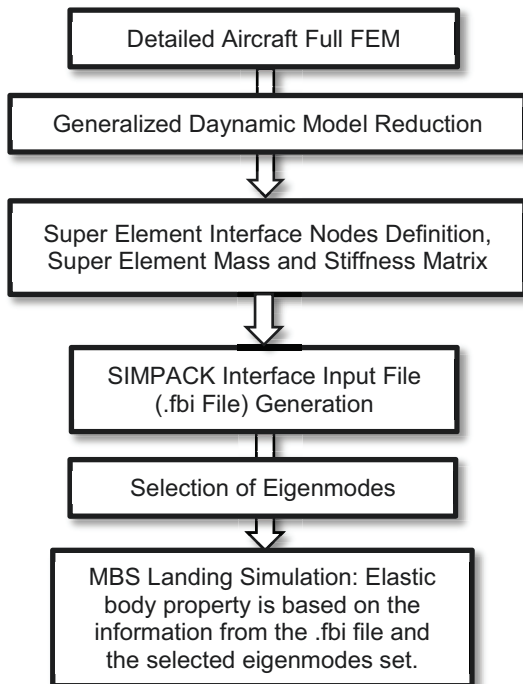
The landing gears are modelled as rigid bodies. This is sufficient for the dynamic response study which has a major focus on the aircraft structure rather than the landing gear structure itself. The airframe, however, must be modelled as an elastic body.

### **3.2.2. MBS Pre-Processing: A Detailed Finite Element Modal Reduction**

Figure 5 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 MSC [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.



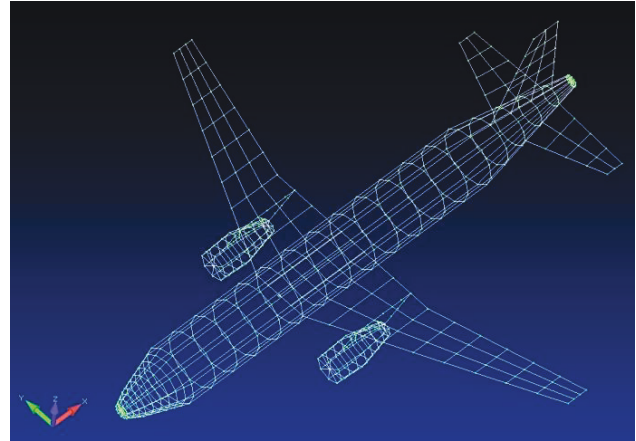
**Figure 5:** Pro-processing diagram of the import of the elastic airframe body into the MBS landing simulation

After the model reduction, a SIMAPCK interface input file, .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.

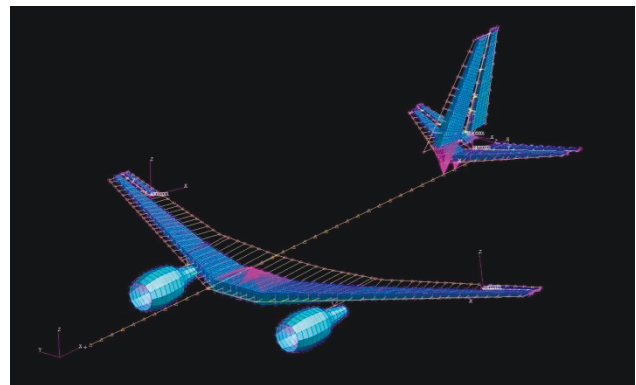
When the MBS aircraft model is set up, the aircraft body is defined to be elastic. The elastic properties of the aircraft body are obtained from the .fbi file. In addition, during the aircraft body modelling, the set of relevant eigenmodes is selected to be used by the numerical solver during the landing simulation.

As mentioned above, the definition of the superelement interface nodes and the selection of relevant eigenmodes play a major role in the realistic representation of the aircraft structure during the MBS landing simulation. The full FEM is completely modelled as 2-D shell elements. Concerning the superelement interface nodes for the conceptual 150 passenger aircraft, due to the small size of 614 nodes of the full finite element model, all of the nodes are set to be the superelement nodes. Figure 6 shows the full finite element of the conceptual 150 passenger aircraft.

The structure of the DLR-D150 is modeled with a lot more detail in the wing and the empennage. The full FEM wing, tails and control surfaces are modelled as 2-D shell elements. The fuselage is modelled as beam elements. Figure 7 shows the FEM of the DLR-D-150 aircraft. The full finite element of the DLR-D150 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].

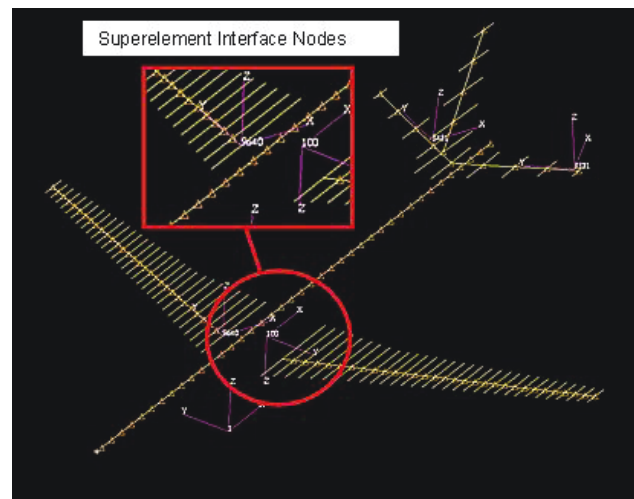


**Figure 6:** A conceptual 150 passenger Aircraft Full FEM



**Figure 7:** DLR-D150 aircraft full FEM

Thus, the DLR-D150 superelement interface nodes are defined at the load reference axis of the aircraft. There are in total 261 superelement interface nodes defined for the DLR-D 150 aircraft, which are illustrated in Figure 8.



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

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.

### 3.2.3. 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.

### 3.3. 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].

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

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 obtain 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.

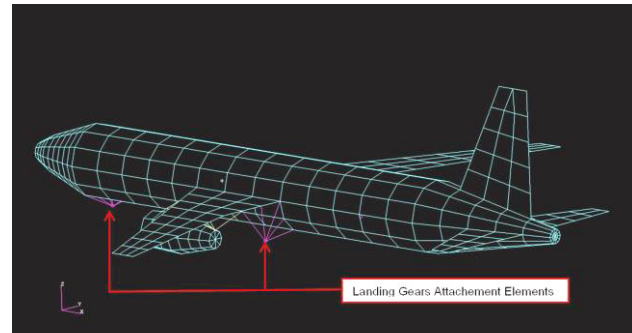
### 3.4. Parameters Study Definition

The following paragraphs described the new process functional test and process parameter study which are performed in this work.

#### 3.4.1. Functionality 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 conceptual 150 passenger 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 9 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.



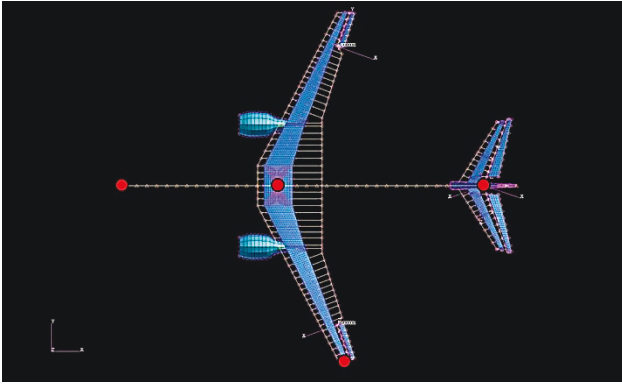
**Figure 9:** Full FEM of conceptual 150 passenger aircraft with landing gear attachment rigid body elements

#### 3.4.2. 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 relevant number of eigenmodes for the landing simulation is selected in the MBS modelling graphical user interface.

The DLR-D150 aircraft full FEM is a model with the complexity level that can represent the global dynamic behaviour of the real aircraft structure. 2-D shell elements are used for the wing box and control surfaces model. The beam elements of the fuselage are suitable for the representation of a long cylindrical structure of a real aircraft. Of course, local effects in the fuselage cannot be represented, which might play a role for the modelling of a realistic load path. The DLR-D150 has been implemented in various DLR aircraft loads and aircraft dynamic research projects in the past, see [12]. Thus, the DLR-D150 FEM has been selected for this study.

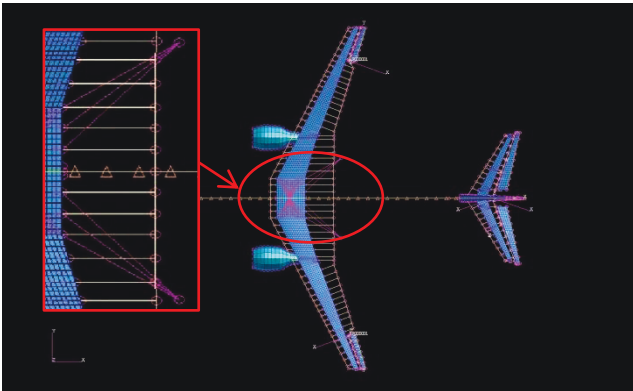
Three sets of the number of the selected eigenmodes have been investigated: 19 modes (all of the modes with eigenfrequency less than 10 Hz), 73 modes (all of the modes with eigenfrequency less than 50 Hz), and 210 modes (all of the modes with eigenfrequency less than 150 Hz). The result of interest of 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 10 shows the four positions. The result of this study will be discussed in detail in Section 4.



**Figure 10:** Monitoring positions on the DLR-D150 full FEM

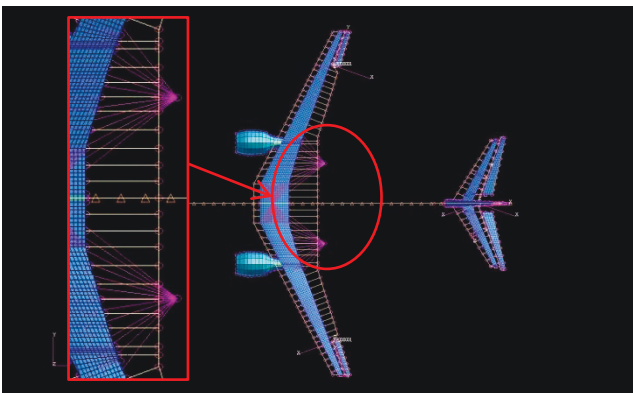
### 3.4.3. Effect of the Landing Gear Attachment Structure Topology

Two configurations for the topology of the landing gear attachment structure in the finite element model are investigated. Figure 11 shows the first configuration, where the landing gears are attached directly and only to the center wing box.



**Figure 11:** Landing gear attachment topology, config. 1

Figure 12 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.

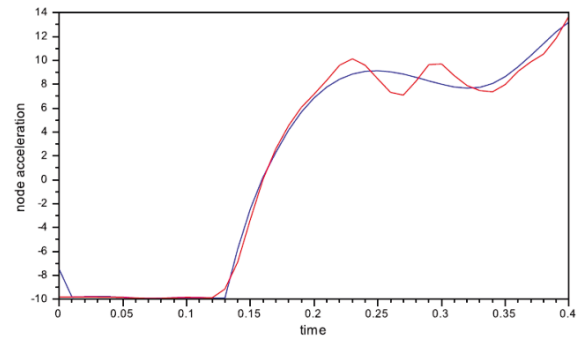


**Figure 12:** Landing gear attachment topology, config. 2

## 4. RESULT AND DISCUSSION

### 4.1. Functionality Test of the New Process

Figure 13 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.



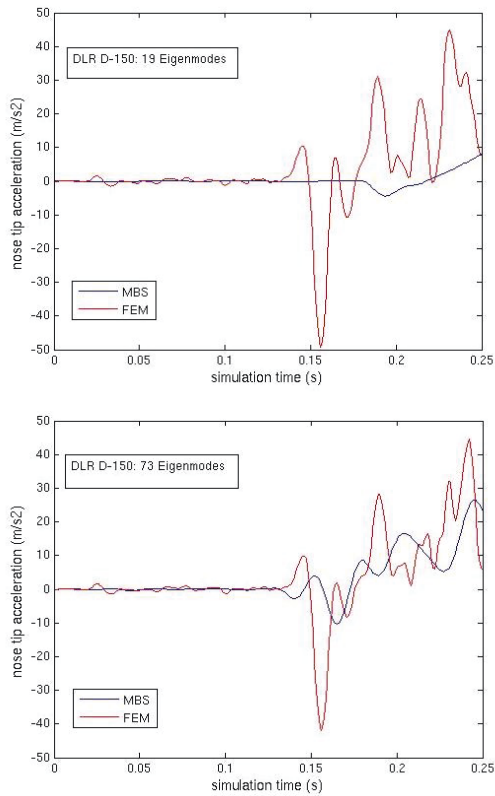
**Figure 13:** The vertical acceleration result at the tail tip position of the conceptual 150 passenger aircraft

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.

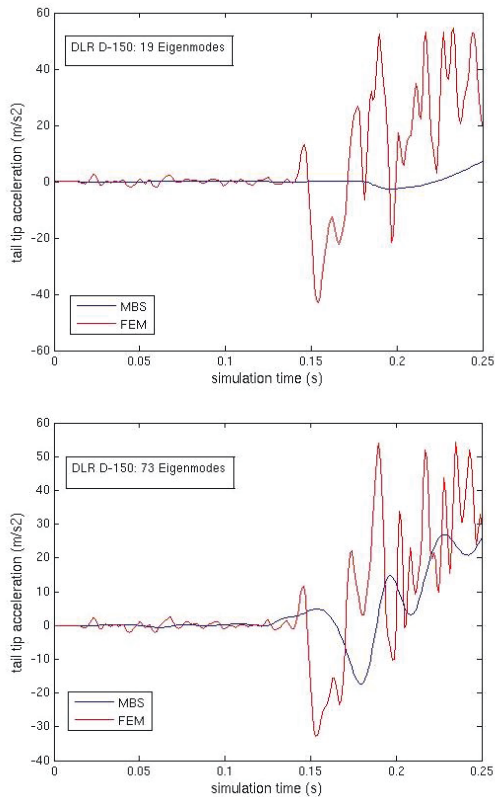
#### 4.1.1. Effect of the Number of Selected Eigenmodes

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 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 11, for both simulations. Figure 14 shows the vertical acceleration result at the nose tip from the simulation with 19 considered eigenmodes (Figure 14, top) compared to the result from the simulation with 73 considered eigenmodes (Figure 14, bottom). The blue line is the result from the MBS analysis and the red line is the result from the FEM direct transient analysis. Figure 15 shows the vertical acceleration result at the tail tip for the same simulation cases.

According to the result expressed in Figures 14 and 15, 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.



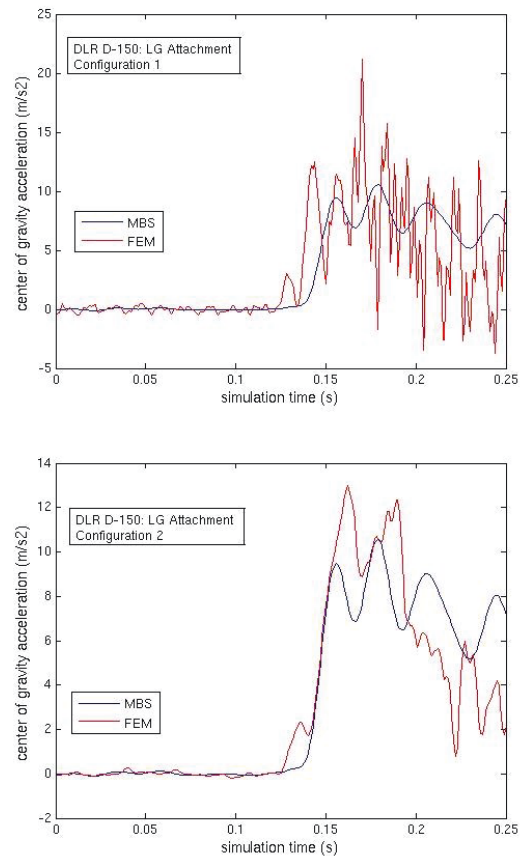
**Figure 14:** Vertical acceleration at nose tip, simulations with 19 and 73 considered eigenmodes for the DLR-D150 elastic body



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

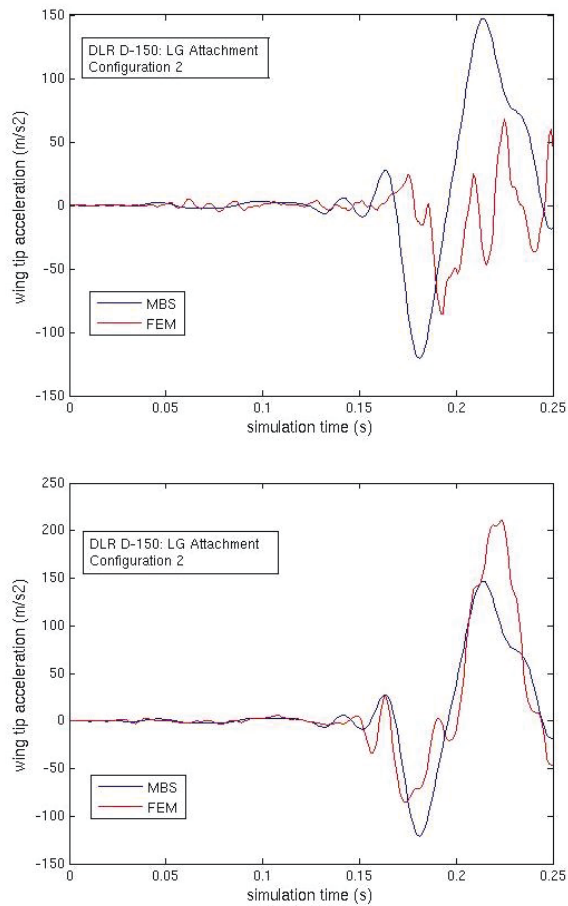
The second parameter study of the new process is the study of the effect of the finite element topology of the landing gear attachment structure. Two landing simulations with two different landing gear attachment topologies are performed for this study. The first simulation has the finite element topology which transfers the loads from the landing gear only to the center wing box as shown in Figure 11. The topology which distributes the landing gear loads both to the center wing box and the inner wing section as shown in Figure 12 is used for the second simulation.

In both cases, the DLR-D150 elastic body is represented by 73 eigenmodes. Figure 16 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 16, top) and configuration 2 (Figure 16, bottom). The blue line is the result from the MBS analysis and the red line is the result from the direct transient analysis. Figure 17 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.



**Figure 16:** Vertical acceleration at aircraft center of gravity, simulations with landing gear attachment structure topology configuration 1 and configuration 2



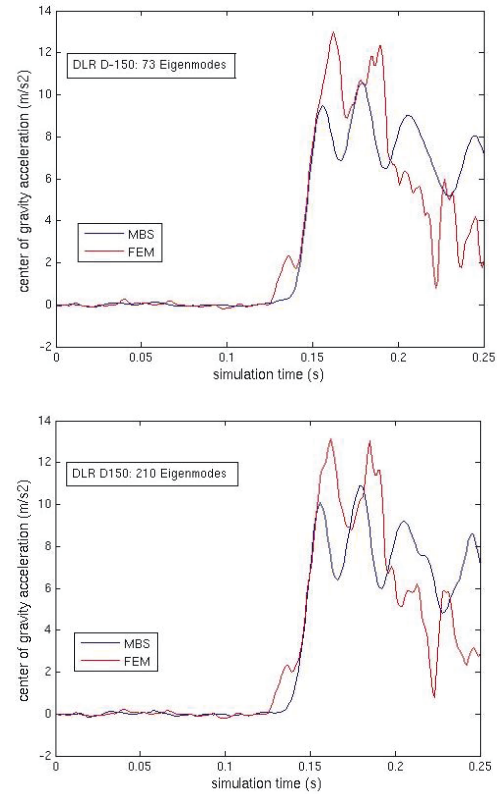


**Figure 17:** Vertical acceleration at aircraft wing tip, simulation with landing gear attachment structure topology configuration 1 and configuration 2

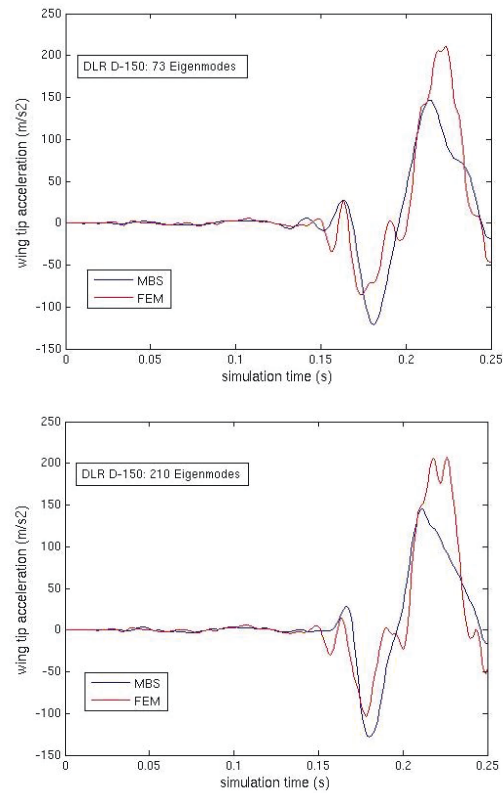
Based on the result shown in Figure 16 and 17 it can be clearly observed that for the landing gear finite element topology configuration 2 results from the MBS are closer to the result from the direct transient finite element analysis. This applies for both monitoring positions.

According to the result shown in Figure 14 through Figure 17 it can be deduced 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 18 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 19 shows the results for the vertical acceleration at the aircraft wing tip for the same simulations.



**Figure 18:** Vertical acceleration at aircraft center of gravity, simulations with 73 and with 210 considered eigenmodes of DLR-D150 elastic body



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

According to the results shown in Figure 18 and 19, 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. The following Section 4.2 gives a more detail discussion about all of the results which have been shown in the different studies.

## 4.2. Discussion of Results

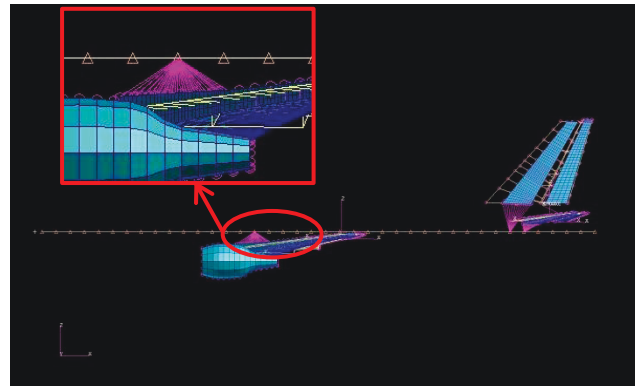
The results which have been described in the section above have proven the capabilities of the new process to determine the aircraft dynamic response due to landing gear loads. Studies have shown the importance of selecting an appropriate number of eigenmodes during the MBS set-up and of modelling a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

This information leads to the suggestion that a pre-processing study of the aircraft FEM is recommended in order to understand the modeshape character of the aircraft and finally take only those modeshapes into consideration that represent the structural parts of interest and which effect the landing impact the most.

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.

However, the result from the MBS and the direct transient finite element analysis still show certain differences even with the application of proper number of selected eigenmodes and of better distributed landing gear finite element topology. One of the possible causes of the difference is the current connection of the wing to the fuselage of the DLR-D150 FEM. As the model has been set up mainly for the study of flight loads [12], the connection between wings and fuselage has not yet been modelled in detail. Currently the wing is connected via a rigid body to only one node of the fuselage beam model. Figure 20 shows this connection. However, this type of connection does not allow, without major modification, the direct transfer of the landing gear loads to the fuselage. In several current civil transport aircraft a part of the landing gear loads is also directly transferred to the fuselage.



**Figure 20:** Finite element topology of the wing fuselage connection of the DLR-D150 model

Based on the information from the result discussion above, the conclusions and future perspectives of this research work are given in the following section.

## 5. 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. In addition, the effect of two major process parameters, the number of selected eigenmodes during the MBS pre-processing and the topology of the landing gear attachment finite element layout have been studied. The study results suggests 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 study result has 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.

## ACKNOWLEDGEMENT

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