EVALUATION OF A LANDING GEAR SEMI-ACTIVE CONTROL SYSTEM FOR COMPLETE AIRCRAFT LANDING

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Abstract. This paper deals with the simulation of landing gear semi-active control for a small trainer aircraft in a multibody framework. The behavior of single passive landing gear drop test simulation models and of a complete aircraft landing simulation model, developed and implemented in the commercial multibody code ADAMS in previous works, is compared to the that of analogous models equipped with semi-active shock absorber controllers. The control strategy and the controller tuning and sensitivity tests are briefly outlined and the results of its application to the landing gears is presented. The reduction in peak vertical attachment load values for the landing gear drop tests ranges from 5% to 35%, depending on the test conditions, and in the complete aircraft landing simulation, it is in the order of 5% to 20%, once again depending on the particular landing configuration. Comparisons between the drop tests and complete landing simulations in corresponding conditions are made, and the significant sensitivity tests are repeated on the complete aircraft model.

1 Introduction

In literature, much attention has been focused on the possibility of implementing active control technology on hydraulic suspension systems, in order to allow better landing gear performance in a wider range of operational conditions. Interest has been shown for the reduction of both impact loads and ground roll induced vibrations [1]. In fact, the primary function of the landing gear (LG) is to absorb aircraft vertical energy during landing impact, but it must also keep the aircraft in a stable position and allow sufficient manoeuvrability during ground operation, which leads to conflicting requirements in terms of the suspension system. Passive conventional gears can only be optimised for maximum dynamic performance in particular design operational conditions, typically hard landings [2]; their performance outside a limited range can deteriorate significantly, leading to unnecessary peak loads which influence the fatigue life of the gear and of the airframe.

Basically two approaches have been proposed for shock absorber control: active control, involving the variation of both the stiffness and damping characteristics [3,4], and semi-active control, which acts only on the viscous element [2,5-7]. In the first case, energy is fed into the compression, extension cycle, usually through the introduction or removal of pressurized hydraulic fluid in the oil chamber, while in the second case, there is no variation in system energy and the damping characteristics are modified acting on the orifice area or on the fluid viscous properties. The increased complexity and weight, along with the energy required to supply the necessary force (usually pressurized oil reservoirs are proposed [3,4]) are the main drawback for the fully active approach, which has been widely studied to improve operation on repaired runways. The semi-active control, whose performance seems to be only marginally inferior with respect to that of a fully active system, once an adequate control law is provided, may even turn out to be lighter and more cost-efficient than the classical passive solution [1,2], nowadays highly sophisticated with its complex valve layout.

In this work, the application of semi-active control is proposed in order to extend the range of optimal gear performance to the entire landing operational envelope, reducing the peak loads [1,7]. The shock absorber can, in fact, be made to pursue an ideal target load, supplying the necessary energy dissipation and avoiding the load levels generated in the passive configuration. Furthermore, the variation of the dissipating properties does not introduce energy into the cycle, thus avoiding the onset of possible instabilities [3].

The test case considered in this work is that of a jet trainer aircraft with a tricycle landing gear. The simulation environment used to develop the control system is the commercial multibody code ADAMS. A multibody model of the complete aircraft, including rigid body aerodynamics and control surface actuation, was developed in previous works [8]. The controller is initially implemented in the single main- and nose landing gear (MLG and NLG) drop test models and parameter tuning is conducted by virtual testing. Once the preliminary aspects have been explored, the controller is implemented in the complete aircraft landing simulation model, without varying the tuned parameter values, and complete landing simulations are run. Sensitivity of the complete aircraft model to the variation of control parameters is checked and comparisons are made with the results obtained in the drop tests.

2 Semi-Active Control Concept

2.1 Preliminary considerations

During aircraft landing impact, i.e. the first stroke of the aircraft suspension during touchdown, the aircraft vertical kinetic energy has to be absorbed by the landing gear. This maneuver involves both the MLG and the NLG, with load distributions depending on the landing conditions, e.g. speed, trajectory, attitude, aerodynamic configuration, CG position, mass and inertia characteristics. The shock absorber is the main energy dissipating element of the landing gear in this phase: its efficiency, defined as the ratio between the overall amount of energy absorbed and the product of the maximum force value and the maximum stroke reached, has a direct effect on the overall gear behavior. With an appropriate regulation of both the elastic and viscous parameters, a good gear efficiency can be achieved. Passive oleo-pneumatic shock absorbers with specially designed metering pin geometries or dynamic valves can reach, at the design point conditions, very high efficiencies (up to 80-90%), but in off-design conditions, their performance deteriorates rapidly, thus introducing unnecessarily high loads into the aircraft structure. The challenge of this work is therefore to exploit the introduction of semi-active control to extend the range of operational conditions in which the gear efficiency is high, decreasing the overall load levels entering the attachment points.

In Figure 1, on the left, an example of a classical passive load-stroke curve is reported, while on the right, the ideal effect of semi-active control is shown: the same amount of energy can be absorbed with lower load peak values. It is important to point out that the first part of the load-stroke curve is virtually unaltered in the two configurations: this part of the gear compression cannot be excessively reduced (thus increasing gear stiffness), as this would be accompanied by a sharp increase in longitudinal spin-up loads: unitary efficiency cannot be achieved.

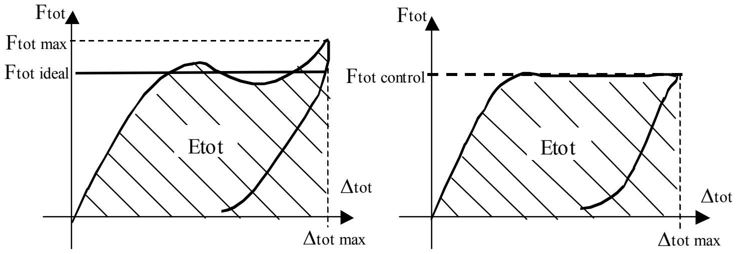

Figure 1: Passive (left) and active (active) gear load-stroke curves with the definition of the ideal load level

For each particular landing configuration, the application of semi-active control to the LG shock absorber requires the definition of a controller target value, i.e. a load value, $F_{tot\ control}$, which allows the gear to absorb the prescribed amount of energy, with a given maximum stroke value $\Delta_{tot\ max}$.

2.2 Controller design

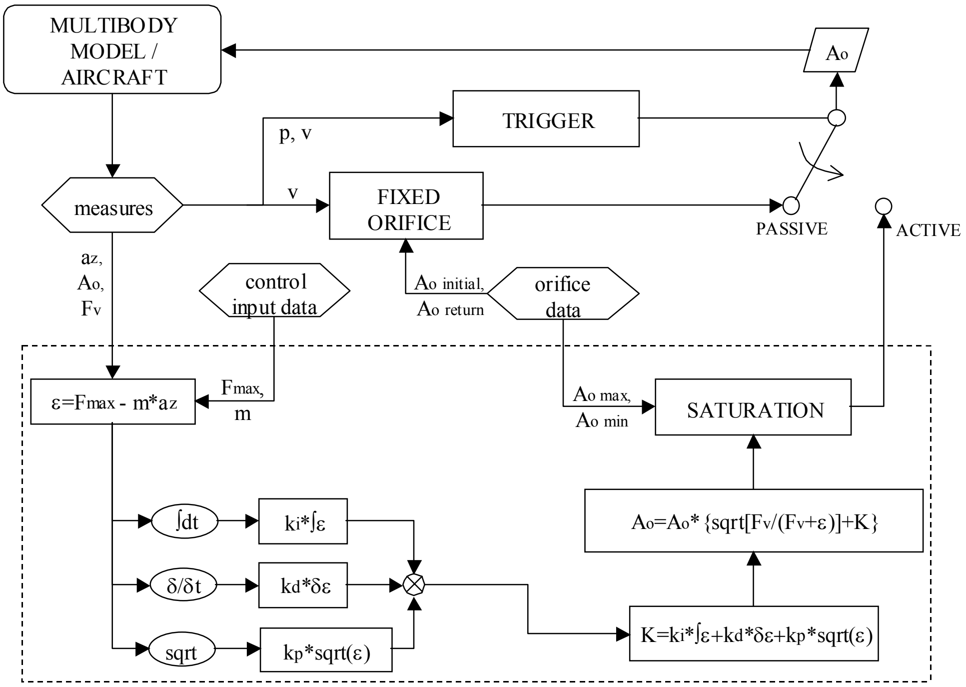

Figure 3: Controller scheme

Semi-active control involves the modulation of the viscous component of the shock absorber force. Under the hypothesis of a completely turbulent orifice flow, the analytical expression of the viscous force component is:

$$F_v = \frac{1}{2}\cdot \rho_{oil} \cdot A_{oil}^{3} \frac{\dot{s}|\dot{s}|}{A_o^{2} c_d^{2}} = k \cdot \frac{\dot{s}|\dot{s}|}{A_o^{2}} \qquad (1)$$

Examining expression (1), the only controllable parameter is the orifice area A_o. After having investigated various control laws, a hybrid approach was chosen [10], combining a non-linear PID and a term based on the expression of the shock absorber viscous force contribution.

$$\Delta A_o = A_o^{(i)} \left(\sqrt{\frac{F_v^{(i)}}{F_v^{(i)} + \varepsilon}} + k_P \sqrt{\varepsilon} + k_I \int \varepsilon dt + k_D \dot{\varepsilon} \right) \tag{2}$$

The controller is active only during the compression stroke and it is triggered by a combination of pressure and shock absorber rate sensors. In this preliminary phase of controller development, the controller gains are constant throughout the operational envelope: gain scheduling can be introduced, if necessary, in a subsequent stage. The overall controller scheme developed is represented in Figure 3.

3 Model description

The test case considered in this work is a jet trainer aircraft with a tricycle landing gear and the simulation environment used to develop the control system is the commercial multibody code ADAMS. A multibody model of the complete aircraft, including rigid body aerodynamics and control surface actuation, was developed in previous works [8-10].

The interaction between the landing gear and the ground is characterised by strong nonlinearities originating from the geometrical and functional characteristics of the shock absorbers, tires and structural component kinematics. With the multibody formulation, the landing gear model is intrinsically correct from the kinematics standpoint, and by implementing validated non-linear elements, such as oleo-pneumatic shock absorber and tire models, the dynamic behavior can be successfully simulated [8-10].

The landing gear single tire units considered represent two typical architectures, telescopic strut for the NLG and trailing arm for the MLG. The basic components of each gear are the structural cylinder, the nonlinear oleo-pneumatic shock absorber, the wheel and the fuselage attachment braces. In this preliminary phase of controller design, the various structural components are modeled as rigid bodies. The aircraft fuselage is also represented by a rigid body, condensed in the aircraft CG. The six components of the aerodynamic forces and moments are applied to the aircraft CG, as is the engine thrust. A trim routine calculates the initial elevator deflection, thrust value and aircraft angle of attack for a given inertial configuration, initial speed and trajectory: this allows the simulation of many different landing conditions.

The non-linear oleo-pneumatic shock absorber behavior is modeled using the classical polytropic compression and velocity-squared damping equations. Seal friction is also modeled, as a fraction of the elastic force. Stroke limitation is achieved through the implementation of a contact force, based on a compression only, non-linear stiffness and damping formulation, which counteracts the shock absorber pre-load in the fully extended position and limits the compression stroke to its maximum value.

The tire model adopted for this particular case study is the built-in ADAMS FIALA model [8], based on the beam on elastic foundation tire model proposed by Fiala in 1964; it consists in a relatively simple approach, useful for ground handling simulation, in cases in which the camber angle is not significantly large and the lateral and longitudinal slip effects can be considered uncoupled. The vertical force component is modelled using a constant parameter linear spring-damper element. For the calculation of the tire longitudinal force component, the friction coefficient is evaluated using the classical slip ratio-dependent piecewise linear approach.

4 Controller tuning

4.1 Target load evaluation

The semi-active control strategy developed in this work is aimed at reducing the maximum vertical load level introduced at the fuselage attachments: the controller target value is defined accordingly. A map of the target loads throughout the range of aircraft operational conditions has been obtained using the method described in Figure 2.

The operational envelope, in terms of CG position, mass and inertia characteristics, approach speeds and attitudes, of the test-case aircraft is used to define equivalent LG drop test configurations. This allows the “mapping” of the ideal target load level through affordable multibody simulations carried out on the passively designed shock-absorber. In fact, the energy to be absorbed for each operational condition is estimated integrating the load-deflection curves obtained with passive drop test models; dividing by the maximum overall deflection value, the ideal target load is obtained. This procedure is a simplified version of a more complete approach developed in [5]: it is approximated, in the sense that there is no guarantee that the final stoke value assigned actually corresponds to the imposed load value on the equivalent system polytropic compression curve. However, in the preliminary phase of controller design, this approximation yields acceptable results, which can in turn be used to extract the functional dependency of the target load on the system parameter values, so that the control system can be completely operative in any condition. For the aircraft considered in this work, the main system parameters influencing the gear-fuselage attachment loads are the vertical touchdown speed, the reduced mass, and, only for the MLG, the aircraft pitch attitude [9]; these seem to be the same also for other aircraft categories.

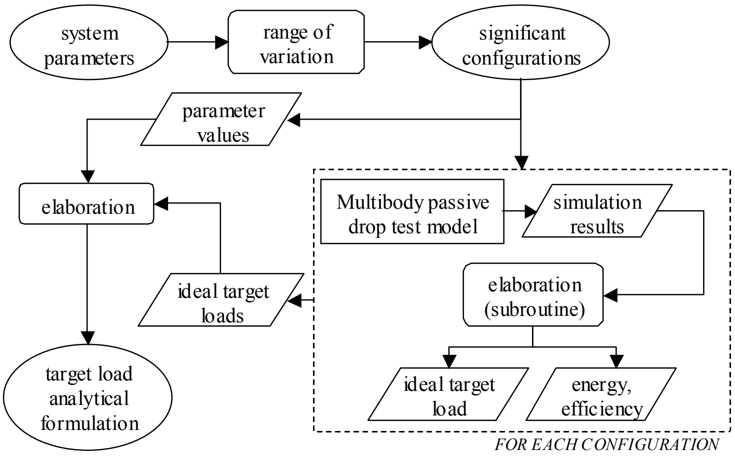

Figure 2: Target load evaluation scheme

4.2 Implementation and parameter tuning

For the implementation of the controller on a real aircraft landing gear, the controller input parameters must be measured with opportunely placed sensors. In the multibody environment, these sensors are replaced by appropriate measuring functions incorporated in the models. The elaboration related to the actual control law must also be expressed in a form compatible with the simulation environment, so that the complete system can function as desired. The tuning of controller parameters is a laborious process and requires an extensive simulation campaign: automated procedures can be very helpful in this stage of development. Sensitivity studies, conducted on the multibody models in order to determine the impact of measure (or analytical estimation) accuracy on the controller performance, are an important index of the robustness of the system.

The same control model has been adopted for both the MLG and the NLG and the parameters have been tuned for a reference drop test condition. Once the controller has been tuned, it can be implemented in the complete aircraft model and full landing simulations can be performed.

The input parameters that need to be measured for the control system are the instantaneous values of the local vertical acceleration at the fuselage attachment point, the shock absorber rate, the gas chamber pressure, the orifice area, the viscous force component and the reduced mass and target load. In the drop test models, a virtual accelerometer, placed at the LG–fuselage attachment point, supplies the vertical acceleration, while a virtual pressure sensor in the shock absorber gas chamber and a virtual rate sensor on the shock absorber supply the pressure and rate values. In the complete aircraft model, the virtual accelerometer is replaced by a virtual load cell placed at the LG-fuselage attachment point, and the controller error term becomes the difference between the desired load and the measured load directly, without passing through the product between the reduced mass and the local acceleration. The reduced mass in the drop test application is the sprung mass value, while in the complete aircraft model, it is estimated analytically, using the CG position, aircraft weight and moments of inertia, CG vertical and angular acceleration (see §6.1). In both applications the instantaneous viscous force component is estimated analytically, on the basis of the shock absorber rate and orifice area. The target load is given by a response surface based on the reduced mass, vertical impact speed, and, for the MLG, aircraft pitch attitude at impact.

The input parameters that have to be tuned during controller implementation are the trigger shock absorber rate and gas pressure values, the initial and return stroke orifice areas, the reversal shock absorber rate value, the maximum and minimum control orifice areas and the controller gains. The first five parameters have to do with the controller activation and the shock absorber behavior when the controller is inactive. The limit orifice areas and gains are instead directly related to the controller behavior. A complete description of the parameter tuning can be found in [9]. One of the objectives of this preliminary implementation is that all of the tuned parameter values must remain unaltered throughout the range of operational conditions. This necessarily leads to the adjustment of some parameters, which represent the best compromise for the overall system behavior, although they will no longer be optimal for the initial reference condition. In a future stage of development, the parameters, along with the target load values, can easily be made to vary.

5 Drop test model application

5.1 Results

An example of the results obtained, in terms of vertical acceleration and the corresponding load-displacement characteristics, are presented and compared to the passive LG results in Figures 5 and 6. Each pair of diagrams refers to a fixed reduced mass value and decreasing vertical speed. The loads and displacements are normalized referring to the maximum active values in the initial reference case.

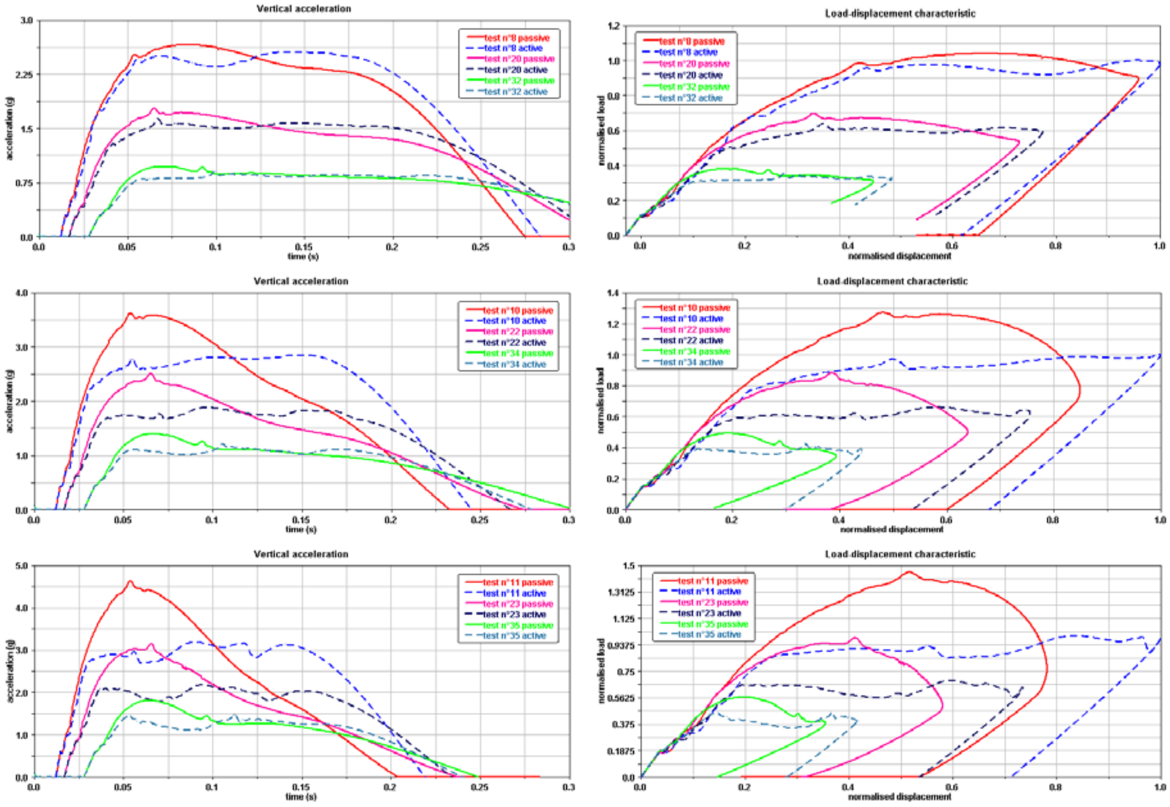

Figure 5: Active (dash) and passive(solid) MLG drop test results for constant mass (from top to bottom: m= 3000 kg, m=2000 kg, m=1500 kg) at varying vertical touchdown speeds (v=3.5 m/s, 2.5 m/s, 1.5 m/s) for a 0° pitch angle

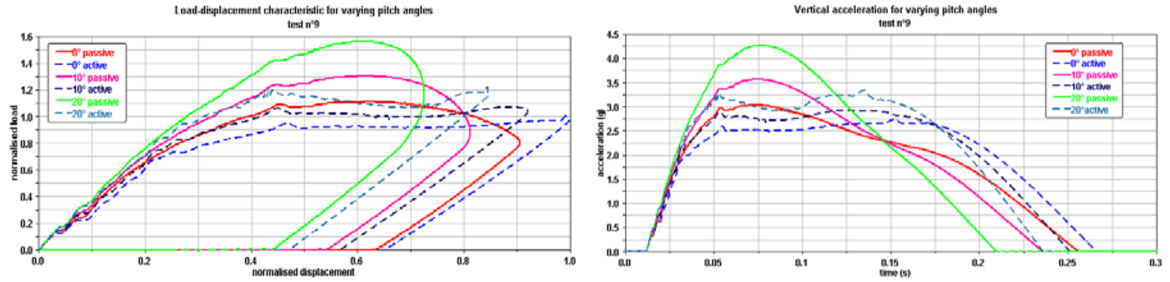

Figure 6: Active (dash) and passive (solid) MLG drop test results for constant mass and vertical speed (m=2500 kg, v=3.5 m/s) at varying aircraft pitch angles (0°, 10° and 20°)

The positive contribution of semi-active control to the LG behavior is evident and the corresponding load-displacement curves are relatively regular, which is symptomatic of an increase in efficiency, even though the normalized displacement increases. It is interesting to note how the controller's effect on the vertical acceleration increases as the mass values decrease, but decreases as the vertical speed values decrease. The controller tends to maintain the acceleration level throughout the compression phase, cutting off the passive initial peak value. The controller action is smoother for the higher mass values and somewhat "bumpier" for the low mass-high speed combinations, where the dynamic system is more reactive. It is very important to keep in mind that the shock absorber viscous force component, object of the semi-active control, depends quadratically on the shock absorber rate: as the vertical touchdown speed decreases, the resulting maximum shock absorber rate also decreases, and the controller is thus slightly less efficient. Notwithstanding this aspect, the vertical acceleration level is in all cases lower in the active configuration. One must also bear in mind that the passive metering pin was optimized for high reduced mass and vertical speed values, corresponding to certification conditions, so for those test cases, the increment in efficiency and decrease in vertical load due to the introduction of the semi-active control system is small. On the other hand, the tuned controller parameters are the result of a compromise aimed at guaranteeing acceptable LG behavior throughout the operational envelope, maintaining constant parameter values.

In all the test cases presented, there is a decrease in vertical load in the first phase of gear compression. This implies that the vertical ground load, and consequentially the spin-up longitudinal ground load, also remain below the passive values, resulting in a decrease in the overall combined gear attachment loads. In Figure 7, the ratio between the maximum vertical force obtained with the semi-active shock absorber and the maximum passive vertical force is mapped as a function of reduced mass and vertical speed. The ratio is in all cases below unity, which implies an improvement in gear behavior in terms of fuselage attachment vertical loads. The poorer improvements are obtained for higher mass and speed values: this is, as stated earlier, due to the particular optimization of the passive configuration.

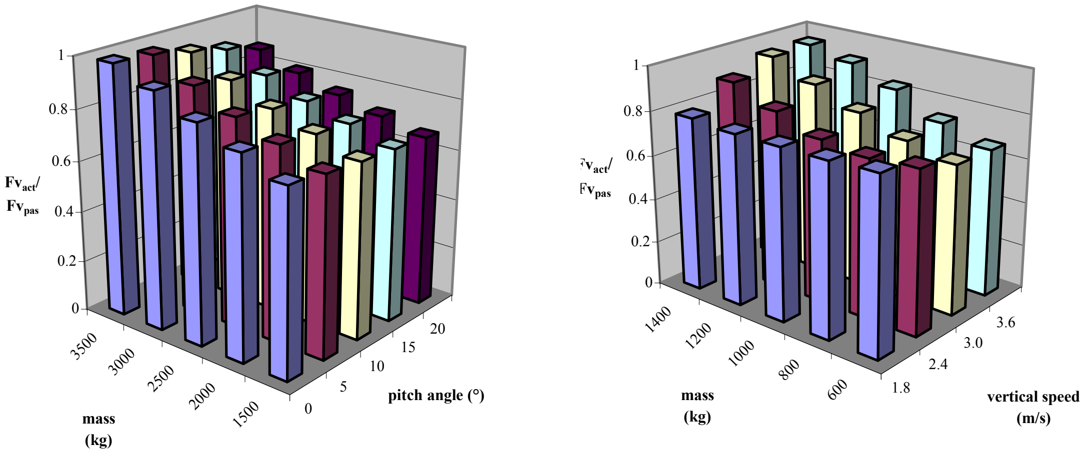

Figure 7: Average MLG active to passive peak vertical force ratio as a function of mass and aircraft pitch angle (left); NLG active to passive peak vertical force ratio as a function of mass and touchdown vertical speed (right)

5.2 Sensitivity analyses

An error in the determination of the parameters used for the evaluation of the target force level, that is vertical touchdown speed, reduced mass and, in the case of the MLG, aircraft attitude, induces an error in the evaluation of the controller target. The control system response in this case will not be optimal, but the controller must be robust enough to guarantee that the fuselage attachment loads do not exceed the maximum allowed value, i.e. the passive certification limit. Errors in the approximation of the instantaneous viscous force component value and in the measurements of the local vertical acceleration and instantaneous orifice area can also influence the controller behavior.

The sensitivity tests on the LG controllers were conducted using the multibody drop test models. The conditions considered correspond to the maximum vertical speed and reduced mass values: it is in fact for these values that the maximum vertical loads at the gear attachments are obtained. On the parameters that determine the target load value, i.e. the vertical touchdown speed, the reduced mass, and in the case of the MLG, the aircraft pitch attitude at contact, a constant error value was used (e.g. ±10%). For the measures entering the controller (instantaneous orifice area, local vertical acceleration and viscous force component values), a random error, proportional to the maximum value, was generated. The maximum error values examined were well above those expected in practice.

The sensitivity study on the MLG controller leads to the conclusion that the controller is robust enough to avoid the onset of higher loads than those obtained in the passive mode. The most critical parameters, that need to be determined with a certain precision, are in this case the vertical touchdown speed and the orifice area value. The least critical parameters seem to be the reduced mass and the viscous force component, along with the vertical acceleration. For the NLG application, the controller is less robust than in the case of the MLG. This can be partially explained by the different gear configuration (telescopic instead of articulated). The parameters that need to be kept under strict surveillance in terms of errors introduced in the system are in this case the reduced mass, the vertical speed and the instantaneous orifice area. Errors committed in the measurement of the local vertical acceleration and in the evaluation of the instantaneous viscous force are less decisive for the behaviour of the NLG controller.

The scarce effect of an error (up to ±50%) in the evaluation of the viscous force component in both LGs, reported in Figure 8, is comforting, as this is the only parameter (apart from the reduced mass) which cannot be measured but must be estimated on the basis of shock absorber instantaneous stroke and stroke rate values. This behavior can be easily explained examining the control law (2), where the viscous force value appears under a square root and both in the numerator and in the denominator of the term multiplying the orifice area.

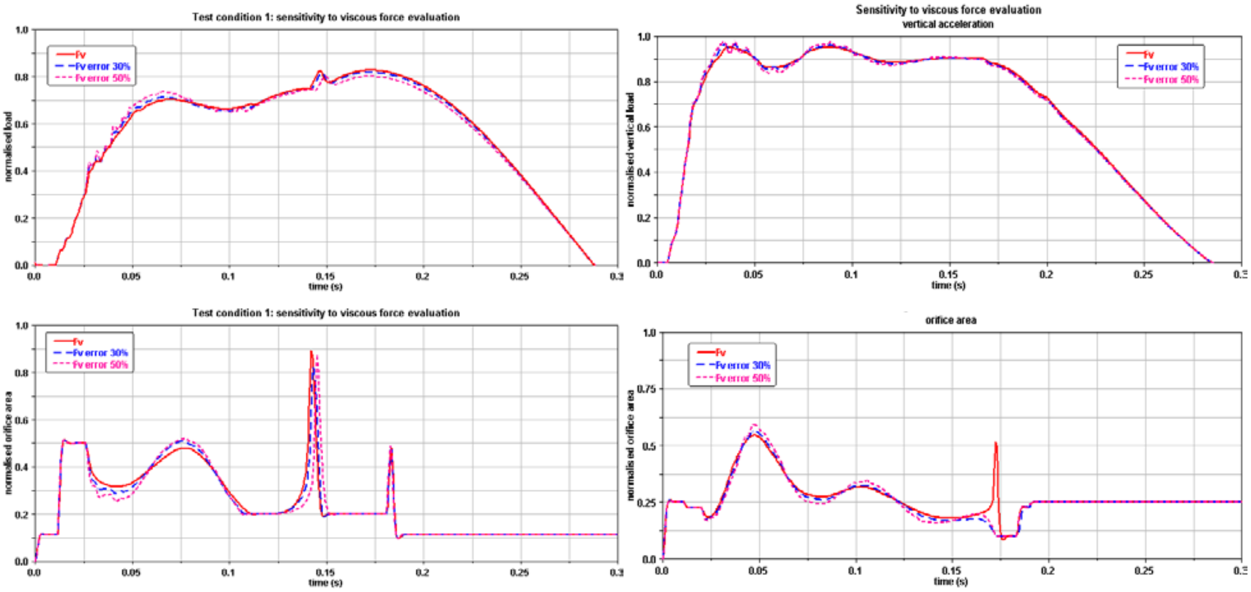

Figure 8: MLG (left) and NLG (right) sensitivity to errors in the evaluation of the instantaneous viscous force component; the attachment loads (top) are normalized with respect to the maximum passive load obtained in the reference condition; the instantaneous orifice areas (bottom) are normalized with respect to the maximum orifice area

6 Complete landing model application

In order to simulate the control system behavior during aircraft landing, the complete aircraft model, developed in previous works [8], was used. The control system was implemented separately on each LG, with the possibility of excluding NLG or MLG semi-active control. The controller parameters, tuned with the drop test simulations, were left unchanged. One of the difficulties encountered in this phase was the determination of the correct reduced mass necessary for the evaluation of the LG target load level [9,11]. An analytical approach was adopted in order to estimate the initial reduced mass value.

6.1 Analytical evaluation of the reduced mass value

Under the hypotheses that the aircraft CG lies on the centerline (symmetry), and that the aircraft approaches the ground in a trimmed condition, the total ground reaction at contact can be estimated through analytical calculation [12]. In the case of a 3-point landing, the total ground reaction acting on the three LGs is simply the product of the landing load factor n times the aircraft total weight W. The CG acceleration a_{CG} in this case can be assumed to be purely vertical, and the equivalent mass acting on the LGs can be easily calculated as the result of a static equilibrium, where the aircraft total mass m is multiplied by the load factor n. The results, expressed in terms of the corresponding mass reduction factor, τ, for each gear are reported in Table 1.

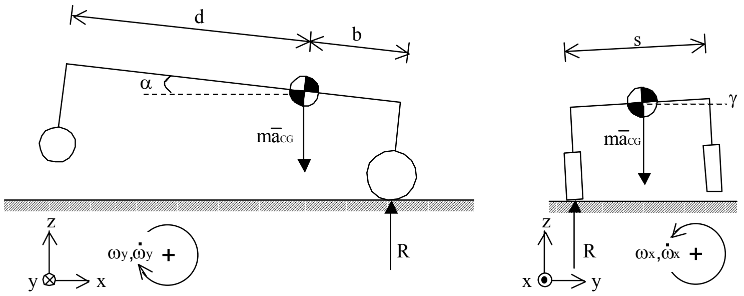

Figure 9: single point landing, first contact

If, as is common practice, the aircraft undergoes a two-point or single-point landing, with the MLG contacting before the NLG, the total ground reaction on the first organ(s) reaching the ground can be expressed as:

$$R_{tot} = \tau \cdot n \cdot W = \tau \cdot m \cdot n \cdot g$$

where τ is the mass reduction factor. The analytical expression of τ can be derived using the equilibrium equations for a generic, pitch-roll asymmetrical landing (the yaw effects are neglected) and is also applicable to a symmetrical two-point condition. Under the hypothesis that α and γ are small, and defining the roll and pitch gyration radii as:

$\rho_x = \sqrt{J_x / m}$ and $\rho_y = \sqrt{J_y / m}$ respectively, the analytical expressions of the mass reduction factors for each gear (MLG1 is the first to touch the ground, MLG2 is the second) are reported in Table 1.

	3 point landing	2 point symmetrical landing	2 point asymmetrical landing
τ_{MLG1}	$\frac{1}{2}\frac{d}{b+d}$	$\frac{1}{2}\left(1+\frac{b^2}{\rho_y^{\,2}}\right)^{-1}$	$\left(1+\frac{b^2}{\rho_y^{\,2}}+\frac{\left(\frac{s}{2}\right)^2}{\rho_x^{\,2}}\right)^{-1}$
τ_{MLG2}	$\frac{1}{2}\frac{d}{b+d}$	$\frac{1}{2}\left(1+\frac{b^2}{\rho_y^{\,2}}\right)^{-1}$	$\frac{1}{2}\left\{\left[1-\left(\frac{\rho_y^{\,2}}{b^2}+1\right)^{-1}\right]+\frac{s}{2}\left[\frac{\rho_x^{\,2}}{\left(\frac{s}{2}\right)^2}+1-\left(\frac{\rho_y^{\,2}}{b^2}+1\right)^{-1}\right]\frac{\dot{\omega}_x}{a_{CGv}}\right\}$
τ_{NLG}	$\frac{b}{b+d}$	$\frac{b}{b+d}\left[1+b\left(1+\frac{\rho_y^{\,2}}{b^2}\right)\frac{\dot{\omega}_y}{a_{CGv}}\right]$	$\frac{b}{b+d}\left[1+b\left(1+\frac{\rho_y^{\,2}}{b^2}\right)\frac{\dot{\omega}_y}{a_{CGv}}\right]$

Table 1: mass reduction factor analytical expressions

6.2 Results

The results obtained with the semi-active complete aircraft simulation model were compared to those obtained in the passive mode in symmetrical two point landing conditions, both with and without elevator actuation after touchdown. The evaluation of control system behavior in a range of landing conditions, including asymmetrical touchdown, are currently underway.

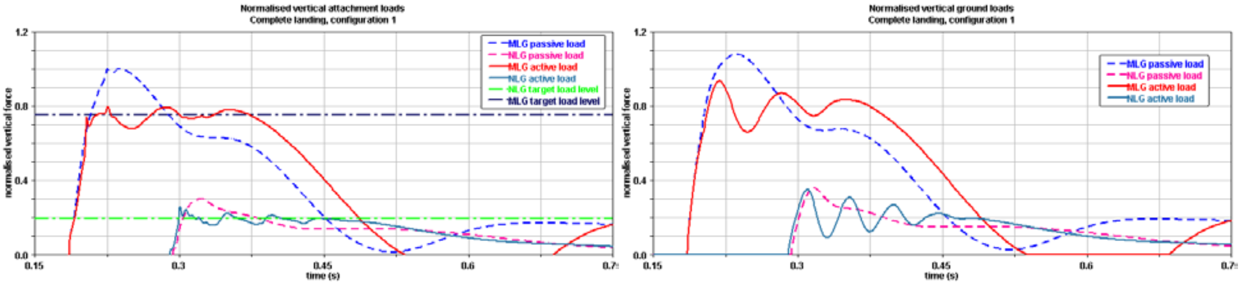

Figure 10: Vertical attachment (left) and ground (right) load time histories with a passive and semi-active LG; all loads are normalised with respect to the maximum passive MLG attachment load value

An example of the results obtained with a semi-active LG is presented in Figure 10. The aircraft configuration is that of minimum landing weight and maximum vertical speed (3.5 m/s). No control surface actuation after touchdown (i.e. elevator maneuver) is involved. The loads are normalized referring to the maximum MLG attachment load in the passive configuration. The reduction in the vertical attachment loads in the semi-active case is evident: the MLG maximum value is only 80% of the passive load, although this level is maintained for a longer period of time than in the passive case. The NLG impacts a fraction of a second earlier than in the passive case and it too shows a reduction in the peak value (almost 14%). A problem which is immediately visible in the load curves presented above is the fact that, although the overall peak value is greatly reduced, the load oscillates.

6.3 Comparison with drop test results

The controller parameters used in the complete aircraft model are those that had been previously tuned for the drop test cases. In order to check whether the tuning was still valid, the gear load-stroke curves obtained in the complete aircraft landing simulations were compared to those obtained using the drop test models with corresponding input parameters (reduced mass, vertical contact speed and, for the MLG, aircraft pitch attitude at touchdown). An example of the results is presented in Figure 11.

Generally speaking, the shape of the passive load-stroke curves differs slightly in the two cases: this can be explained by the fact that the drop test reduced mass is constant, while the equivalent reduced mass on each gear during a complete landing simulation varies (the NLG may witness a 40% increase during the compression stroke, in some cases). On the other hand, the lift during the complete landing simulation no longer completely compensates the weight. In the case presented in Figure 11, the effect on the MLG is a slightly higher reduction in peak loads with respect to the passive condition, while for the NLG the contrary is true. The NLG controller, in this case, suffers an overshoot in the initial compression phase: this can be avoided by re-tuning the initial orifice area value. The oscillations in the NLG load curve can be easily seen also in the drop test case: this is due to the fact that the particular operational condition corresponds with a low mass-intermediate speed combination, for which the control parameters are not optimal (one must not forget that, in the preliminary phase of the controller design, the parameters were to remain constant throughout the operational envelope, thus they had not been optimized for each operational condition, but were the result of a compromise). Further analyses are, in any case, needed before re-tuning the controller parameters: variable, scheduled parameters could be a solution to the problem of load oscillation.

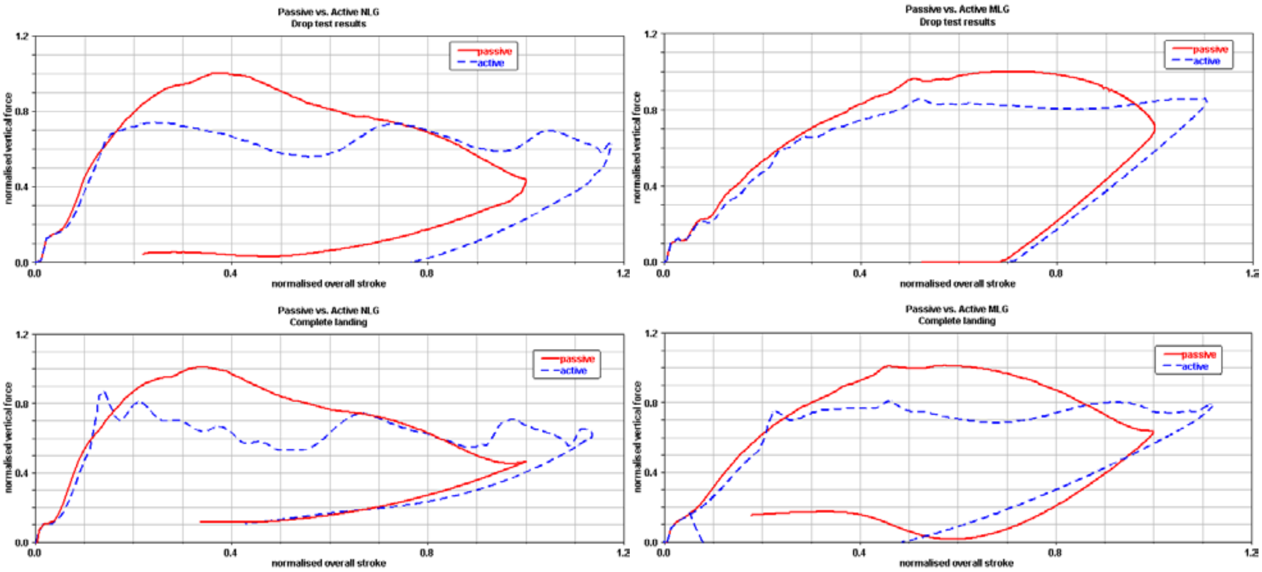

Figure 11: Comparison between the load-stroke curves obtained with the drop test (top)and with the complete aircraft (bottom) simulation models for the NLG (left) and MLG (right)

6.4 Sensitivity analyses

Sensitivity tests analogous to those run on the drop test models (§5.2) were run on the complete landing model in order to check controller robustness, introducing constant errors (±10%) in the evaluation of the reduced mass and vertical contact speed and a random error (±10% of the maximum value) in the measurement of the instantaneous orifice area, both for the MLG and for the NLG. In fact, the sensitivity study conducted on the drop test models had brought to the conclusion that the MLG controller is most sensitive to errors on the vertical touchdown speed and the orifice area value, while the NLG controller is sensitive to errors on the reduced mass, the vertical speed and the instantaneous orifice area.

The error ranges chosen are the same used for the drop test sensitivity analyses, although the assumption that on a modern aircraft a flight control system is present and instruments capable, for example, of supplying an accurate measure of the vertical speed are mounted is not farfetched. The landing gear control system could in fact be made to share information with these systems, directly using the measures or elaborating them in order to extract other measures. In the first case, the error committed on the measure depends directly on the instrument used, while in the second case, it is the result of a combination of errors. An example of measures that can be directly used by the control system are the vertical touchdown speed and the aircraft attitude. The reduced mass must instead be estimated, for example using the analytical approximations reported in §6.1. In this case, the aircraft instruments could be used to measure the necessary CG angular and vertical accelerations.

The results obtained for the complete landing model, in terms of vertical attachment loads, are reported in Figure 12. Both controllers seem to be particularly sensitive to errors on the vertical speed evaluation (±10% of 3.5 m/s for the MLG and of 2.7 m/s for the NLG results presented), while the sensitivity to reduced mass and orifice area are far less important than in the drop test case. For the reduced mass, this can be explained by the fact that the controller error is non longer calculated as the difference between the target load value and the instantaneous acceleration times a constant reduced mass value, but directly as the difference between the target and the load measured by the load cells. The error on the reduced mass value thus only affects the target load value. The controllers, in the complete aircraft model appear to be more robust, although further analyses, in a wider range of operational conditions, are needed before a conclusion can be drawn.

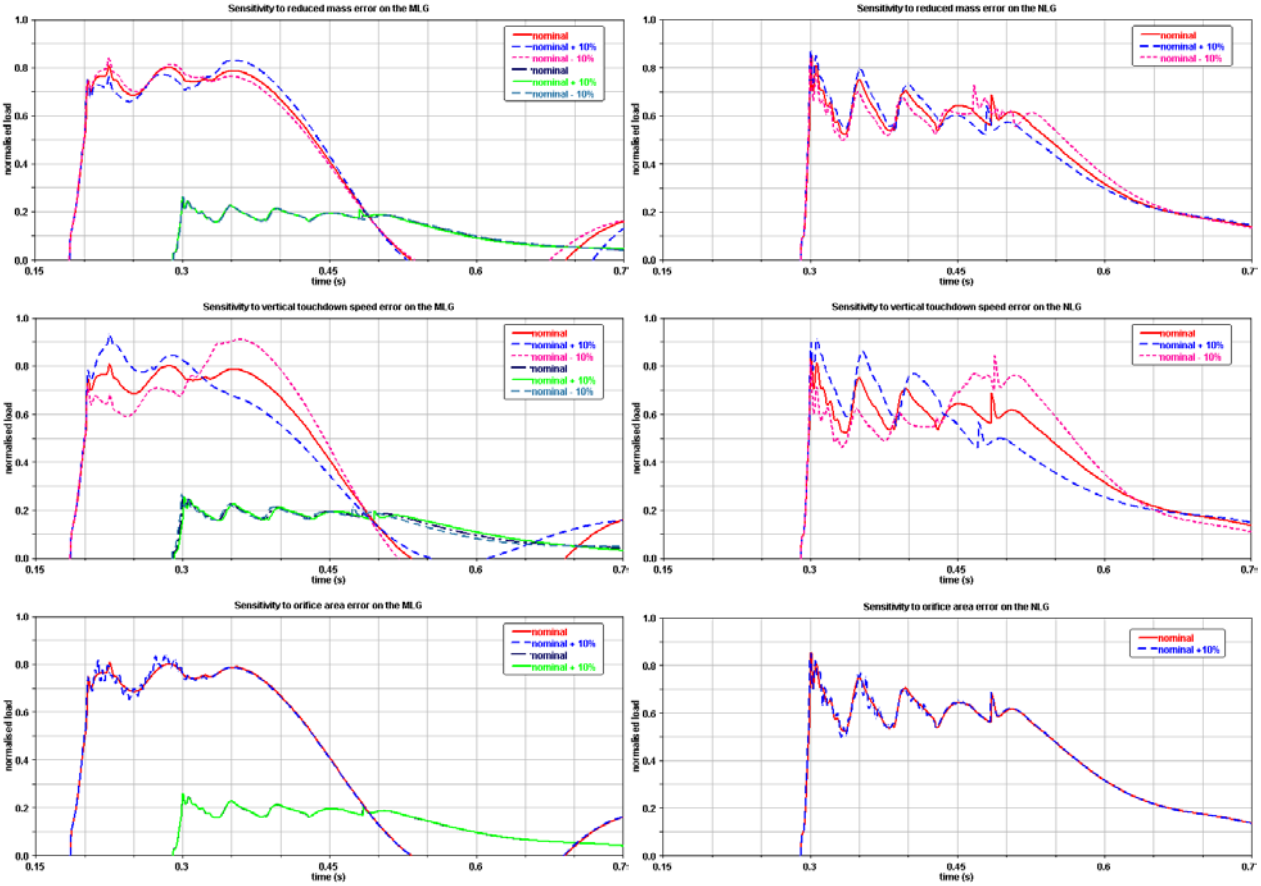

Figure 12: MLG (left) and NLG (right) vertical attachment load sensitivity to errors on the reduced mass calculation (top), the vertical contact speed measurement (middle), and the orifice area measurement (bottom); all loads are normalized with respect to the maximum passive values in the given configuration

7 Conclusions

Multibody landing gear models were used to study the behavior of a semi-active shock absorber controller during drop test and complete aircraft landing simulations. The control strategy, aimed at reducing the vertical attachment loads during landing impact, was applied to both an articulated and a telescopic layout, typical of aircraft main and nose landing gears respectively. The simulation drop test models were used to tune the controller parameters and check for robustness. The results obtained in the drop test simulations show reductions of the vertical load at the gear attachments, with respect to the corresponding passive values, ranging from 5 to 35%, depending on the operational condition considered. The complete aircraft landing model was tested in symmetrical landing conditions without varying the drop test tuned parameter values. The reduction in attachment vertical load with respect to the passive case ranges from 5 to 20% on the gears, depending on the particular operational condition.

The control strategy adopted can be said to apparently improve the gear drop test behavior throughout the operational range considered. The complete landing simulations were conducted only in symmetrical two point landing conditions, thus the conclusion in this case can only be partial: in the configuration considered, the control strategy effectively leads to a decrease in vertical load. The controller behavior must be improved in the complete landing case, through re-tuning of the control parameters, in order to eliminate load oscillations during the compression phase. It is important to note that issues such as fail-safety have not been addressed in this work, nor have the implications of an experimental setup for the actual drop testing of the gears; the latter is the object of current research.

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