HARD LANDING AND REBOUND LANDING LOADS – IFASD 2017

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Abstract: Landing is one of the most critical phases in the aircraft operation, as most of the accidents occur during this manoeuvre. National Transportation Safety Bureau (NTSB) statistics show that more than 40% of aircraft accidents occur during landing manoeuvres, and most of them use to imply a substantial damage for the aircraft and/or the crew/passengers.

During landing, the vertical velocity of an airplane is quickly reduced to zero when the wheels strike the ground. This process is accomplished by a transfer of energy from kinetic energy of the sinking airplane to internal energy in the shock absorption system, where it is dissipated. The vertical velocity of the airplane is brought to zero within a fraction of a second, and hence the forces applied to the structure through shock strut change from zero to a maximum also in a fraction of a second. This rapid change in velocity, or equally in application of force, excites the lower vibration modes of the structure. Therefore, the structural dynamic characteristics of the structure must be taken into account.

Nevertheless, flight test have proved that the assessment of the severity of a landing impact needs to be based not only on sink rate, but also in lift/weight ratio at landing (load factor). According to this fact, there are two scenarios that can make landing manoeuvre particularly critical and severe:

- Hard landing: event in which an aircraft has a controlled landing with a large sink rate
- Rebound landing: event in which the aircraft touches the ground normally, but goes back to the air for 2-3 seconds and then falls again over the ground. This second impact uses to happen with the spoilers deployed and so, with an important decrease of wing lift, making load factor during the second impact around 0.5-0.7g.

This paper presents the continuation of the works performed at Airbus DS Military Transport Aircraft Aeroelasticity and Structural Dynamics department in the last years [1-4]. It will show the methodology to calculate both hard landing and rebound landing, and how these simulations are compared with Flight Test data. It will also prove that sink rate is not the unique relevant parameter in order to assess landing severity.

1 INTRODUCTION

The classic approach to landing loads is based on lift equal to weight (as indicated by Airworthiness Regulations); this in turn suggests that sink rate and weight will be the most relevant parameters to assess landing severity among others (pitch angle, roll angle, forward velocity, flap settings…). Nevertheless, in-service experience has shown that one new parameter is as relevant as sink rate and weight: lift/weight ratio (load factor) at touchdown.

The importance of load factor to assess landing severity can be explained by the appearance of two effects:

- A new term is added to the kinetic energy implying a higher need for energy dissipation in the landing gears. It represents the work of gravity forces along with the vertical displacement of the aircraft centre of gravity during touch-down.
- The reduction of 1G contribution in the wing, making it more feasible to reach down-shear and down-bending limit loads. This is very important, as wing is not the typical component of the aircraft expected to be harmed during landing manoeuvres.

Hard Landing and specially rebound landing loads imply to account for some important challenges:

- Landing gear non-linearity related with its kinematics and with the elastic characteristics of some of its components
- Full coupling of flexible landing gear and flexible aircraft, this will lead to a much more accurate loads calculation.
- “1g-steady flight” will be in reality “1g-quasi-steady flight” and therefore, time-dependant along the rebound manoeuvre. In the first impact it will be roughly around 1g, but the second impact will imply a reduction of load factor that shall be included as the transition from one impact to the other.

This paper will focus on the methodology to accurately calculate dynamic loads for a heavy military transport aircraft in both situations: hard landing and rebound landing. It will also present comparisons between numerical simulation model and flight test measured firm landings, for both loads and accelerations. These experimental data were acquired during a heavy military transport aircraft flight test campaign.

The paper will end with suggestion for further work in this topic, particularly in the possibility of carrying out loads-prediction tools based on statistical techniques that will take advantage of the inclusion of these two parameters (sink rate and load factor) among others (total weight, fuel weight, pitch angle, roll angle, pitch rate…) to provide a quick and accurate load level for each event. It will be very useful for rising early maintenance warnings and might also be used for predictive maintenance, if requested.

2 AIRCRAFT – LANDING GEAR COUPLED MODEL

The desirable starting point is a Ground Vibration Test (GVT)-adjusted structural model (Figure 1). The objective of the GVT is to obtain experimentally the normal modes of the complete aircraft and in particular:

— Frequencies & mode shapes.
— Damping & modal mass.
— Non-linearities.

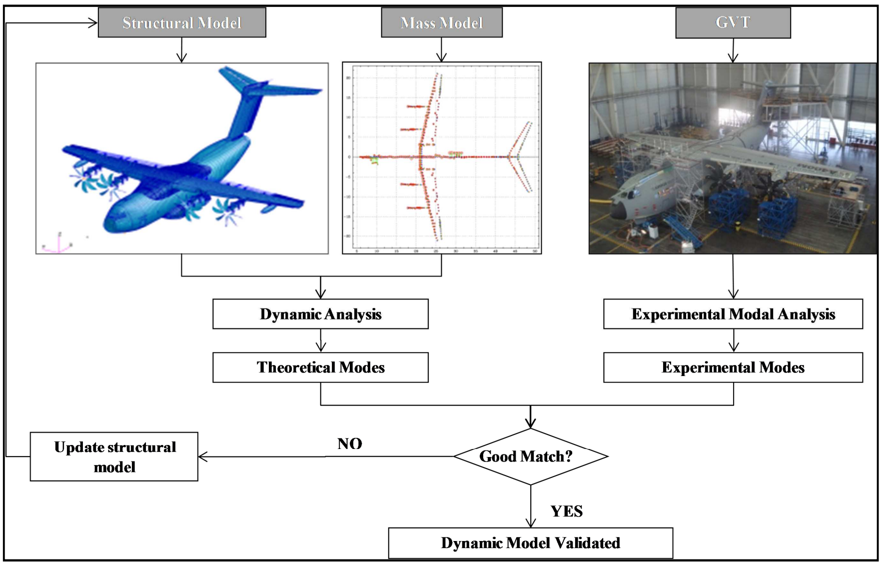

Figure 1: GVT flow-chart

Next step is to account for Landing Gear (LG) non-linearities, which constitute the main difficulty in these loads determination. These non-linearities are related with its kinematics and with the elastic characteristics of some of its components. LG model is tuned through Drop Test and Free Extension Test (Figure 2).

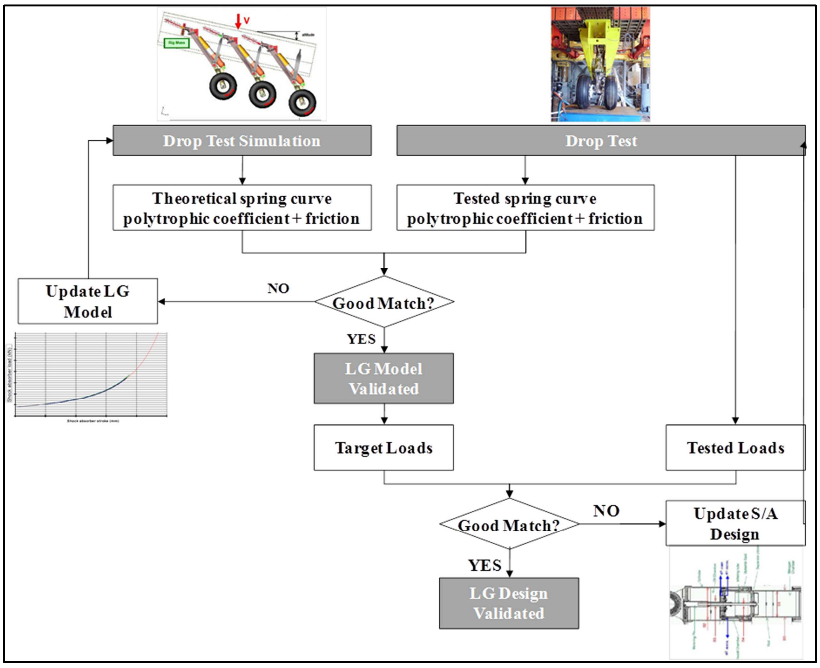

Figure 2: LG model and design validation flow chart

The coupled system of equations that defines the aircraft-landing gear system movement is a non-linear system that should be solved numerically in an iterative process in the time domain. The flexibility of the LG is an essential feature for an accurate determination of Dynamic Landing (DL) loads. During tire “spin-up” the LG bends rearward, followed almost immediately by a “spring-back” in which the LG bends forward.

The problem can be solved either uncoupled (conservative) or coupling the LG with the aircraft (A/C). Airbus D&S is using the modern coupled approach for some years in the A400M design, an aircraft in which dynamic landing cases are sizing large parts of its structure. The approach uses the Finite Element Method (FEM) technique to model completely the L/G, the A/C and the coupling:

— L/G modeled using MSC.ADAMS
— A/C modeled using MSC.NASTRAN
— Coupling using MSC.ADAMS

In order to obtain LG-A/C attachment loads taking into account the A/C flexibility, the appropriate way to introduce the A/C FE model is by using Component Mode Synthesis, a technique to tailor a modal basis to capture both the desired attachment effects and the desired level of A/C dynamic content. The most common CMS technique is Craig-Bampton method ([5]).

Information of Craig-Bampton reduction is contained in an mnf file (provided by MSC.NASTRAN SOL 103). Once the A/C mnf file has been introduced, MSC.ADAMS solves the coupling (non-linearities and mechanisms) and provides the pintle loads. These loads are subsequently introduced to a model of the A/C without the LG model to obtain the modal response of the A/C (DYNRESP). From the modal response, the integrated distribution of internal loads is obtained using in-house software (DYNLOAD).

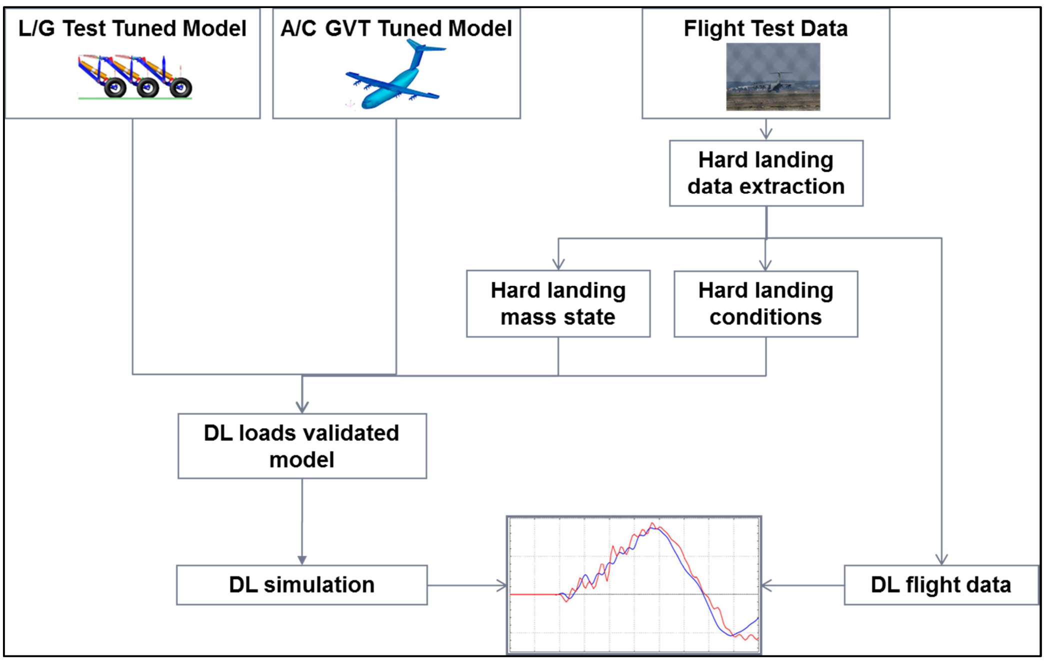

Figure 3: Dynamic Landing validation flow-chart

3 AIRCRAFT INSTRUMENTATION FOR LANDING FLIGHT TEST

3.1 Loads

Different kinds of loads have been monitored among the entire A/C in order to compare the flight tests results with the computed values:

— Integrated loads: The measurements at the extensometers placed along the wing, the fuselage, the HTP and the VTP (Figure 4, red lines) are post processed with the method suggested by Skopinski [5] to obtain the integrated loads (Figure 4).

	FY	FZ	MX	MY	MZ	TOTAL
Wing	-	10	10	10	-	30
Fuselage	3	3	3	3	-	12
HTP	-	2	2	2	-	6
VTP	2	-	2	-	2	6
						54

Table 1: Integrated loads measurements summary

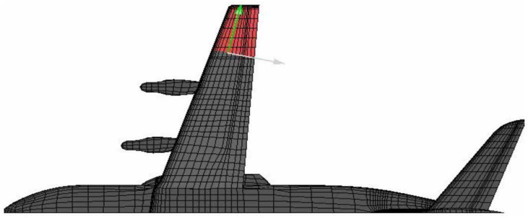

Figure 4: Example of integrated wing load

— Interface loads: 112 magnitudes measured:

	FX	FY	FZ	FXZ	TOTAL
Landing gear to aircraft (pintles)	26	26	26	-	78
Wing to fuselage	4	-	4	4	12
Engine mounting system (EMS) to wing	8	-	8	-	16
Vertical to horizontal tail planes	2	2	2	-	6
					112

Table 2: Interface loads measurements summary

3.2 Accelerometers

In addition to the loads, the 114 accelerometers shown in Figure 5 (green dots) and Table 3: Accelerometers summary have been selected to monitor the behavior of the aircraft during the flight test campaign:

	NX	NY	NZ	TOTAL
Wing	12	-	28	40
Fuselage	6	6	6	18
HTP	6	-	16	22
VTP	4	9	-	13
LG	7	7	7	21
				114

Table 3: Accelerometers summary

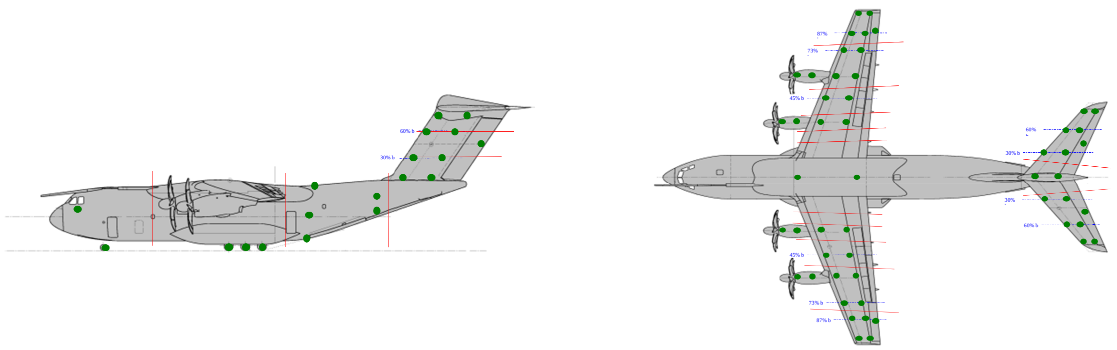

Figure 5: Accelerometers (dots) and loads (lines) recorded during flight tests

4 HARD LANDINGS

4.1 Description

Hard landings or firm landings consist of the action of landing with a high sink rate while keeping the aircraft under control (load factor ~1g). This “high sink rate” depends on the aircraft design; in commercial aircraft use to be fixed it as vz > 10 ft/s, but military aircraft may apply larger figures (for example, in the military transport aircraft of this study it is fixed as vz > 12 ft/s).

These events are particularly suitable for validating Dynamic Landing models because they allow loading the model with high loads and so, assessing how accurate limit load levels are. Figure 6 represents this event.

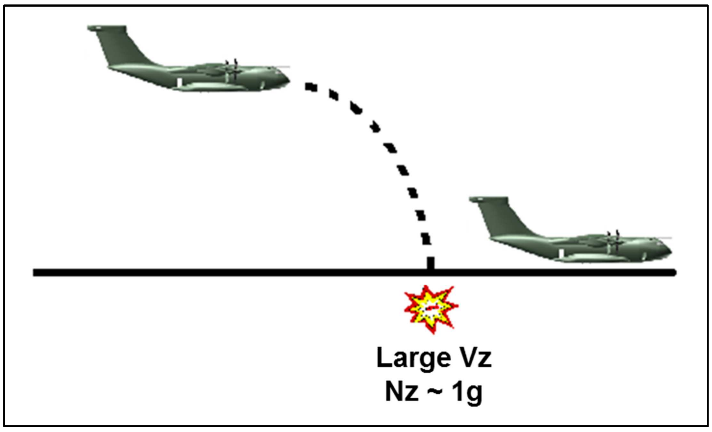

Figure 6: Hard landing sketch

Hard landing events are the typical events easily reported by pilots because the feeling is very clear as the impact is severe. Thus, inspections use to be launched and this means that the aircraft integrity uses to be under control. It is difficult to miss a remarkable event, as the most employed detectors work very well: sink rate or the “delta-Nz” (variation of c.o.g acceleration), which is correlated with sink rate and is much easier to measure.

Fuselage and landing gear are the most affected parts of the structure during these events, as they are the typical aircraft components sized by landing manoeuvre. Of course, the larger sink rate (or delta-Nz) is, more parts of the aircraft will be suspicious of reaching (or exceeding) limit load.

4.2 Hard Landings Simulation

The way to simulate these events consists on running a coupled solution using as input parameters the data obtained from Flight Test (FT) or from pilot report, being the most important ones:

- A/C mass configuration: OWE, fuel and payload distribution. This will make possible to build an accurate modal basis.
- Landing parameters: sink rate, load factor, pitch and roll angles and derivatives…

Both dynamic solution and steady condition can be obtained with those data. Then, incremental loads and 1g ones will be added to obtain total loads.

4.3 Hard Landings FT comparison with numerical simulations

Figure 7 presents the comparison of a hard landing (vz = 11.5 ft/s, nz = 1.2g) simulation incremental loads (in red, called “Sim”) against load measurements obtained during the real event by A/C instrumentation (in blue, called “Test”):

- Top left picture presents the comparison of fuselage shear force loads between simulation and FT data.
- Bottom left picture shows the comparison of fuselage bending moment loads between simulation and FT data.
- Top right picture exhibits the comparison of fuselage shear force loads between simulation and FT data.
- Bottom right picture reveals the comparison of fuselage bending moment loads between simulation and FT data.

As this study is devoted to assess the model goodness to represent landing impact loads, only incremental loads have been considered.

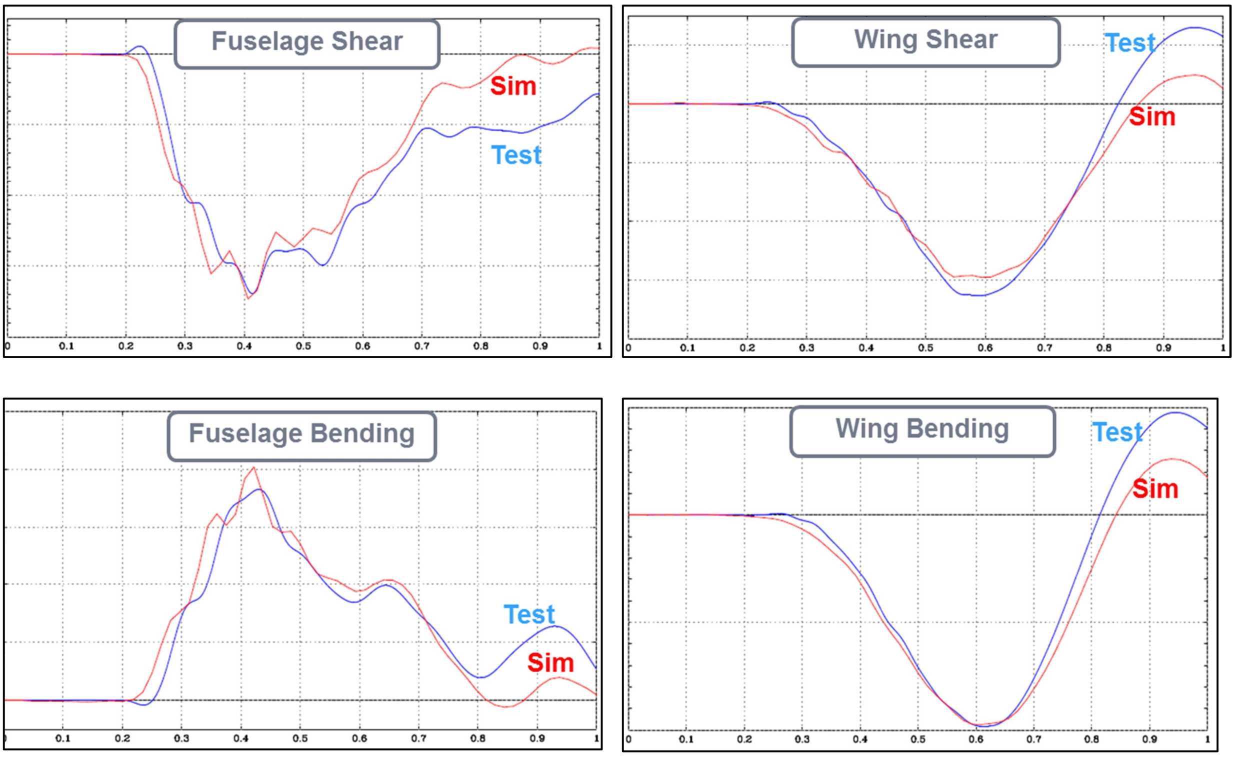

Figure 7: Hard landing results vs FT data

The correlation is excellent in terms of time-history shape and load levels. All these results prove that this fully coupled model dynamic landing model provides very good results and is totally suitable for dynamic landing and hard landing loads calculation.

5 REBOUND LANDINGS
5.1 Description

A rebound landing is a manoeuvre that consists on landing in two steps: the A/C touches down normally and after that, instead of remaining on the ground, the aircraft goes back to the air for 2-3 seconds and hits the ground again. The interesting point in this event is the second impact, as it uses to happen with spoilers deployed (the A/C uses to deploy them when detecting weight on wheel in order to reduce landing distance).

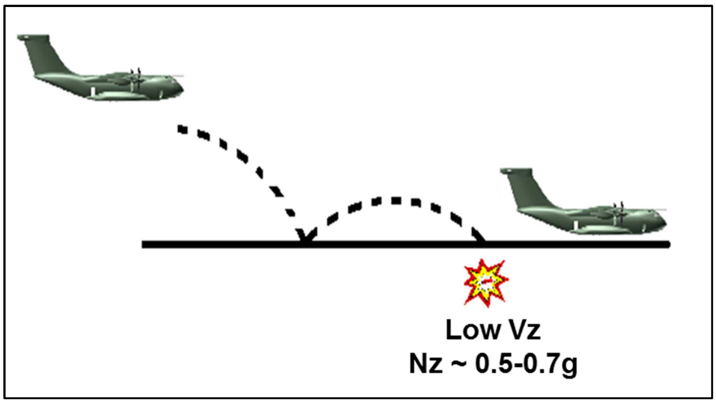

Figure 8: Rebound landing sketch

The fact of going back to air with spoilers on has two implications:

— Lift is smaller than weight in the second impact, and this produces an extra contribution of landing impact kinetic energy that shall be dissipated in the landing gears and absorbed by aircraft structure. It represents the work of gravity forces along with the vertical displacement of the aircraft centre of gravity during touch-down. This behaviour can be seen in Table 4 (based in an aircraft whose baseline case is vz = 12 ft/s & Nz = 1g, whose impact energy represents the 100% in the table).

$$\frac{\Delta E_{impact}}{\Delta E_{cert}} = \frac{\frac{1}{2}mv_z^2 + (1 - N_z)mg\Delta h}{\frac{1}{2}mv_{z0}^2}$$

		Vz (ft/s)										
		5	6	7	8	9	10	11	12	13	14	15
Nz (g)	0.5	66%	76%	87%	99%	113%	128%	144%	162%	181%	201%	223%
	0.6	54%	63%	74%	86%	99%	114%	130%	148%	167%	187%	209%
	0.7	42%	52%	62%	74%	87%	102%	118%	135%	153%	173%	195%
	0.8	32%	41%	51%	63%	76%	90%	105%	122%	141%	160%	181%
	0.9	24%	32%	42%	53%	66%	79%	94%	111%	129%	148%	168%
	1	17%	25%	34%	44%	56%	69%	84%	***100%***	117%	136%	156%
	1.1	12%	19%	27%	37%	48%	61%	75%	90%	107%	125%	145%
	1.2	9%	14%	22%	30%	41%	53%	66%	81%	97%	115%	134%
	1.3	6%	11%	17%	25%	35%	46%	58%	73%	88%	105%	124%
	1.4	4%	8%	13%	20%	29%	40%	52%	65%	80%	97%	115%
	1.5	3%	6%	11%	17%	25%	34%	45%	58%	73%	88%	106%

Table 4: Energy balance between Vz and Nz

— A reduction on lift (roughly 30-50%) and this provokes the second impact occurs with a lack of 1g load on the wing making it more prone to reach wing negative limit load (down-shear & down-bending)

This means that during rebound landings it is more likely to get closer to down-bending limit load even in “apparently” low energy landings. This fact makes these manoeuvres very dangerous; as they are not so easy to be detected by pilots (sink rate is quite smaller than design one) and because the component whose integrity is most affected by these events is the **wing**, as wing loads depend directly on 1g condition (and wing 1g loads change dramatically). This is very important, as wing is not the typical component of the aircraft expected to be harmed during landing manoeuvres.

Figure 9 presents this phenomenon in a rebound landing (vz = 7 ft/s & nz =0.53g) in an aircraft whose design sink rate is 12 ft/s. Rebound loads (red dots) look like having been translated downwards getting really close to down-shear and down-bending limit loads; and this effect is more important, ceteris paribus, as fuel weight in the wing increases.

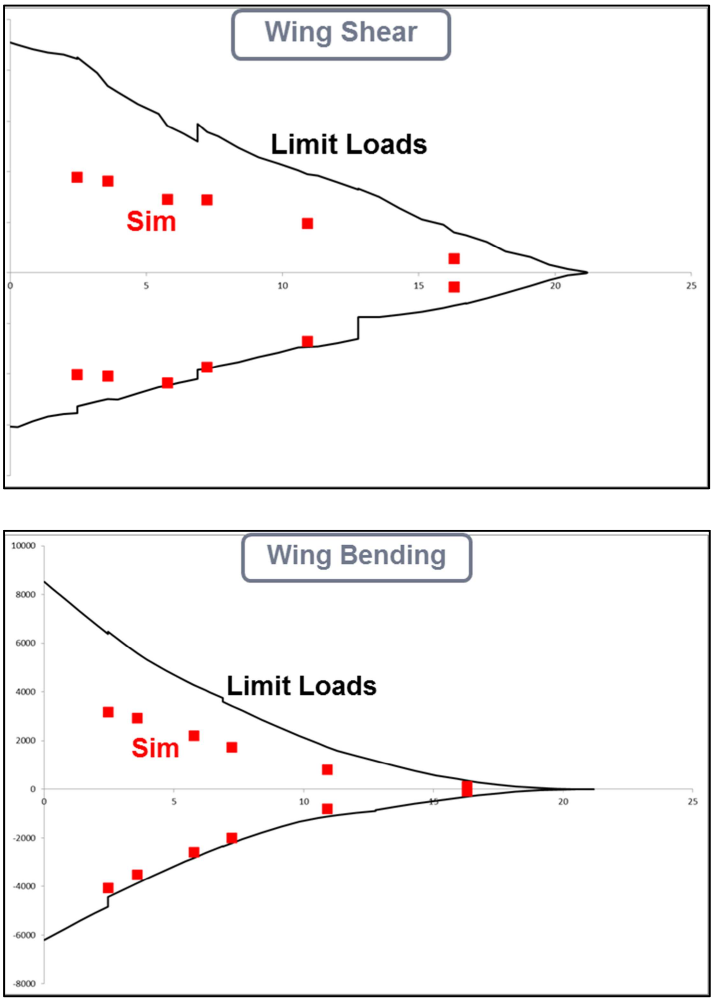

Figure 9: Rebound wing shear & bending loads against Limit Load

5.2 Rebound landings simulation

The way to simulate these events requires composing the two impacts (gathering each impact data, the same as before) in such a way that they happen one after the other leaving in-between the time that the A/C spends in the air:

— Pintle loads: first of all each impact is isolated (vz & nz), next step is to calculate pintle loads of each impact and then build an unique pintle time-history that represents both impacts and the time on the air between them; dynamic solution will be run using this composed pintle time-histories as input loads. Figure 10 shows a typical rebound landing pintle time-history of either Fx, Fy or Fz.

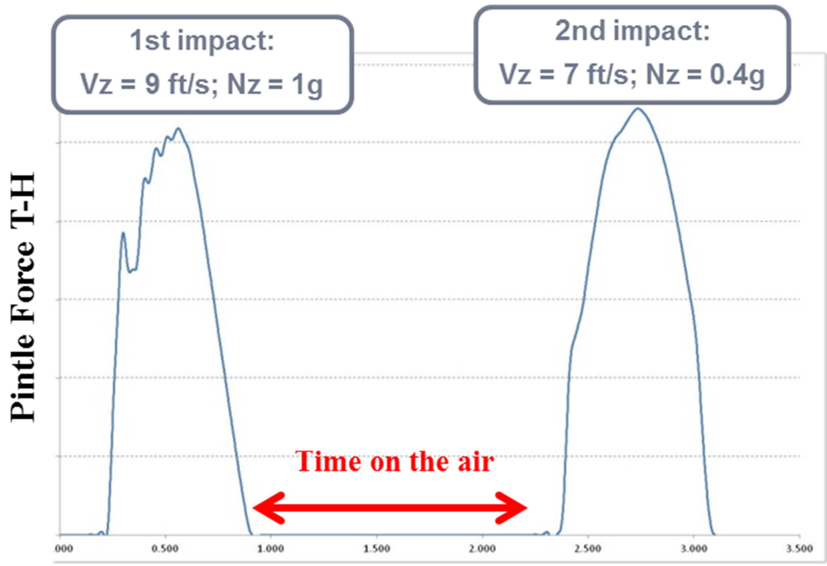

Figure 10: Rebound landing pintle time-history

— 1G loads: in the same way as for pintle loads, 1g condition is calculated for each isolated impact. Then a composed time-history of both 1g conditions is built assigning to each 1g condition the time that each impact lasts; and time between impacts represents a linear variation between both 1g conditions. It is important to remember that this process shall be done for each of the monitor stations analysed. Figure 11 depicts this composition for one wing monitor station.

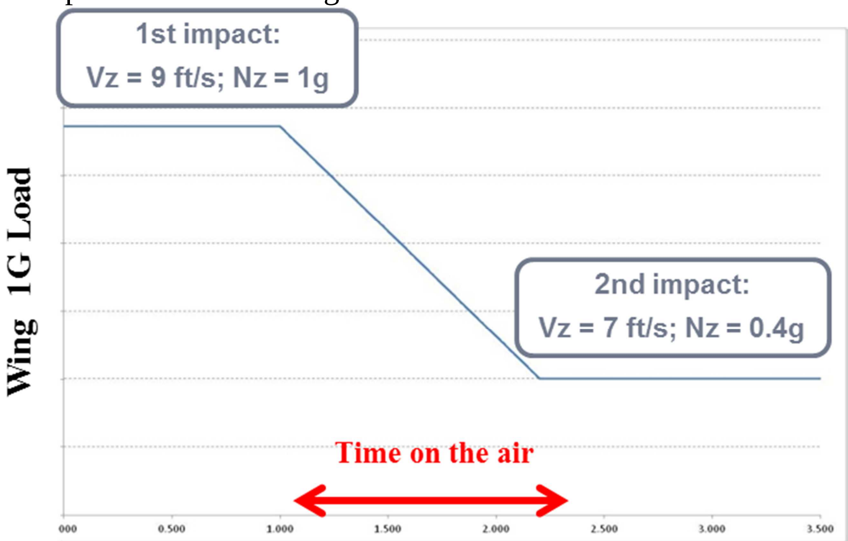

Figure 11: Rebound landing 1g condition time-history

— A/C total response: after having obtained dynamic incremental response with pintle loads composition for each monitoring station, “1g condition time-history” is added in order to obtain aircraft total loads. Note that aircraft free response is accounted for in the “time on the air”.

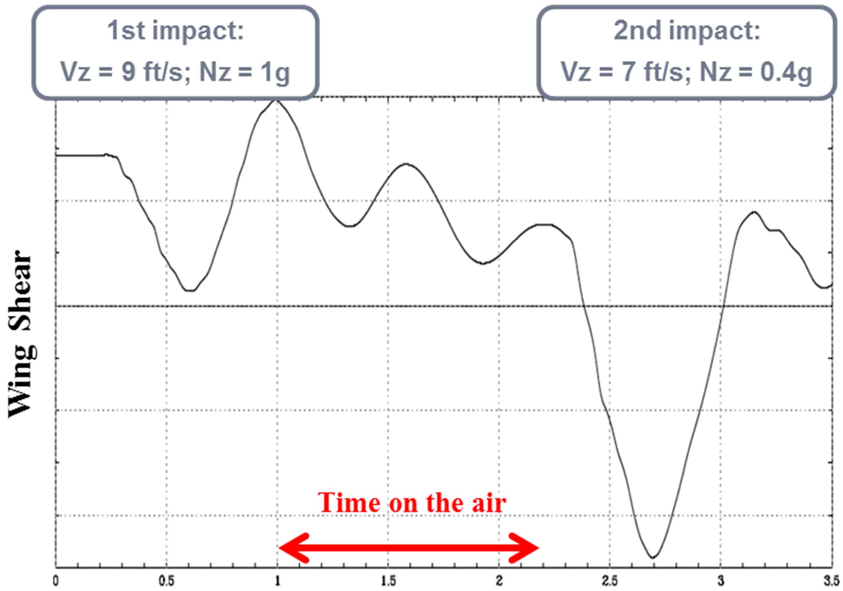

Figure 12: Rebound landing total load

5.3 Rebound landings FT Comparison with numerical simulations

Figure 13 presents the comparison of a hard landing (vz = 11.5 ft/s, nz = 1.2g) simulation total loads (in red, called “Sim”) against load measurements obtained during the real event by A/C instrumentation (in black, called “Test”). This analysis is devoted to wing loads, the ones more likely to be affected by this phenomenon:

- Top left picture presents the comparison of inner wing shear force loads between rebound landing simulation and FT data.
- Middle left picture shows the comparison of inner wing bending moment loads between rebound landing simulation and FT data.
- Top right picture exhibits the comparison of outer wing shear force loads between rebound landing simulation and FT data.
- Middle right picture reveals the comparison of outer wing bending moment loads between rebound landing simulation and FT data.
- Bottom picture makes known the comparison of outer wing vertical acceleration between rebound landing simulation and FT data.

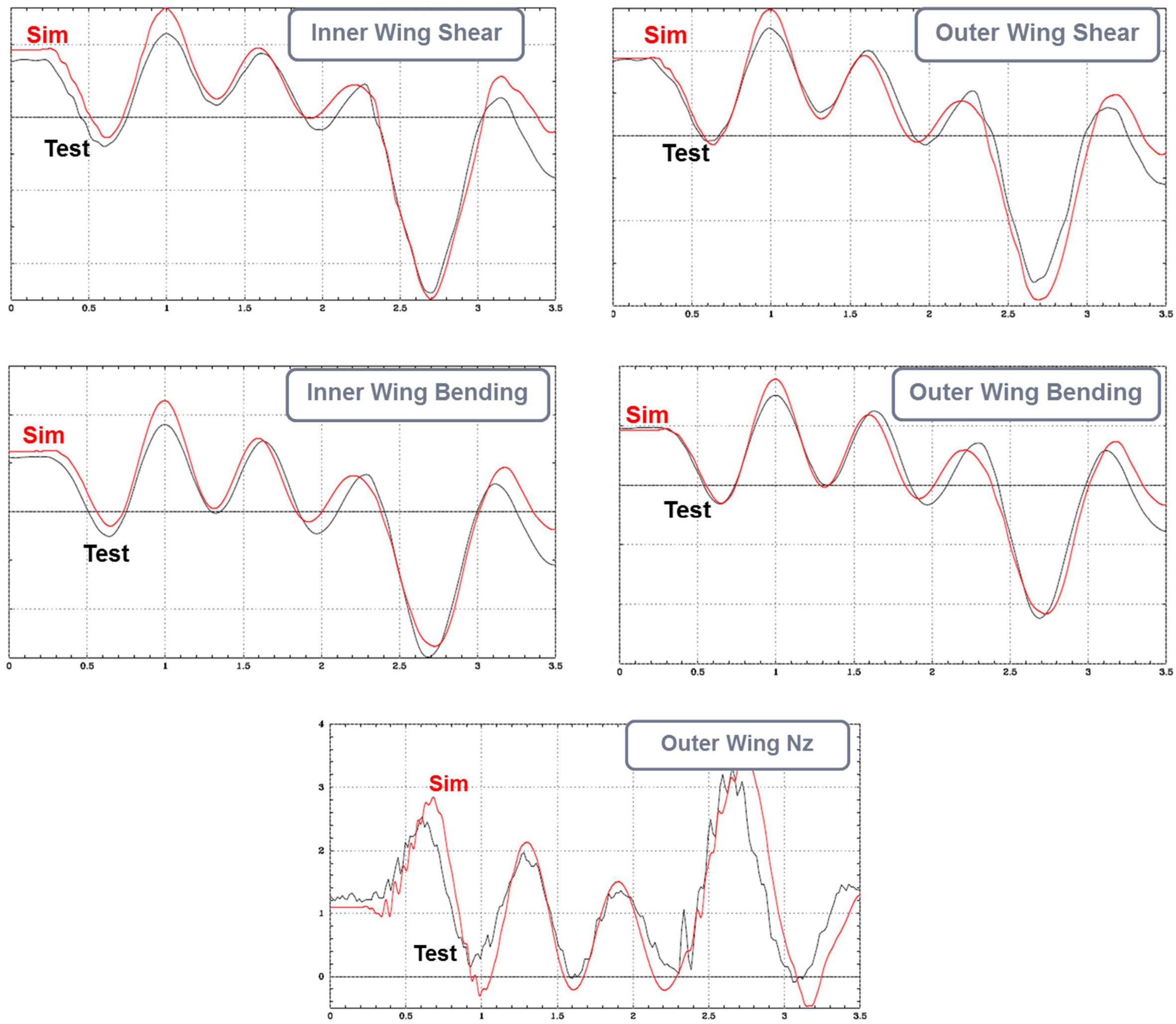

Figure 13: Rebound landing results vs FT data

These results prove two facts:

- The feasibility and accuracy of this methodology to calculate rebound landing loads
- The behaviour of wing negative peak loads, which result to be clearly than positive ones.

6 USAGE OF DIGITALIZATION FOR LANDING SEVERITY ASSESSMENT

After having assessed the importance of sink rate (delta-Nz) and load factor in landing loads, it is also possible to move forward and research on the relative importance of other landing parameters:

— Fuel weight
— Aircraft weight
— Pitch angle
— Roll angle

The target component for this analysis is mainly the wing, as the rest of components are, either strongly sized by sink rate and load factor (fuselage, landing gear and engines) or widely covered by other flight static and dynamic loads (tails). Using quite a fine mesh, roughly 100000 cases have been run modifying these parameters.

Current state-of-the-art of mathematical and statistical theories provide a wide variety of tools that would make this study feasible. From pure multi-variable interpolation to complex Big Data / Data Mining methodologies (Bayesian methods, genetic algorithms, neural networks, clustering, segmentation…) , there are many different possibilities as explained in [7].

As an advance, Figure 14 presents the trends of limit load percentage achieved by varying each one the four (ceteris paribus) parameters studied.

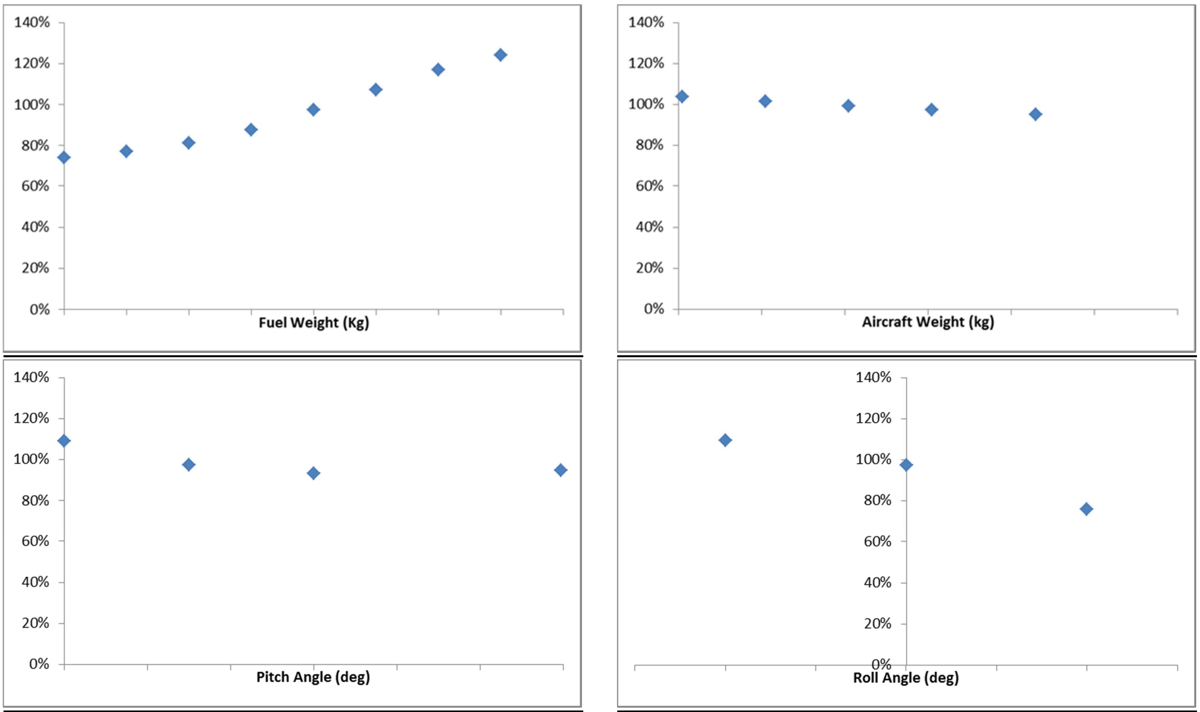

Figure 14: Landing wing loads dependence woth other parameters

Fuel Weight. As expected, the larger this parameter is, ceteris paribus, the higher wing loads are obtained. This is provoked by the increase of wing weight that implies a more negative 1g condition shear and bending and also a larger inertia down; these two effects take loads closer to limit load as fuel weight increases

Aircraft Weight. This parameter provides a surprising conclusion, as wing loads slightly decrease as total aircraft weight increases if the rest of parameters (and specially, fuel weight) remain constant. This is provoked by the increase of fuselage inertia (where loads will increase) whereas wing inertia remains the same.

Pitch Angle. This parameter does not affect much to wing loads, but highest loads are provided by lowest angles.

Roll Angle. This parameter is important for wing loads of the side that touches the ground first, that see their loads increased.

7 CONCLUDING REMARKS AND FUTURE WORK

Looking at the tendencies shown by this severity assessment it seems useful to build a quick response loads estimation tool based on all the data available. This tool would be very useful for aircraft manufacturers in many areas:

- Predictable maintenance
- Life-time monitoring systems
- Reduce lead times of possible re-design loads calculation loops…
- Improve customer experience by reducing time to manage in-service events.

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