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Multibody rigid models and 3D FE models in numerical analysis of transport aircraft main landing gear

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Abstract. Dynamic analyses of a transport aircraft landing gear are conducted to determine the effort of such a complex system and provide capabilities to predict their behaviour under hazardous conditions. This kind of investigation with the use of numerical methods implementation is much easier and less expensive than stand tests. Various 3D models of the landing gear part are defined for the multistage static FE analysis. A complete system of the main landing gear was mapped as a deformable 3D numerical model for dynamic analysis with the use of LS-Dyna code. In this 3D deformable FE model, developed in a drop test simulation, the following matters were taken into consideration: contact problems between collaborating elements, the phenomena of energy absorption by a gas-liquid damper placed in the landing gear and the response of the landing gear during the touchdown of a flexible wheel with the ground. The results of numerical analyses for the selected drop tests and the results from the experiments carried out on a real landing gear were used for verification of FE models and a methodology of the landing gear dynamics analysis. The results obtained from the various simulations of the touchdown have proved the effectiveness of the 3D numerical model and how many problems can be solved in the course of only one numerical run, e.g. geometric and material nonlinearities, a question of contact between the mating components, investigation of the landing gear kinematics, investigation of the energy dissipation problem in the whole system and the stresses influence on the structure behaviour, which can appear in some elements due to overload.

Key words: transport aircraft main landing gear methodology of numerical tests, rigid and 3D FE models.

1. Introduction

With regard to their specific character of operation, aircraft structures undergo complex research procedures, regulated by specific codes and detailed aircraft regulations [1–3]. In order to examine them, researchers more and more often use computer simulations, which together with experimental research are especially useful for study, conceptual and diagnostic-exploitative works.

Aircraft landing gears, due to their complex structures, changeability of working conditions, diversity of conditions accompanying their exploitation and at the same time occurrence of extreme loads, are mainly examined in simplified models [4]. Another approach to solve such problems is multistage analysis of partial models in the chosen quasi static stages of structure motion with the use of the research or exploitative landing gear load spectrum [5, 6]. Recently, researchers have been mainly using multibody models in numerical analysis of an aircraft landing gear complete system, as presented in papers [7—9].

The problems concerning the aforementioned aircraft landing gear research approach can be solved using dynamic computer analysis methods with complete models of the main landing gear [10]. No idea of a deformable landing gear complete model use in dynamic analysis has been discussed so far in any of local and international papers known to the authors [5–9, 11, 12].

This publication refers to a series of papers by authors [13–22], where the various issues related to the numerical analysis of the landing gears were discussed. The selected aspects of studies of both a main and front landing gear of a transport aircraft as well as corresponding numerical models were presented with the results of the stand tests. They were used to tune and accurately evaluate the numerical models and analysis. Some aspects of the application of analytical methods and a multibody methodology in studies of the front and main landing gears of the transport aircraft are discusses in [4, 10, 13]. The operation of the landing gear is analyzed in [14–17] based on the multi-variant numerical tests of the touchdown of isolated systems. The results for a nominal representation of the main landing gear and the experimental test conditions from the drop stand and numerical tests of a landing gear with damages are presented in [18–22].

The paper presents a methodology of models evaluation and numerical research of a complete landing gear. The procedure used by the authors is presented in Fig. 1 as a functional algorithm describing particular stages of the research.

The first stage of the research is carried out using the analytical method of substitute landing gear damping evaluation and a linear damper model. This method is particularly useful

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when the exact parameters describing more precise characteristics of the damper are not given.

The linear damper model with preliminarily determined rigidity and damping is subsequently used in a 2D multibody model of a complete landing gear system to adjust damper work parameters for particular options of touchdowns conducted on the test stand [12].

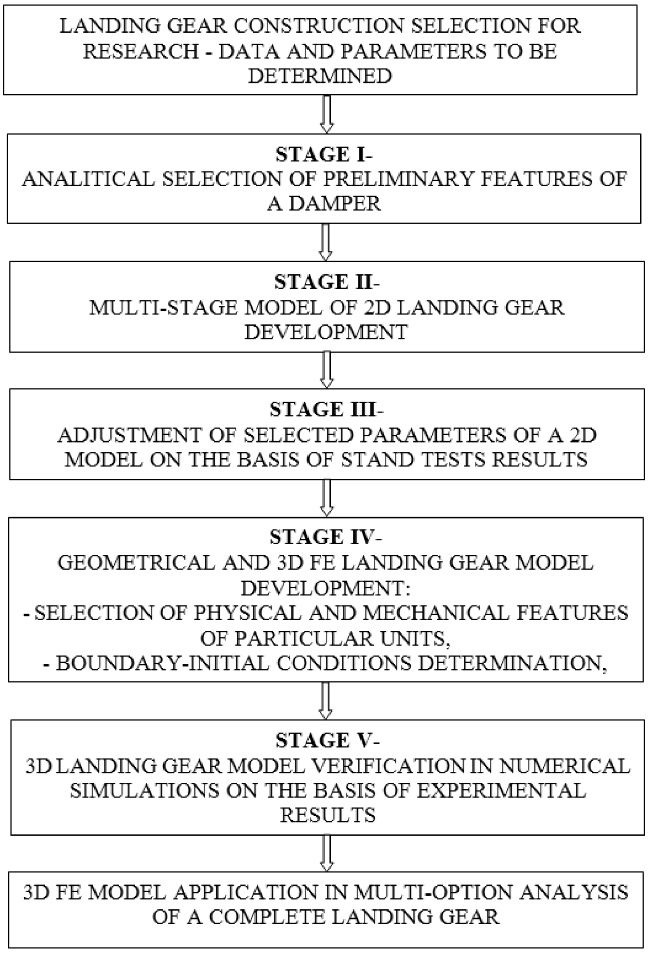

Fig. 1. A functional algorithm describing particular stages of the research

To achieve it, the researchers used a methodology of the simulation research with the use of a linear damper model, variable mass forces interaction in motion, friction interaction in construction components, friction interaction with the substrate and the selected results of the landing gear stand research.

The second stage shows evaluation of solid geometrical models of the complete main landing gear units and fully deformable 3D models of a complete landing gear. The parameters of the system developed in 3D models (characteristic for a damper, landing gear wheel tire, etc.) are verified on the basis of numerical tests. These tests describe in detail the conditions of the selected stand tests that correspond to the basic options of the touchdown of a real landing gear construction Such prepared 3D FE model can be used to conduct a multi option simulation of the complete landing gear touchdown.

2. Theoretical description of multistage system research

The aircraft landing gear system analyzed in the work is a typical mechanical system, which is also defined as a multistage system [7-11]. This system is distinguished by a relatively big extent of complexity. An analysis of a chosen aircraft landing gear way of operation is a relatively complex process difficult to conduct. The most difficult is the simulation of the phenomena during which very complex conditions of load are considered (e.g. driving on rough surface). The basic interpretation of the landing gear system (examined in work [11]) used during conducting the analyses is division of the system into single units. In the next step, the researchers apply constraints which result from presence of kinematics in the original system. This implies development of many differential-algebraic equations which correspond to Newton & Euler dynamic equation theories.

Newton & Euler equations (Newton 2nd law and theorem related to a rigid solid angular momentum change) are often used in order to describe rigid-body motion [4, 7, 8, 12]. These equations [8, 12] are formulated on the assumption that the proper system $\xi\eta\zeta$ (system related to analyzed rigid solid) is a central system (Fig. 2). The aforementioned assumption results in:

$$\vec{\rho}_c = 0 \tag{1}$$

i.e., any analyzed point O corresponds to the center of mass.

Then, basic dynamic equations take the following vector form:

$$m\dot{\vec{\mathbf{v}}}_c = \vec{\mathbf{F}}, \qquad \dot{\vec{\mathbf{K}}}_c = \vec{\mathbf{N}}_c. \tag{2}$$

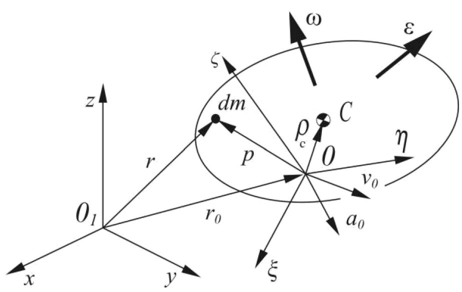

Fig. 2. Inertial system xyz and proper system $\xi\eta\zeta$ of the considered unit

The velocity components of the center of mass C in this case are defined within the axes of inertial system xyz and take the form of $v_c = [v_{cx} v_{cy} v_{cz}]^T = [\dot{x}_c \dot{y}_c \dot{z}_c]^T$, where v_c is the generalized velocity. Angular momentum vector components $\vec{\boldsymbol{K}}_c$ of the analyzed object in relation to the center of mass are presented in $\xi\eta\zeta$ axes system and are defined in the following way: $\boldsymbol{K}_c = \boldsymbol{J}_c\boldsymbol{\omega}$, where $\boldsymbol{\omega} = [\omega_\xi \ \omega_\eta \ \omega_\zeta]^T$. In this case, a solid substance motion equation takes the following form:

$$\begin{bmatrix} m\boldsymbol{I} & 0 \\ 0 & \boldsymbol{J}_c \end{bmatrix} \begin{bmatrix} \dot{\boldsymbol{v}}_c \\ \dot{\boldsymbol{\omega}} \end{bmatrix} + \begin{bmatrix} 0 \\ \tilde{\boldsymbol{\omega}}\boldsymbol{J}_c\boldsymbol{\omega} \end{bmatrix} = \begin{bmatrix} \boldsymbol{F} \\ \boldsymbol{N}_c \end{bmatrix}, \tag{3}$$

where $\boldsymbol{J}_c$ – solid polar moment of inertia, $\boldsymbol{N}_c$ – moment of external forces ($\boldsymbol{F}$) in relation to the center of mass C.

The above equation in a symbolic record takes the form of:

$$\boldsymbol{M}\dot{\boldsymbol{v}} + \boldsymbol{h}(\boldsymbol{v}) = \boldsymbol{f}(\boldsymbol{p}, \boldsymbol{v}, t), \tag{4}$$

where the right equation side, i.e. $\boldsymbol{f}$ is dependent on the location, velocity of the system and time t.

Kinematical dependences in the analyzed case take the form of:

$$\dot{\boldsymbol{p}} \equiv \begin{bmatrix} \dot{\boldsymbol{r}}_c \\ \dot{\boldsymbol{\alpha}} \end{bmatrix} = \begin{bmatrix} \boldsymbol{I} & 0 \\ 0 & \boldsymbol{A}_\omega \end{bmatrix} \begin{bmatrix} \boldsymbol{v}_c \\ \boldsymbol{\omega} \end{bmatrix} \equiv \boldsymbol{A}(\boldsymbol{p})\boldsymbol{v}, \tag{5}$$

where $\boldsymbol{r}_c = [x_c y_c z_c]^T$ – vector leading to the center of mass C in relation to system *xyz*, $\boldsymbol{I}$ – unit matrix 3×3, $\boldsymbol{\alpha}$ – describes three angles defining $\zeta\eta\xi$ system location change in relation to *xyz* system.

In the dynamic FE tests on the developed numerical model with nonlinearities resulted from material models and the contact phenomena, the analyses are conducted with the use of the Lagrange-Finite Element methodology [9], an explicit code and calculation algorithms [7–11].

Equations of a dynamic problem in the time domain are solved by the central difference integration. The explicit codes are relatively more efficient. In an explicit solution [23, 24]:

- The time step size is usually set by the requirements to maintain the stability of the central difference integration. The stability limit can be approximated by the smallest transient time of the wave to cross the smallest element.
- The stability limit is defined in terms of (6):

$$\Delta t \leq \frac{2}{\omega_{\max}} \left(\sqrt{1 + \xi^2} - \xi \right), \tag{6}$$

where $\omega_{\max}$ – the highest eigenvalue in the system, ξ – a fraction of critical damping in the highest mode.

Damping can be introduced by the bulk viscosity pressure of viscoelastic material behavior or other means.

Courant Criterion [23] has been used in the numerical simulation as well. The time step used with this criterion should be smaller than the smallest natural period of the mesh used in the numerical models.

Explicit FE methodology [23] used in the numerical tests is characterized by:

- Small time step,
- (There are) no big matrices or matrix inversion due to usage of a diagonal matrix (lumped mass),
- Robust solution procedure even for a high degree of nonlinearities.

On the basis of the above theory, the authors suggest a multistage complex system of a numerical simulation method. The further part of this work presents a short description of this method. The computation methodology can be presented in the form of the following algorithm:

Stage 1.

- Calculation of stiffness and mass features for particular components that are part of the analyzed landing gear system,
- Kinematical scheme structure,
- Imposition of kinematical and loading initial – boundary conditions, for the analyzed numerical model.

Stage 2.

- Differential equation system construction on the basis of the aforementioned Newton & Euler method from a mechanical system into a free substances system with adjustment of boundary conditions determining a connection with other components.

Stage 3.

- Choice of integration stage and conditions related to the accepted tolerances,
- Choice of integration method (e.g. of Kutt & Merson),
- Solution of dynamic equation system for the analyzed mechanism of the multistage system for the chosen moment of time t.

Stage 4.

- Execution of dynamic analysis for a new multistage mechanism system location configuration in moment $t + \Delta t$ according to stages 1 to 3.

Stage 5.

- Repetition of the aforementioned calculation method until obtaining a full simulation, i.e., to a large extent of the formerly defined analysis time.

As a result of the performed simulation, there is obtained a complete solution for multistage mechanism motion dynamics (kinematical dimensions, forces values in components and reaction forces in joints).

3. 2D model in numerical analysis

This part of work shows a methodology of the choice of a transport aircraft main landing gear dynamic substitute feature. The authors propose an analytical method of substitute landing gear damping evaluation and a linear damper model. This method is particularly useful when parameters describing more precise characteristics of the damper are not given.

Numerical dynamic analyses of the landing gear system in the selected cases of touchdown are carried out. For this purpose, the authors apply the aforementioned Euler's method solution, a 2D rigid model and a simulation research methodology with the use of a damper analytical model. Moreover, the researchers include the variable mass forces interaction in motion, friction interaction in construction components, damper components interaction during the dynamic phenomena accompanying the landing gear operation at the time of the touchdown. In order to determine a spring – damping substitute feature of the damper of the analyzed landing gear system, the authors conduct a series of simulations describing the real airdrop tests related to a complete landing gear at the laboratory stand.

Two ways of fluid – gas damper modelling are found in literature. In the analytical approach [8, 9], a damper is modelled on the basis of geometrical and physical parameters. In this method, forces in the damper are determined on the basis of a differential equation system as functions of damper piston shifts, velocity and acceleration. Any tests of introducing into this model the nonlinear features resulting from compliance of damper work hysteresis or impact response in its system lead to the necessity of solving a differential equation of a nonlinear system with the use of numerical methods [6, 7].

In the parameter approach, the researchers use parameters describing a damper as an inlet -outlet system defined on the basis of the experimental research results of a selected damper. In this approach, a damper model is treated as a specific "black box" with dimensions determined by the carried out experiment of a limited extent.

The parameters of this model have or do not have a physical equivalent, however, at the same time, they are strictly related to an experimental measurement. This shows a limited use of the analyzed parametrical damper model. Nevertheless, it should be emphasized that this model is very helpful in numerical simulations of the systems with fluid – gas dampers.

Contemporary professional computational systems, used in simulation works of complex mechanisms with fluid - gas dampers (as aircraft landing gear), allow the use of more advanced modelling tools. LS-Dyna System [23] offers a ready component which is special for modelling of fluid - gas dampers with a possibility to program their parameters by choosing appropriate equation coefficients describing a finite model. Operation characteristics included in such a model assume two-stage work of a fluid - gas damper – predicted in the recently designed newest structures.

The fundamental condition of the application of the aforementioned modelling methods of cooperation of mechanism components, including absorption, is the knowledge concerning functional characteristics of the absorbing component. Paper [25] describes a methodology of substitute nonlinear stiffness and damping of damper working in the landing gear system. Such characteristics are used to model numerical landing gear work including system vibrations with CAE software. A linear damper model presented in the paper [25] is often more useful than nonlinear models, especially when the exact parameters describing more precise characteristics of a damper are not given.

It is the simplest method of modelling a phenomenon of damping in relation to cooperation of single units of a complex system as, e.g., an aircraft landing gear includes the use of a component – "damper" type. Components classified as special components are available in libraries of majority of specialized applications for simulation of mechanism operation [26, 27]. A damper interpreted in this way, used as a component in a numerical model, generates a force between two points of a modelled structure. This force directly depends on a velocity difference of these points. It does not generate any force if the considered points move with identical velocities (in relation to magnitudes and directions). Application of absorbing components with simple multinomial features of the second, third or even higher degree allows reflection of an approximate influence of damping on mechanisms work in the simplified models assuming that fundamental parameters of such cooperation are given. A damper can substitute, e.g., a damper in a simplified model of an aircraft landing gear or in a car suspension.

An example of the simplest model of a damper used in aircraft landing gear research is the aforementioned linear model. The researchers mainly use a mixed shock absorber model, i.e., combination of a spring with a hydraulic (oil) damper modelled as a hydraulic component which works since the oil flows through the nozzles placed in the piston. What should be taken into consideration in this model is that oil properties change depending on temperature and pressure. The research of aircraft landing gear operation with an oil-pneumatic (oil-gas) damper is also described in work [28].

3.1. Analytical method of preliminary choice of substitute damping of a damper. The analytical method of evaluation of substitute damping of the landing gear system, which is presented in this work, is created on the basis of a theoretical model of a fluid - gas damper model (described in work [29]). The authors presented the dynamic equations that describe fluid – gas damper work in a military aircraft main landing gear which is used for aircraft carriers operations. Additionally, the relation between forces in the considered system components and the pressure inside the damper are formulated. The model assumes that the gas, which fills part of one chamber of the damper, cumulates part of touchdown energy. This model suggests that this process is performed assuming an adiabatic character of ideal gas thermodynamic changes. The gas pressure change was described using a dependence (7) supposing that it undergoes a polytrophy change.

$$p_1 = p_2 \left(\frac{V_2}{V_1}\right)^{\kappa}. \tag{7}$$

For initial computations, when a polytrophy real exponent is not given, it can be assumed that the change is isotropic and the exponent of such a change takes the value of $\kappa = C_p/C_v$, where: C_p is specific heat of isobaric change and C_v is heat of isochoric change, p – gas pressure, V – volume of gas. This is the effect of Clapeyron equation transformation $pv = RT$ for ideal gas, i.e. Poisson equation. Since the cylinder volume is directly proportional to the height, a quotient of the volumes can be replaced by a quotient of its height:

$$p_1 = p_2 \left(\frac{X_2}{X_1}\right)^{\kappa}. \tag{8}$$

It should be added that hydraulic fluid pressure in a fluid – gas damper is equal to gas pressure described in (7) and (8).

In order to analytically evaluate the value of a damping substitute of a damper (Fig. 3), the authors used Hagen & Poiseuille law (9):

$$\Delta p = \frac{128\mu l}{\pi d^4} Q. \tag{9}$$

where $Q = \dfrac{\pi d^2}{4} \cdot u$ is fluid volume consumption assuming incompressible and continuity maintenance, μ – dynamic viscosity, u – outflow velocity, d – diameter of nozzles in the piston, D – cylinder diameter.

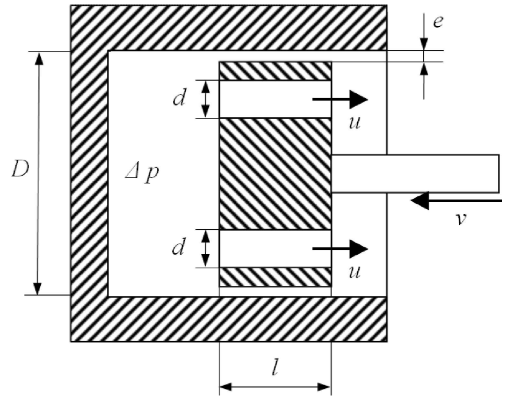

Fig. 3. Scheme of damper with linear damping

On the basis of Eq. (10) outflow velocity u marked in Fig. 3 can be determined as (11).

$$\frac{1}{4}\pi D^2 v = \frac{1}{4}\pi d^2 nu, \tag{10}$$

$$u = \frac{1}{n}\left(\frac{D}{d}\right)^2 v, \tag{11}$$

where v is piston shift velocity, n – number of nozzles in the piston,

This model assumes generation of absorbing forces by flow of a labor factor between an inside wall of the piston and an inside surface of the damper sleeve. When two planes separated by sticky fluid are in motion, tangential stresses appear in the fluid, what results in occurrence of absorbing forces. Thus, it can be supposed that the force (12) that comes out of the piston inside surface motion in relation to a damper sleeve will directly depend on the dimensions of the collaborating planes.

$$F_b = C_b \cdot \nu = \frac{2\pi r l \mu}{e} v, \tag{12}$$

where e is a gap between the planes (Fig. 3), r – radius of the piston.

An absorption coefficient adopted in the linear model, which includes the absorption phenomena as a result of a piston flow is as follows:

$$C_b = \frac{2\pi r l \mu}{e}. \tag{13}$$

The aforementioned method of absorption parameters selection is used in MATLAB computations. It allows damper characteristics to be estimated automatically. Application of the results is especially important while assessing the simplified numerical models used in dynamic analyses which are essential for the first stages of the structural analysis. The analytical model was used to develop substitute absorption of a fluid – gas damper operating in a light transport aircraft landing gear. The computations are performed for different options of the structural flanges that absorb a labor factor flow. The researchers set coefficients of a damping substitute of a damper with the flanges with flow orifices diameters equal to Φ3.7 mm and Φ8.0 mm. These diameters correspond to the minimal and maximal diameters of the damping flanges in the damper analyzed during the stand tests.

3.2. 2D multibody model. In order to elaborate a model for such dynamic analyses, the researchers use a geometrical model of a complete landing gear system developed on the basis of design documentation [12]. On the basis of this model, the authors developed a numerical model used in computer simulations implemented in Working Model 2D system [26]. In this model, the researchers take into account the aircraft fuselage mounting knots, the joints with connectors, a damper with spring – damping system, a landing gear strut body, a wheel axis with wheel and tire. Masses of the particular units of the modelled landing gear system are determined owing to geometrical parameters in 3D Solid Edge.

The developed model is a system of rigid solids connected by appropriate joints including the reduced units susceptibilities. The model includes the concentrated mass describing the aircraft fuselage influence on its landing gear at the time of the experiment adapted on the air-drop stand. The preliminary spring – damping characteristics of a damper modelling component are estimated on the basis of an analytical method using own application implemented in symbolic MATLAB language. The model prepared in this way was subjected to the appropriate dynamic constraints adopting motion conditions of the system not only at the touchdown moment but also at the time of the selected taxiing cases. Moreover, the researchers take into account the aircraft progressive motion velocity and resistance forces generated between an apron and an landing gear wheel.

Masses of the components implemented as massless numerical model parts, e.g., spring – damping components, joints connectors parts are reduced and added to the components masses as in Fig. 4. The model includes the component mass (Fig. 4) equal to 2278 kg that describes the aircraft fuselage influence on the landing gear. The accepted value is equal to the reduced mass of a landing gear load at the time of the experiment carried out on the air-drop stand [4, 11, 12].

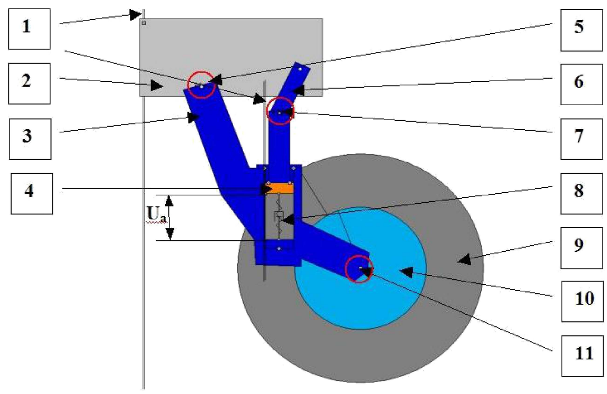

Fig. 4. 2D model of analyzed main landing gear; 1 – constraint – runner type, 2 – reduced aircraft mass, 3 – body with sleeve, 4 – pivot, 5 – fuselage for body mounting, 6 – connector, 7 – pivot fuselage, 8 – spring - damping system, 9 – tire, 10 – wheel, 11 – wheel axis

In a 2D model of the transport aircraft main landing gear, the researchers use a linear damper model. The authors choose such parameters of a spring system and a damper which reflect the interaction of gas and fluid that fill the damper and the pressure of the chamber filling equal to 5 MPa is also considered. Furthermore, the researchers include motion resistances in connection with the movable parts of the system.

3.3. Numerical test of vertical air-drop. The methodology of selecting the landing gear system substitute damping with the use of an analytical model and a 2D multistage model of a transport aircraft main landing gear is discussed on the basis of numerical representation of a landing gear vertical air-drop realized on an air-drop stand. The preliminary parameters of substitute rigidity and damping of a resilient – damping component used in the 2D model of the landing gear is determined on the basis of the analytical method. The researchers use the 2D model of a landing gear system with the preliminary estimated parameters of a spring – damping component and perform a series of numerical simulations of vertical air-drops mapping the parameters of the laboratory research on an air-drop stage.

Thus, a substitute dynamic characteristic of the modelled system is determined on the basis of the results of the experimental research carried out on the air-drop stage. While performing the simulation of a series of landing gear air-drops from the height $H = 283$ mm with touchdown vertical velocity $V_z = 2.13$ m/s, the researchers chooses a system substitute damping coefficient C_z.

The authors adopt a touchdown force value set in the air-drop research of a real structure as a reference parameter in the landing gear system numerical model adjustment [4, 10, 12]. In the system adjustment simulations, the values of overall force are as follows: $P_x = 0$ and $P_z = 63390$ N. The vertical touchdown simulation time is over 2.5 s. Substitute absorption parameter C_z of the landing gear system taken from tests results is equal to 14000 N·s/m.

The final results of the simulation in the adopted model are presented in Fig. 5 in the form of vertical force mileage computed at the wheel axis. The changes of damper pivot relative shift are presented in Fig. 6 and associate mass acceleration (component no 2 in Fig. 4) as a time function is presented in Fig. 7.

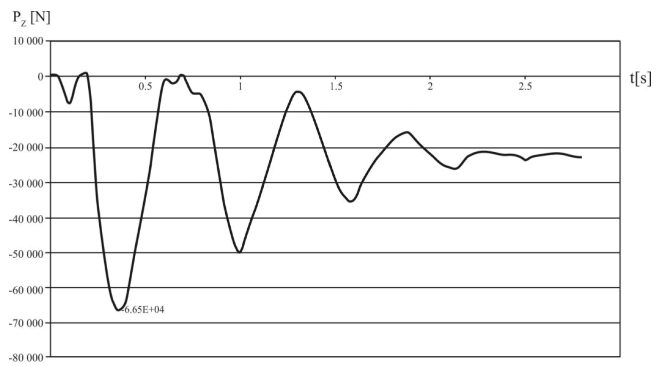

Fig. 5. Results of landing gear vertical air-drop simulation from height $H = 283$ mm for substitute damping coefficient $C_z = 14000$ N·s/m – vertical force change course computed at wheel axis in simulation time function

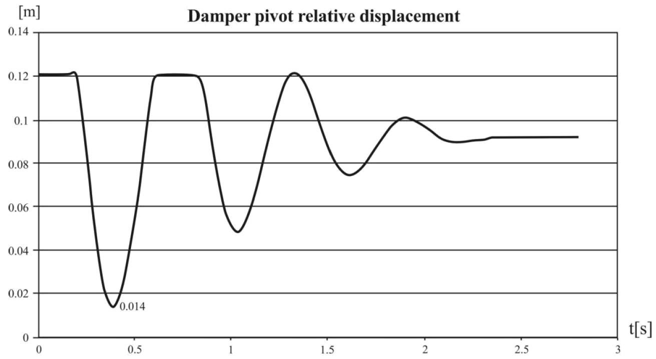

Fig. 6. Results of landing gear vertical air-drop simulation from height $H = 283$ mm for substitute damping coefficient $C_z = 14000$ N·s/m – damper pivot relative shift change in simulation time function

Figure 8 shows the representative simulation results that verify a damping coefficient value estimated on the basis of a series of vertical air-drops. The results are presented in Figs. 5–7. This numerical research also maps a vertical air-drop, however, for different initial parameters. The simulation of a landing gear vertical air-drop is conducted from height $H = 383$ mm. The initial velocity of the system in the vertical direction is equal to $V_z = 2.74$ m/s. In the verifying simulation, the researchers use a substitute damping coefficient equal to $C_z = 14000$ N·s/m, received after an adjusting series presented above (maintaining the following simulation parameters: reduced mass equal to 2278 kg, air-drop height equal to $H = 283$ mm and touchdown vertical velocity equal to $V_z = 2.13$ m/s).

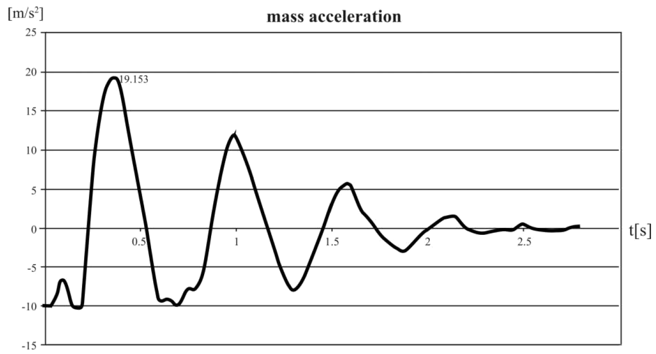

Fig. 7. Results of landing gear vertical air-drop simulation from height $H = 283$ mm for substitute damping coefficient $C_z = 14000$ N·s/m – associate mass acceleration change (component number 2 in Fig. 4) in simulation time function

The maximum value of the vertical force elaborated on an landing gear model wheel axis after the simulation time equal to 0.4 s has the value of 74200 N. The maximum vertical force registered during the vertical air-drop test for the identical outcome parameters is equal to $P_{z\,\max} = 78570$ N. The maximum relative difference of these values does not exceed 6%.

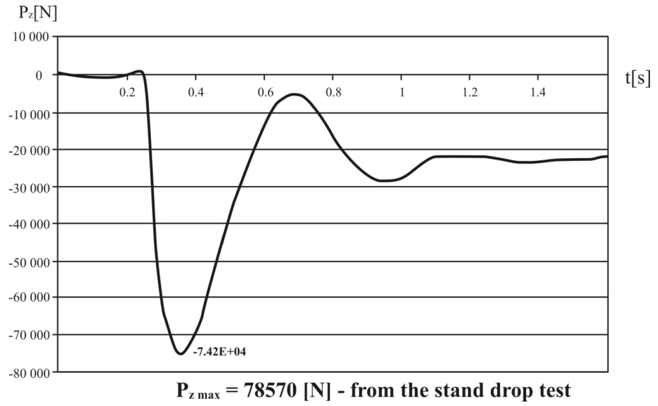

Fig. 8. Vertical force change computed at wheel axis vs. simulation time function (copy of landing gear vertical air-drop from height $H = 383$ mm, $V_z = 2.74$ m/s, substitute damping coefficient $C_z = 14000$ N·s/m)

On the basis of the experimental research performed on the air-drop stand and dynamic simulations with model adjustment, the researchers receive the substitute spring-damping characteristics essential for dynamic simulation realization in a totally deformed 3D model [30] of a complete landing gear system described in detail in the next section.

3.4. Optimal parameters choice for landing gear dynamic substitute characteristics. The tests aiming at optimal reduction of resilient substitute component rigidity are the next stage of the simulations in the 2D model. The tests are conducted in a way that allows damping constant change and net force maximum value maintenance in the wheel axis at the level of a force value registered in the experiment on the air-drop stand ($P_{Z\,\max} = 63390$ N).

These changes are introduced with the assumption that too significant reduction of resilient components rigidity in a 3D model causes a pivot and damper cylinder sleeve resistance surface oscillation effect. This procedure is conducted also because there is a necessity to change the coincidence of the results received in a 3D model of the complete landing gear.

The first stage of numerical analysis introduces the initial values of elastic constant $K = 1.2 \cdot 10^6$ N/m and damping coefficient $C = 80000$ N·s/m, computed earlier in an analytical model.

The analysis present landing gear operation parameters that allow the interpretation of the wheel axis load dependencies in a time function (Fig. 8). The maximum force in the wheel axis is equal: $P_{Z\,\max} \approx 65600$ N.

The net force values set in the wheel axis of a landing gear 2D model with different combinations of the aforementioned coefficients are presented in Table 1. Figures 9 and 10 present curves illustrating a force character course in a simulation time function.

The smallest value of a spring constant for a substitute element in the range of the net force maximum value in the axis is $K = 430000$ N/m (received vertical force: $P_{Z\,\max} \approx 63390$ N). Using this smallest value, the researchers adjust parameters received during the experimental research (vertical air-drop corresponding with the touchdown for 3 points). Further reduction of a spring component coefficient causes instability of the system – osculation of a pivot to the damper cylinder resistance surface and problems with coincidence achievement while solving the problem. The increase of a damping constant is not helpful since it causes the increase of net force in the wheel axis and makes the adjustment of the value received in the experiment impossible (i.e. 63390 N). Owing to fact it was necessary to determine the most advantageous relation between them (**K** and **C**) considering the stability of the calculation process.

Table 1
Simulation results list

Elasticity **K** [N/m]	Damping constant **C** [N·s/m]	Force in wheel axis **P** [N]
1200000	80000	65600
500000	100500	63380
430000	106700	63390

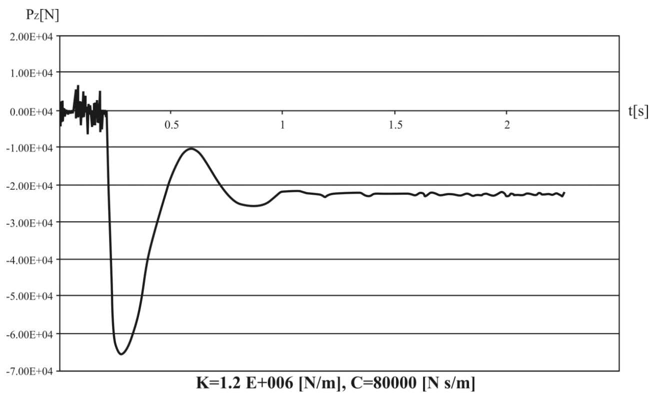

Fig. 9. Net force value change course in wheel axis in time function for initial parameters

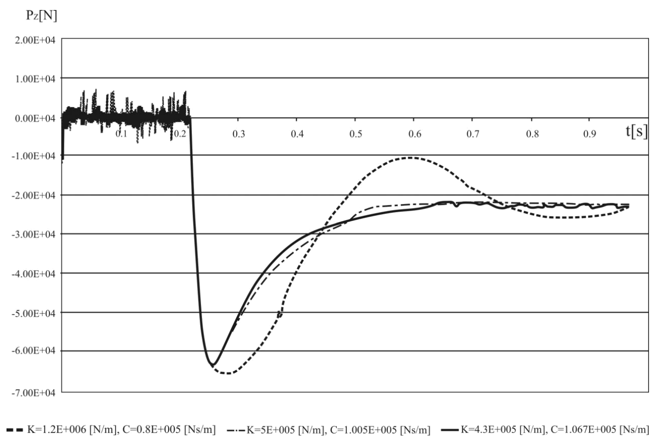

Fig. 10. Force value dependencies vs. time with different substitute component parameters values

On the basis of the dynamic analyses conducted in landing gear 2D models, the researchers select the additional spring – damping parameters values (Table 1) of components that substitute a fluid-gas damper used in the landing gear in the 3D model [30]. This allowed an increase of the integration stage and reduction of the time required to obtain the results of the numerical analysis conducted in the 3D model of the complete landing gear with the use of LS-Dyna software [23].

In a deformed 3D model of the complete landing gear, the researchers substitute a single component of the spring and the damper (Fig. 11) for 40 components of springs and dampers. For this purpose they remove MPC components nets with the central knots between the additional rigid rings connected with damper cylinder resistance surface sections in the landing gear strut body and the damper pivot section, to which the spring and the damper are mounted ($K = 4.3 \cdot 10^2$ N/mm, $C = 1.06 \cdot 10^2$ N·s/mm Fig. 12).

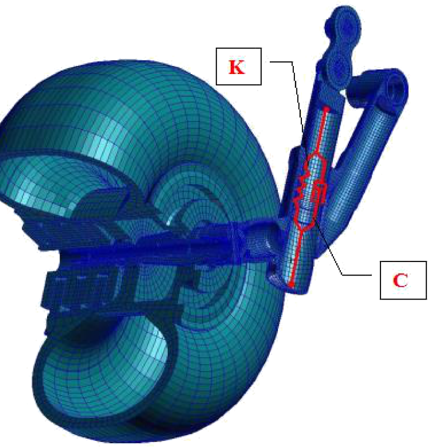

Fig. 11. View of 3D landing gear model with single spring – damping component substituting damper

40 spring components and 40 damping components are directly added to nodes on the edge of the additional rigid rings modelled between the landing gear lower lever bottom sections and the damper pivot section. Implementation of the discussed components in the 3D model [29] is presented in detail in Fig. 12.

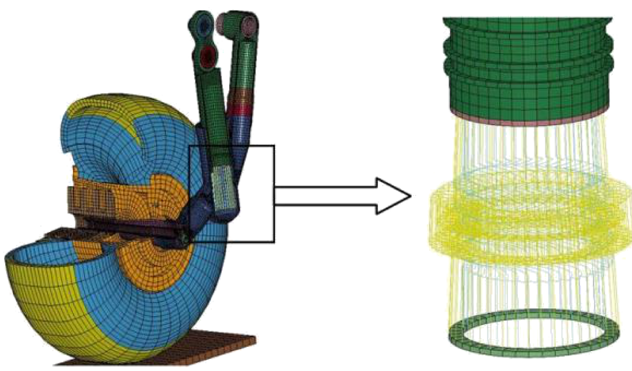

Fig. 12. View of implemented spring - damping components substituting damper in 3D model of main landing gear

For each resilient component in a modified substitute damping model in the 3D landing gear system (Fig. 11), there is defined constant rigidity equal to $K_{n=40} = \frac{1}{40} \cdot K$. A constant viscous damping value equal to $C_{n=40} = \frac{1}{40} \cdot C$ is defined for a damping component as well.

4. MES numerical simulation of landing gear vertical air-drop – 3D model correctness verification

A numerically researched landing gear vertical drop from height h is carried out in laboratory conditions on a drop stand [11, 12]. The aim of this numerical simulation is the main landing gear dynamic characteristics evaluation while mapping a vertical drop test (with no progressive velocity) and 3D model [30] application correctness verification by comparison of experimentally and numerically elaborated values of selected parameters describing landing gear components exertion and deformations. Moreover, the researchers conducted numerical tests of mapping the aircraft landing gear drop test. The mass of aircraft take off and touchdown was 7500kg. The touchdown numerical simulations are conducted maintaining parameters corresponding to stand tests:

- $m_r = 3750$ kg – reduced mass for the analyzed main landing gear equal to all components masses of the dropped system,
- $V_z = 2.13$ m/s – aircraft vertical drop velocity at the moment of tire contact with the surface,
- $V_x = 0$ m/s – aircraft touchdown horizontal velocity,
- $h = 231$ mm – model drop height,
- $\alpha = 0$ deg – angle of inclination of the contractual aircraft plane in relation to the ground,
- $P_{am} = 5$ MPa – damper filling pressure,
- $P_{op} = 0.55$ MPa – tire filling pressure.

It should be emphasized that a numerically copied test corresponds to a real range of touchdown time equal to 0.2 s. In the landing gear model, the researchers introduce marginal conditions that correspond to the realized option of a numerical test. External constraints in the form of non-sliding articulated supports are introduced in the landing gear mounting knots (central knots on the upper pivot side surfaces and the upper lever sleeve) to an aircraft fuselage construction. In numerical tests, the researchers receive a number of data describing cooperation of particular areas in the contact area. This concerns both kinematics and dynamics of the analyzed complex structural mechanism. The selected numerical test results are presented in Figs. 13–18.

Figure 13 presents a lever exertion map with the landing gear mounting knots and a diagram of stress changes in the notch construction in the landing gear vertical drop simulation time. The maximum stress values appear in the landing gear lower lever and concern the connection between a lever arm and a damper cylinder wall that forms the notch construction. The maximum stress is equal to 550 MPa and is generated in 0.03 s of the landing gear vertical drop simulation time.

A significant increase of stresses at the time of the landing gear wheel contact with the drop plate in the drop test simulation appears also in knots that mount an landing gear to an aircraft fuselage and in the landing gear upper lever arm. These units together with the appropriate stresses registered in 0.15 s of the landing gear vertical drop simulation time are presented in Fig. 14.

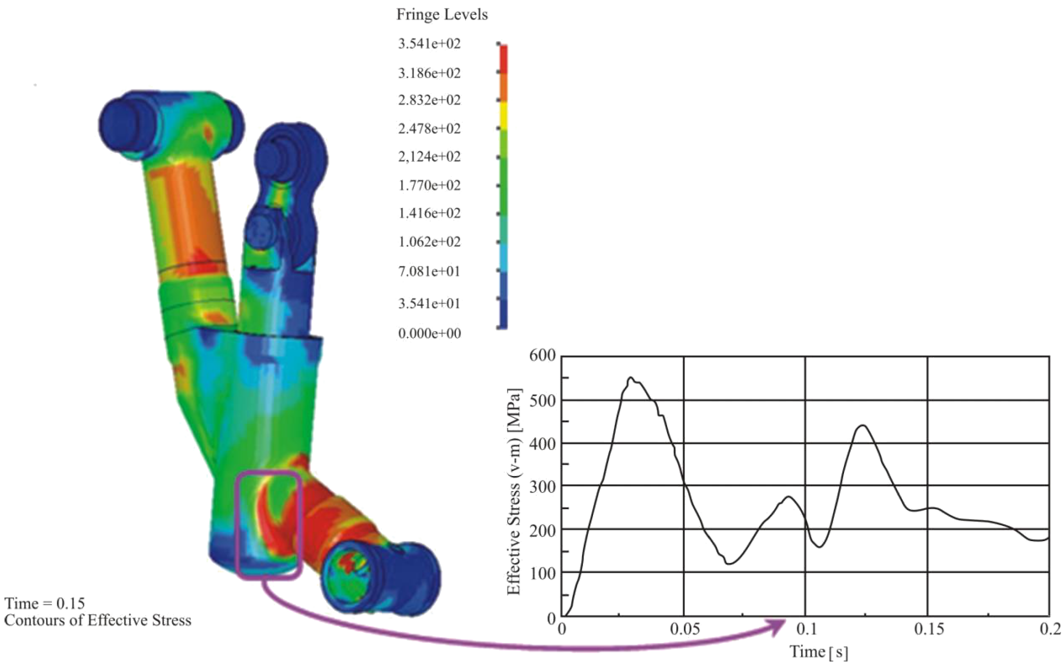

Fig. 13. Lever exertion map with landing gear mounting knots and diagram of stress changes in notch structure in drop test ($\sigma_{\max} = 550$ MPa)

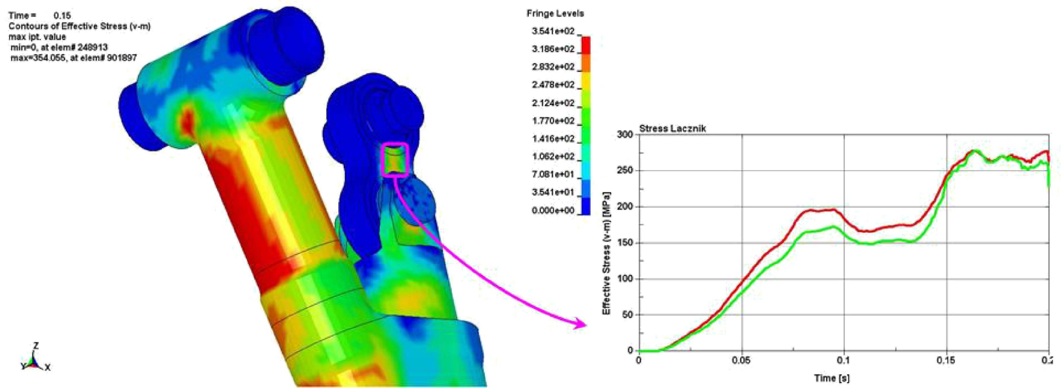

Fig. 14. Map of stresses in knots mounting landing gear to aircraft fuselage, in landing gear lever upper arm ($\sigma_{\max} = 354$ MPa) and diagram of stresses change in rocking lever connector between mounting joints

The maximum stresses recorded in the notch structure of the upper lever arm that cooperates with the landing gear mounting sleeve exceed 350 MPa. On the external surface of a rocking lever connector between the mounting joints, the stress increases to the maximum value of approximately 275 MPa. According to the diagram in Fig. 14 this value appears in 0.17 s of the landing gear drop test simulation time.

Figure 15 presents a map of maximum stresses in the contact area of the damper shaft and the landing gear rocking lever connector cooperating with the pivot knot shaft forks.

The area of increased stress in the discussed units of the knot joining the damper shaft and the landing gear suspension rocking lever is limited to the area of direct contact of the damper shaft forks edges and the pivot. The stress value registered locally at the pivot surface in 0.15 s of the drop test simulation is higher than 350 MPa. The maximum value of registered stresses in the same phase of touchdown on the surface of the damper shaft forks orifices (Fig. 15) equals $\sigma_{\max} = 163.4$ MPa.

In the landing gear 3D model used for the vertical drop test simulation, the researchers mapped in detail the wheel units and their mounting to the landing gear lever lower arm. The use of such a model in the landing gear dynamics research allows the researchers to follow the wheel units cooperation phases (including movable parts), their deformation in the vertical touchdown time and particular parts stress state monitoring. In the area of contact of a wheel hub and a landing gear brake stator, the maximum main stresses registered in a touchdown phase achieve the value of $\sigma_{\max} = 123.5$ MPa – Fig. 16. They are located on the brake stator orifice edge. The landing gear wheel axis is set in this orifice.

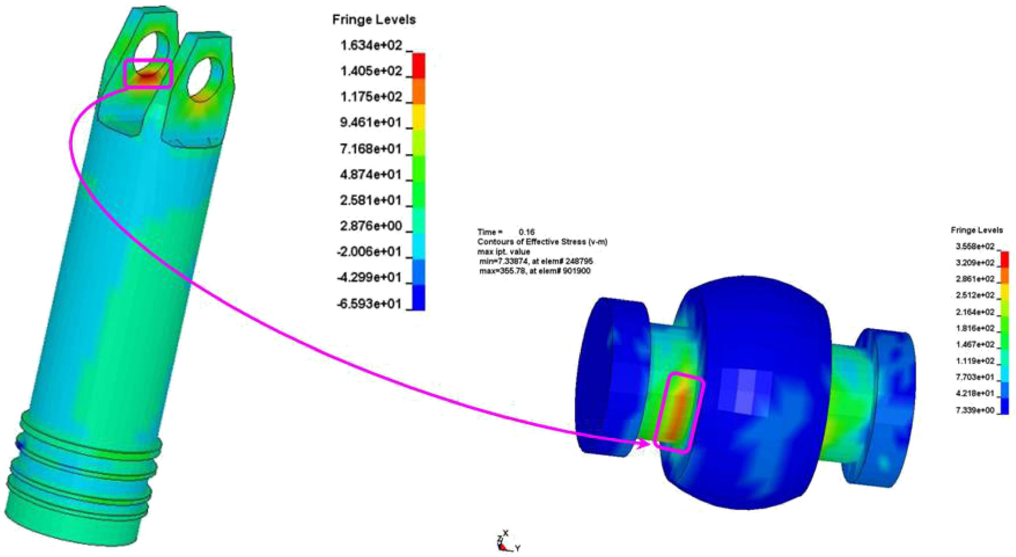

Fig. 15. Map of maximum main stresses in the area of contact of landing gear damper shaft forks ($\sigma_{\max} = 163.4$ MPa) and in pivotal mounting knot to rocking lever connector recorded in touchdown phase ($\sigma_{\max} = 356$ MPa)

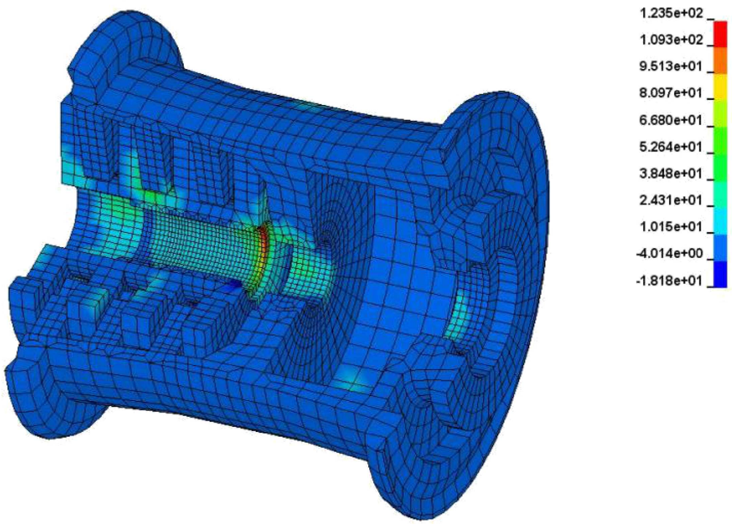

Fig. 16. Map of maximum main stresses in the area of contact of wheel hub and main landing gear brake stator registered in touch down phase ($\sigma_{\max} = 123.5$ MPa)

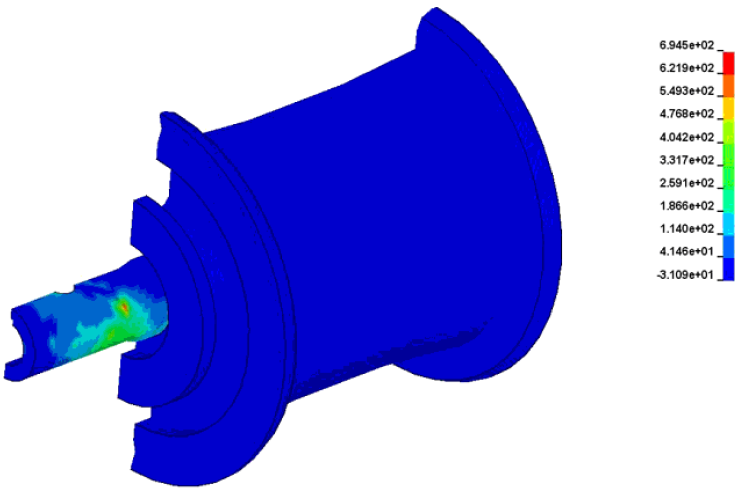

Fig. 17. Map of maximum main stresses in the area of axis and main landing gear wheel bearing registered in touchdown phase ($\sigma_{\max} = 694.5$ MPa)

It is possible to observe more significant contact stresses in the area of cooperation of the axis and the main landing gear wheel bearing internal track (Fig. 17). The maximum main stresses in a small area on the wheel axis achieve the value close to 700 MPa.

The landing gear construction shows many places (Figs. 13–17) in which local concentrations of stresses can cause, e.g., fatigue break initiation. Nevertheless, it is important to emphasize that the analyzed 3D model is an ideal model which does not include any break process in any of its stages.

Figure 18 presents a map of stresses and a diagram of their changes in components marked in the area of a welded joint connecting the lower and the upper lever of the main landing gear.

The stress map received as a result of realization of the aforementioned simulations confirms that in the area of a weld joining the unit of the lower and the upper lever of the analyzed landing gear there are significant local pile-ups of stresses. This observation is confirmed by the results of studies conducted with the use of a real object. It turned out that, at the time of conducting the stand tests (copying of a complete exploitative cycle), the analyzed landing gear was damaged.

Although the researchers accepted simplifications in copying work of the damper, the proposed 3D landing gear model allows resilient and damping forces course control in particular phases of the landing gear drop test simulation. Figure 19 presents the diagrams of a dynamic reaction force change and forces generated in the damping components in a damper model. Resilient reaction force achieves the maximum value equal to 3 kN in 0.07 s simulation time and damping force in a damper model increases up to 36 kN in 0.2 s of the analysis time.

Furthermore, the work also includes the selected results of the analysis presenting the quality of a numerical copy of the landing gear drop conducted in the laboratory conditions. In order to do this, Fig. 20 presents the changes of shaft displacement in relation to a damper cylinder registered in a drop plane model.

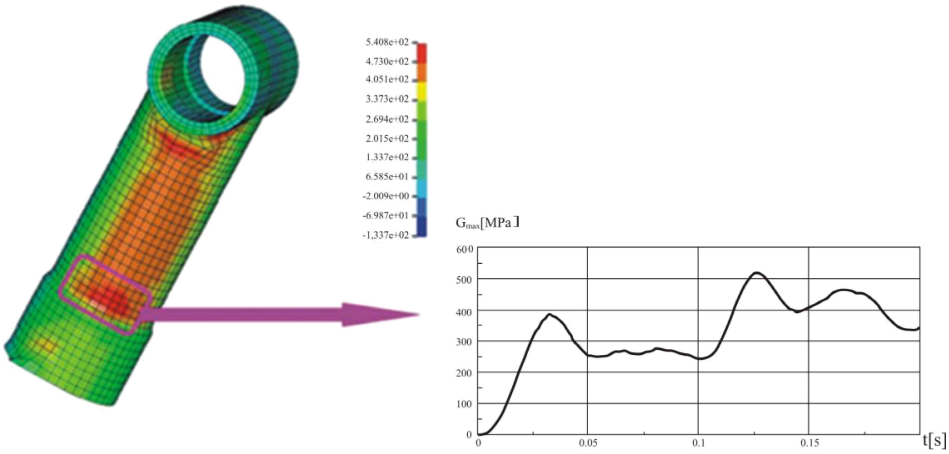

Fig. 18. Map of maximum main stresses and their changes in the area of welded joint that joins landing gear lower and upper lever registered in touchdown phase ($\sigma_{\max} = 540.8$ MPa)

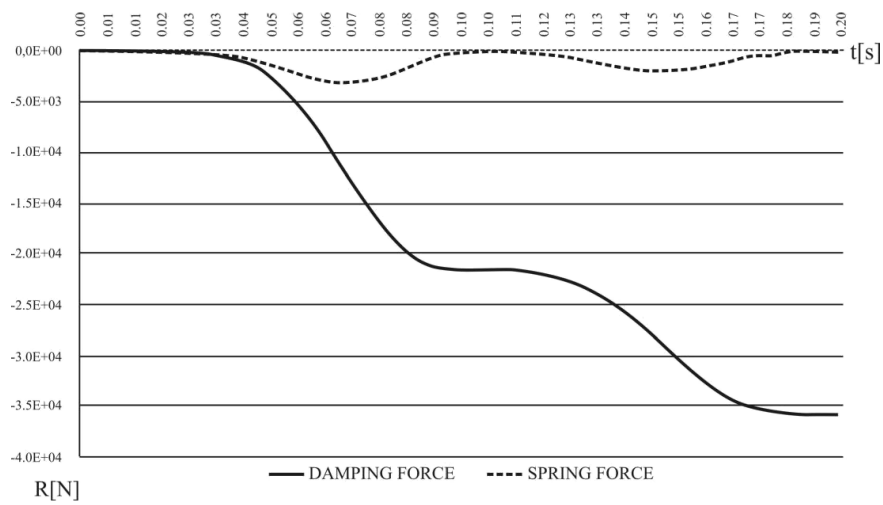

Fig. 19. Spring and damping forces change in particular phases of landing gear drop test simulation

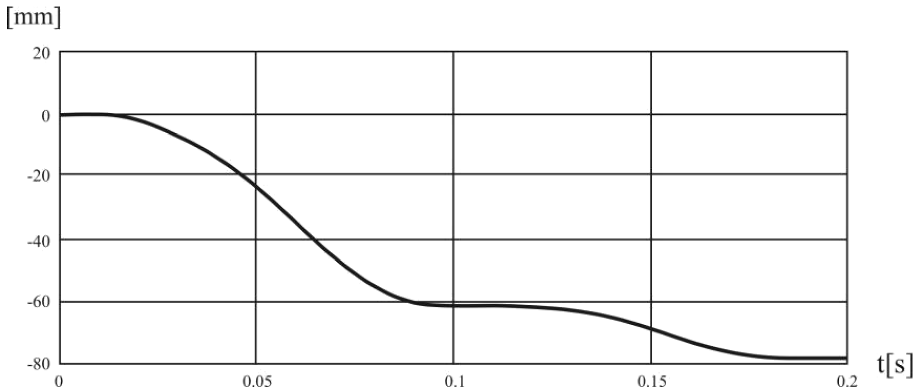

Fig. 20. Shaft displacement change in relation to damper cylinder registered in drop plane model during touchdown phase

Work of resilient – damping components, used to model a landing gear damper, achieves the maximum value after about 0.18 s of the simulation time.

This observation is also confirmed by analysis of a damper shaft displacement in relation to a cylinder sleeve. A diagram illustrating a damper shaft displacement in relation to a cylinder sleeve in a drop simulation time function is presented in Fig. 17. The maximum value of a damper shaft displacement in relation to a cylinder sleeve set during the landing gear vertical drop numerical simulation is equal to almost 78 mm. The registered value on the drop stand at the time of a main landing gear vertical drop laboratory test is equal to 82 mm. Thus, a relative difference of the compared results does not exceed 5%.

The researchers confirmed a significant coincidence of the numerical analysis results and laboratory drop test parameters (possible to register) on the basis of reaction force registered on the drop plate in a touchdown phase. The maximum value of vertical reaction registered statically (with substitute load corresponding to damper diffraction equal to 82 mm) on the laboratory stand is equal to 39.5 kN. The maximum value of vertical reaction registered in the drop numerical simulation exceeds 45 kN. Thus, the difference of the compared values is only approximately 12%.

5. Conclusions

The appropriate selection of landing gear characteristics is a complex process. Nevertheless, these characteristics allow loadings that appear in landing gear components to be reduced at the time of the touchdown. For this purpose, the researchers conducted landing gear dynamic analyses to predict work of such systems in dangerous conditions. Realization of a research with the use of numerical methods is easier and cheaper than the stand tests. Nevertheless, it is necessary to elaborate appropriate MES models of the analyzed object in the form of a transport aircraft main landing gear. The work presents a method of the main landing gear numerical model construction designed for dynamic analyses and the parameters selection procedures which are essential for copying the real construction features.

The comparison of the maximum values of the experimental research results carried out on the test stand with a real landing gear and the results obtained from numerical analyses in the aforementioned vertical drop test confirms a high quality of the obtained results as a result of dynamic simulation in a deformable 3D model of the complete landing gear system.

Such models will be used to conduct numerical analyses that simulate different touchdown conditions in both a nominal and in a damaged landing gear. The presented deformable 3D model of a complete landing gear system can be used in the analysis of an influence of a progressive destruction process of one component (fragile break) on complete landing gear exertion [31, 32].

The main advantage of the presented numerical method is a possibility of applying it into the landing gear research. It is impossible to conduct the landing gear research using other methods, including the experimental ones, since there is always the necessity of staff and equipment safety assurance.

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