



# EFFECT OF VERTICAL AND HORIZONTAL LANDING SPEED ON AMOUNT OF ABSORBED ENERGY BY SHOCK ABSORBER THAT EQUIPS A LANDING GEAR WITH TRAILING ARM

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**Abstract:** The purpose of this paper is to analyze the influence of aircraft vertical landing speed (sink speed) and horizontal landing speed (approach speed) on amount of energy absorbed by shock absorber that equipped a landing gear with trailing arm. A landing gear multibody model was built by using Virtual Lab software which makes possible to simulate drop test runs in order to check the speeds effects. The model allows setting different initial conditions and computing the amount of absorbed energy from each run. Settings and results from each drop will be analyzed according to 2k Factorial Design in order to determine the factors (speeds) effects as well as the interaction between them.

**Keywords:** Drop Test, Shock Absorber, Absorbed Energy, Horizontal Speed, Sink Speed

## 1. BASIC INFORMATION

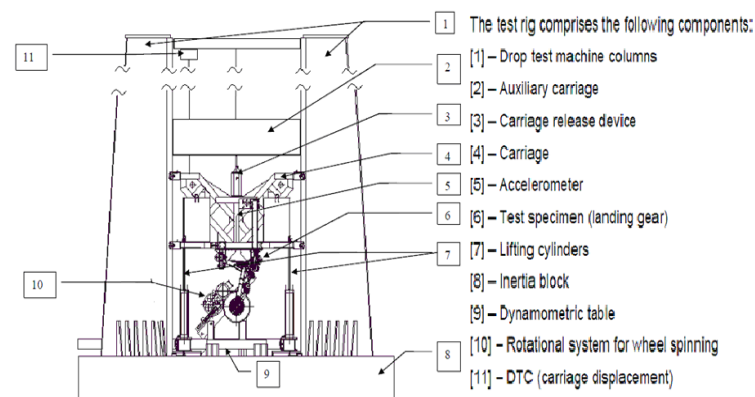
At beginning, first aircraft landing gears designs did not have major concern with impact and vibration attenuation. These projects only provided a structural support of aircraft in relation to the ground by using wheels and making easier the aircraft rolling. According to specialized literature [1], since the Second World War many types of landing gears designs that equip military, commercial and executive aircrafts has been developed to attend the increasing demand for load and impacts and vibrations absorption. In many designs, shock absorber can be considered as part of landing gear and its main function is damping and absorbs impacts and vibration generated during the taxing, takeoff and landing operation. The shock absorber considered in this paper is basically composed of cylinder and piston with relative movement between them as illustrated below:



Pneumatic Shock Absorbers [Sources: Currey, 1988]

## 2. DROP TEST

Drop Test is an experiment that simulates the aircraft landing conditions in order to check if the landing gear and shock absorber design successful meets the design requirements. To perform the drop test the landing gear (6) has to be attached to a carriage (4) that runs through rails of vertical columns (1) as illustrated below:



**Fig.2. Test Rig of Drop Test**

The landing gear with a rig mass is lifted to predetermined height and then released by carriage release device (3) to drop and hit against a dynamometric table (9). The carriage (4) provides attachment points to install the landing gear in different angular positions allowing reproducing the aircraft attitude (tail down or flat position) during touchdown. This apparatus controls the vertical velocity, or sink speed ( $V$ ), the wheel speed rotation to simulate horizontal speed ( $H$ ) and lift force reproducing the conditions that happens during the aircraft landing operation. Lift force is applied by pilot through elevators and flaps command, and has upward direction. The landing gear considered in this case of study is one that equips a mid-size executive jet aircraft and FAR25 Amdt.25-23 recommends that force can be equal to aircraft weight and it is simulated by hydraulic actuators, or lifting cylinders (7).

Wheel speed rotation simulates the aircraft horizontal speed ( $H$ ) during touchdown and this effect can be obtained

through rotational system for wheel spinning (10). Sensors are installed to collect data of pressure, force, wheel speed rotation, accelerations, stroke (displacement of shock absorber piston) and tire deflection during impact. At the end of each drop is possible to obtain the amount of absorbed energy by shock absorber and the magnitude of loads at attachment points in horizontal, vertical and lateral directions.

### 3. MODEL

This analysis has been developed considering a model of particular type of landing gear with trailing arm. This gear is a typical landing gear for executive mid sized jet equipped with oil-pneumatic shock absorber with metering pin. The model and its main parts are shown in the Fig.3 below:

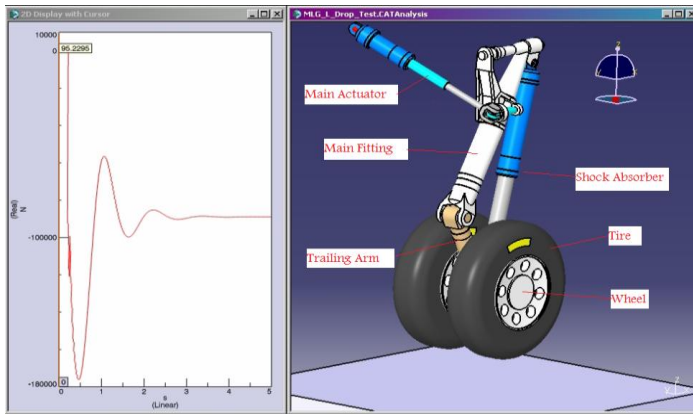


Fig. 3. Landing Gear Model

First of all, landing gear parts (such as: main fitting, trailing arm, actuators, wheels, tires and shock absorber cylinder and piston) were built with appropriate dimensions and positions by using CATIA. Then, each part was created as a body with correct mass value in multibody software environment and bodies inertia is automatically determined providing an adequate dynamic behavior of landing gear. After the bodies creation, they were connected by preselected joints in a way that the final degrees of freedom allows vertical descent movement, the wheel rotation, joints articulation and the relative movement between piston and cylinder of shock absorber (as occurs in landing gear submitted to drop test). This model simulates drop test and is able to reproduce the landing gear dynamic behavior with accuracy of 95% up to 98% as shown on Fig.4 below:

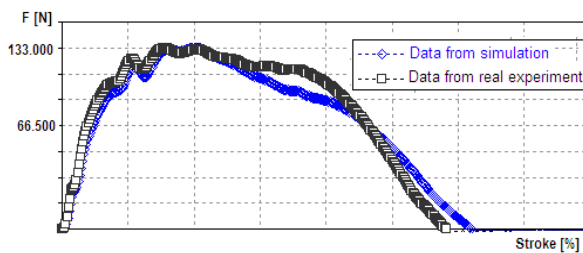


Fig. 4. Experiment and Simulated Data Comparison

During drop test simulation the wheel rotates (by using a driver) to simulate aircraft approaching speed at the moment of touchdown. Model also allows controlling the lift force

and sinking speed (vertical speed). The aircraft attitude can be change from flat to tail down position by changing the joints that attached the landing gear to the carriage.

The shock absorber considered in the model is the one with metering pin. The typical oil-pneumatic shock absorber with metering pin is shown in Fig.5 below:

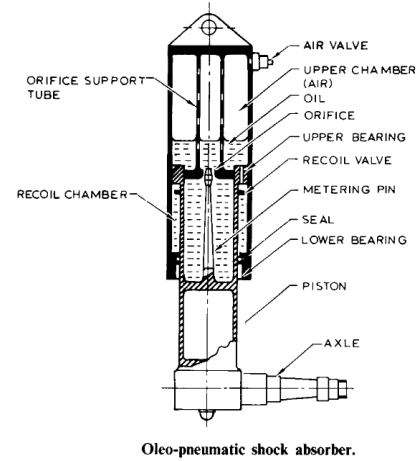


Fig. 5. Shock Absorber [Source: Currey, 1988]

This type of shock absorber is basically governed by pneumatic and hydraulic forces. The lower chamber is full with oil; when the aircraft lands and touchdown occurs the oil is forced from lower to the upper chamber through the orifice. This flow dissipates most part of impact energy due its turbulence and heat yielding. The orifice area is controlled by varying-diameter metering pin, as depicted in Fig.5 above. Hydraulic force ( $F_h$ ) that acts into shock absorber can be obtained by the product of available hydraulic area ( $A_h$ ) and hydraulic pressure ( $Ph$ ) as shown in Eq. (1):

$$F_h = Ph \cdot A_h \quad (1)$$

According to [4] the orifice coefficient is given by Eq. (2):

$$C_d = \frac{V_t^2}{\frac{2 \cdot Ph}{\rho} \cdot \left(\frac{A_o}{A_h}\right)^2} \quad (2)$$

Where:  $\rho$ - fluid density;  $A_h$  – Hydraulic Area;  $C_d$  – Orifice Discharge Coefficient;  $A_o$  – Net Orifice Area;  $V_t$  – Shock Absorber Deflection Velocity or Piston Velocity.

Thus, the hydraulic force can be written as Eq. (3):

$$F_h = \frac{\rho \cdot A_h^3}{2 \cdot (C_d \cdot A_o)^2} \cdot V_t^2 \quad (3)$$

Note that the orifice area ( $A_o$ ) varies with piston stroke due metering pin restriction and this information is available to model trough spline. Displacement sensor of piston was installed on shock absorber model making possible to get the orifice area ( $A_o$ ) correlated to each piston position. As mentioned in [5] the orifice discharge coefficient ( $C_d$ ) varies in terms of Reynolds number (which is determined in function of piston velocity and orifice dimensions) and the restriction from upstream cylinder area to the orifice area. These data are supplied to model through spline surface and with velocity obtained trough sensors and the orifice area

(Ao) is possible to obtain the Cd by the spline surface. Thus the hydraulic force can be determined

for each piston position since the hydraulic area (Ah) and fluid density ( $\rho$ ) are well known quantities.

The pneumatic force is obtained by firstly considering isothermal gas compression curve (polytropic coefficient is equal to one). This curve is obtained by slowly applying a gradual load to compress the shock absorber. As long as the force is applied, the piston surface exerts a pressure on the oil and this pressure is transmitted to the gas (see Fig.5) obeying an isothermal gas transformation:

$$P_1.V_1 = P_2.V_2 = nRT \quad (4)$$

Where: P1-Initial Pressure (fully extended position); V1-Initial Volume; P2-Final Pressure; V2-Final Volume; n-moles; R-Universal Gas Constant; T- Temperature.

Similarly to hydraulic force, the pneumatic force (Fp) can be obtained by the product of pressure (P) and pneumatic area (Ap):

$$F_p = P.A_p \quad (5)$$

Pneumatic force can be obtained by replacing pressure from equation (4) on (5):

$$F_p = P_1.A_p \left( \frac{V_1}{V_1 - A_p.S} \right)^n \quad (6)$$

Where: Ap- Pneumatic Area; S- Piston Displacement

Based on experience and on works statements ([3] and [6]), force pneumatic in dynamic deflections such as those that occur in drop test obeys a polytropic curve where coefficient varies from 1.03 to 1.13. The adopted value in this model is 1.1. The oil compressibility has to be taken into account in order to get accurate results. Hydraulic and pneumatic forces were applied in shock absorber by using springs (force element). Mass rig value used in the model is 7.466Kg, landing gear is fixed to the carriage with flat position and the gas and oil data was considered in 20°C of temperature (temperature of real experiment).

The analysis used by software LMS Virtual.Lab Motion workbench was the Dynamic mode which solves the constrained equations of motion for position, velocity, and acceleration values for each body for a specified period of time. The results are reported at intermediate time steps specified by the variable Print Interval and the value of time used for this print interval is 0.001s. The step specified for integration was 0.001 and the tolerance used to determine the maximum residual or error allowed for both position and velocity constraints is determined by Solution Tolerance which was specified in model as 0.001. The integration algorithm used to solve the system of equations is BDF ("Backward Differentiation Formula"). An implicit integrator which uses a backward differentiation formula method [7] and iteratively solves a large system of DAEs to converge to a solution at each time step. The iteration matrix is calculated by a finite difference scheme. The implementation of the integrator is based on DASSL, which has been developed by L. Petzold [8]. It is inherently stable for stiff systems where the eigenvalues differ by large margins. This method is preferred for dynamic systems which are overdamped, or which have degrees of freedom that become inactive due to motion that damps out.

#### 4. EXPERIMENT

The objective of this experiment is to analyze the influence of vertical and horizontal aircraft speed on quantity of absorbed energy by shock absorber during drop test. The simulations will be accomplished by varying the horizontal and vertical speed (factors) in two levels (low and high level) to comply with factorial design methodology. Notations H-; H+ represents low and high level of horizontal speed respectively and V-; V+ refer to low and high level of vertical speed. All remaining parameters such as: aircraft mass; aircraft landing attitude and lift force still at the same values in order to isolate the speeds effects. According to [3], the amount of absorbed energy by shock absorber can be determined by the area under the curve of force that acts on piston versus its displacement (stroke) as shown on plot of Fig. 6 below:

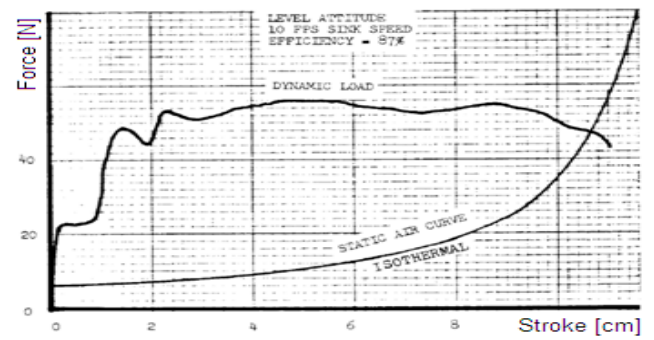


Fig. 6. Absorbed Energy [Source: Currey, 1988]

This area is automatically computed by the software. According to [9], a factorial design considers all possible combination between factors (vertical and horizontal speeds) levels. Thus the following runs have to be performed: (H-V-); (H-V+); (H+V-); (H+V+). The values for each factor level are: H- = 0 Km/h; H+ = 200 Km/h; V- = 1,8288 m/s (6 fps); V+ = 3,048 m/s (10 fps). These values are coherent to the operational envelope of the type of aircraft considered in this paper. The low level of horizontal speed equal to zero Km/h was purposely selected to prove that this factor has no significant effect on energy absorbed for landing gear with trailing arm. The table below shows the quantity of absorbed energy for each run:

Table 1. Runs and correspondents Energy Values.

Run	Energy [J]
H-V-	11853,48
H-V+	31757,68
H+V-	11602,77
H+V+	31761,05

#### 5. RESULTS

In last section, the factorial design method provides all possible combinations between the speeds (treated as factors) to be simulated. Now we will determine the effect (or influence) of each speed on amount of absorbed energy

as well as the interaction between them. Figure below shows drops (runs or factors combinations) and the correspondents quantities of absorbed energy:

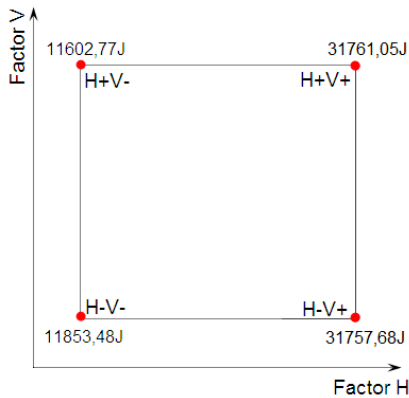


Fig. 7 – Runs and Results

The speeds effects can be obtained as follows:

$$EV = \frac{1}{2}[(H^+V^+ - H^-V^+) + (H^+V^- - H^-V^-)] \quad (7)$$

$$EH = \frac{1}{2}[(H^+V^+ - H^-V^+) + (H^+V^- - H^-V^-)] \quad (8)$$

$$IHV = \frac{1}{2}[(H^+V^+ - H^-V^+) - (H^+V^- - H^-V^-)] \quad (9)$$

Where: EV, EH is the effect of vertical and horizontal speed on absorbed energy respectively and IHV is the interaction between them. Interaction effect measures the influence that one factor exerts on result (absorbed energy) at different levels (lower and higher) of the other factor. Replacing the energy values shown on Fig.7 in equations (1), (2) and (3) we obtain: EV=20031,24 J; EH= -123,67 J and IHV= 127,039 J. These results reveal that the vertical speed (V) has significant influence on amount of absorbed energy while horizontal speed and interaction are small. Plots of force versus piston displacement can confirm these results:

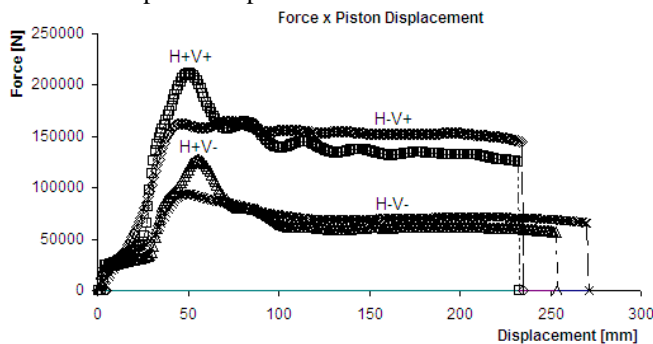


Fig. 8 – Plots of Force versus Piston Displacement

The upper plots (H+V+; H-V+) was obtained by fixing the vertical speed on upper level (V+) and varying the horizontal speed from lower to upper level (H- → H+). Areas under these curves give the amount of absorbed energy for each drop and they are approximately the same. This confirms the small effect of horizontal speed (aircraft speed approach). The lower plots (H+V-; H-V-) show the same behavior but on lower level of vertical speed (V-). It is easy to see that the horizontal speed application (H+) yields

peaks of hydraulic force. To clarify the insignificance effect of horizontal speed on absorbed energy (areas equality) and peaks of force let's understand how this speed is simulated and the drag force action: Aircraft horizontal speed is simulated by applying rotation on wheels during drop test. When a tire with rotation movement hits against ground, friction between tire and ground appears and as tire deflects it acts like spring applying a vertical upward reaction force on wheel axis as shown on Fig.9 in red color:

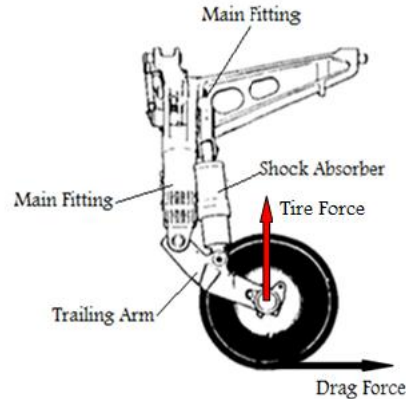


Figure 9. Landing gear with trailing arm [Source: Currey, 1988]

This scenario where friction and vertical tire force act simultaneously leads to occurrence of a horizontal friction force usually called drag force which can be modeled as follows:  $D_f = \mu \cdot F_t$  (Where:  $D_f$ - Drag Force;  $\mu$ - Friction Coefficient and  $F_t$ - Tire Force). Right after the touchdown, the drag force acts by pulling the trailing arm in afterward direction as shown on Fig.9. This load can be divided into two components: 1- One is perpendicular to trailing arm axis; 2- Other one is coincident to trailing arm axis.

Analysis of Perpendicular Component: The perpendicular drag force component causes a torque and makes trailing arm rotates faster and this explains why force on shock absorber reaches larger values with peaks when the wheel speed rotation is applied (the peaks of force are indicated on Fig.8). The faster movement of trailing arm forces the piston against the oil and an amount of energy is dissipated due the flow of oil trough hydraulic orifice (initially the pneumatic force is low). Since the vertical speed (V) still at same level (V- or V+), the initial energy (kinetic energy =  $\frac{1}{2}MV^2$ ) is the same for both drops (with and without horizontal speed application, H+ and H- respectively), but the drop with wheel rotation has an additional energy that is the energy necessary to makes the mass composed of wheels, brakes and tires rotates. As mentioned before this extra energy causes peak of force, it implies that, initially, a larger quantity of energy is dissipated and, thus less energy remains to deflect the shock absorber and this explains why curve goes in lower level after peak force. At the end, areas or quantities of absorbed energy still approximately the same and the difference is the force behavior during strut deflection. The analysis of perpendicular force explains the peak of force and why curve with horizontal speed (H+) goes in lower level, but is not enough to explain the insignificance of horizontal speed on amount of energy absorption.



Analysis of Coincident Component: The force component that acts in coincident direction with trailing arm axis is transmitted directly to main fitting structure through trailing arm. This force yields oscillating movement (forward-and-back) due spring-back and does not cause relevant impact on shock absorber deflection because lower and upper joints allow freely rotation and prevents from bending moment occurrence. This characteristic is important to justify the low effect of horizontal speed (or drag force) on amount of absorbed energy because if bending moment occurs, shock absorber deflection becomes harder due the friction increasing on bearings. To illustrate this, consider the telescopic shock absorber which is frequently used to equip nose landing gear as shown in picture below:

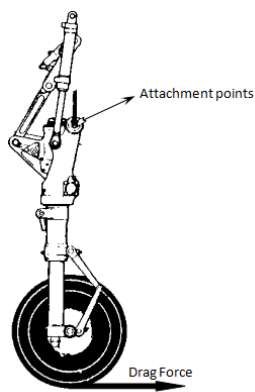


Fig. 10. Telescoping Struts [Source: Currey, 1988]

Note that this type of landing gear is attached to aircraft structure through attachment points and when drag load acts, this landing gear does not avoid bending moment occurrence and thus this moment yields high reactions forces on piston and cylinder bearings. These forces are perpendicular to the bearings sliding surfaces and in conjunction with friction create a resistive drag force which is parallel to piston displacement, has opposite direction and contributes to increase the absorbed energy during shock absorber compression because the piston force becomes higher. The increasing on amount of absorbed energy due the effect of bending moment is not necessary advantage because it increases a friction force component which makes the shock absorber harder and larger loads are transmitted to aircraft structure.

## 6. CONCLUSION

The main objective of this paper is to analyze the horizontal and vertical speeds effects on amount of absorbed energy based on results from drop test simulations. The results (or quantities of absorbed energy) were treated according factorial design  $2^k$  where two factors ( $K=2$ ) has been considered: vertical and horizontal speed. Results reveal that the horizontal speed does not have significant influence on amount of absorbed energy and vertical speed has high effect. The landing gear equipped with trailing arm has been proved to be robust against drag load effect during aircraft landing operation. This strength is due the way that

drag force acts on landing gear structure and also due the freely rotation of shock absorber joints avoiding bending moment occurrence. This advantage makes this type of landing gear adequate to equip midsize jets aircrafts. This paper concentrates on amount of energy absorbed by shock strut, but is important to be aware that despite drag load (or horizontal speed) does not have major affect on the shock strut efficiency, it can be critical for design once it makes the horizontal and vertical loads at attachment points reaches higher levels. More information about the landing gear behavior and drop test experiment will be provided soon in my thesis.

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