Dynamic approach to cargo and barrel design and analysis – Simulation and testing

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Abstract

There is an increasing demand in aerospace industry for more and more efficient aircrafts to fulfil economical and ecological requirements. A way to satisfy these requirements is to optimize structure design loads based on a more precise physical understanding of an Aircraft (A/C) and its dynamics. Optimized design solutions can often be realized using dynamic load approaches instead of static load approaches. The focus of this paper is to investigate the dynamic behaviour of an a/c structure and cabin & cargo equipment and their interrelations. An extensible test and simulation approach was built up along a typical example, i.e. the challenge for future aircrafts to demonstrate the usability of standard Unit Load Devices (ULDs), i.e. containers and pallets, in spite of calculated high dynamic accelerations to optimize the Cargo Loading System (CLS) and to avoid cargo weight limitations. The existing design criteria were challenged based on a better understanding of the impact process and interface loads on CLS. Two different aspects have been investigated in detail for an optimized CLS design.

1. INTEGRITY OF STANDARD UNIT LOAD DEVICES

Standard ULDs are in use worldwide and aircrafts have to be able to transport them. These ULDs are statically designed for up to 1.5g ultimate in lateral direction. Design load factors of future aircrafts might exceed these levels and call for a specific confirmation to allow the transportation of these standard ULDs. The static lateral ULD design considers just the total cargo mass. Assuming that probably only a part of the total mass acts on the ULD housing sides, ULDs are able to sustain more than the specified quasistatic loads. The integrity of standard ULDs like shown in Figure 1 was confirmed by a shaker test campaign by taking the dynamic effects due to moving loading into account.

Figure 1: ULD Shaker Test campaign has been performed on a six-axis shaker table at ESTEC, Noordwijk (NL).

2. DESIGN LOADS ON CARGO LOADING SYSTEM OWING TO DESIGN LOAD FACTORS

ULDs are attached with latches to the aircraft floor. They are accelerated within defined gaps between ULDs and latches to a maximum impact speed owing to dynamic flight- and ground manoeuvres. Based on simulated acceleration vs time characteristics, the initial ULD speeds can be calculated by worstcase assumptions. These impact speeds result in high CLS and structural loads due to impact loads and are key for the CLS design load levels.

3. INTEGRITY TESTS OF STANDARD ULDS

3.1.1. Motivation

Keeping in mind the idea of a second order spring-mass-damper model for the overall ULD and cargo system, the influences of

- gaps between an ULD and the latches,
- gaps between an ULD and its loading,
- loading friction and
- pre-stress

have notable effects on the loads level. These nonlinear dynamic effects have to be considered in a reasonable simulation. These effects influence significantly the system dynamics and often yield reduced loads levels compared to the quasi-static levels.

Maximum possible ULD and loading deflections were calculated by double integration of simulated acceleration time histories with respect to time. These possible deflections were just a few centimeters in contrast to the result of adding up all single gaps between the different loading components. It was assumed, that only a part of the total loading mass, the virtual mass, would act directly on the ULD via the housing sides or straps.

Figure 2 demonstrates the physical phenomenon of the virtual mass. Just parts of a cargo mutually touch owing to a sideward acceleration. Before the remaining cargo touches, the motion direction reverts and accelerates the cargo to the opposite side. Only the cargo partly in contact with the ULD side affects the ULD side. Thus, ULDs should be able to sustain higher dynamic load factors than they have been statically certified for.

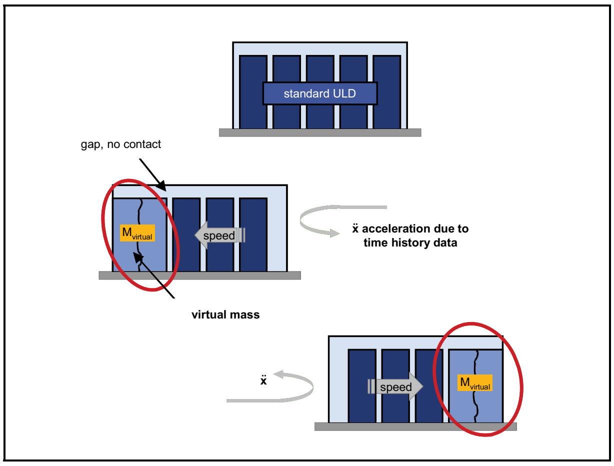

Figure 2: Virtual mass effect

3.1.2. ULD shaker test

Future aircraft certification requests a demonstration of the described theoretical assumption. With respect to time, effort and costs, an ULD Shaker Test campaign has been performed on a six-axis shaker table at ESTEC (European Space Research & Technology Centre in Noordwijk, NL). The total mass of the test unit was approximately 3 tonnes. The maximum test acceleration was 4.5g in a frequency range between 1 and 15Hz.

Several tests have been performed with frangible and also rigid cargo. Frangible cargo is defined as cargo with energy absorption potential. In contrast with rigid cargo, which has the property of being quite stiff without notable inner friction? Thousands of loading configurations consisting of all permutations in view of ULD sizes and types can be imagined for a realis tic freighter aircraft cargo loading. Nevertheless, only a manageable number of configurations representing all worst-case scenarios could be considered.

Figure 3 shows some tested cargo combinations, which cover all critical cargo types for a freighter. Only rigid cargo, fixed on a pallet via screws or welding without any gaps, would have the same effect as a single mass. No benefit could be expected for that really rarely flown cargo configuration.

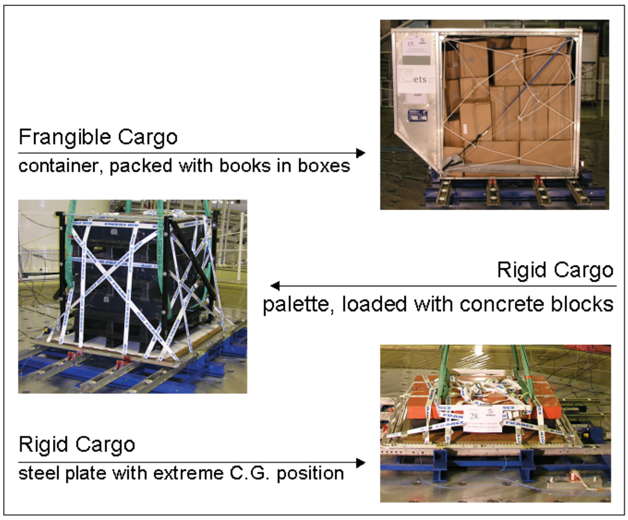

Figure 3: Examples for tested frangible and hard mounted cargo types

The six-axis shaker has been excited by several varied acceleration time history sequences in lateral x- and y-directions. All sequences were based on time history data sets simulated by Nastran FEM (Finite Element Method) model and represented critical dynamic flight and landing cases.

The test campaign had to cover the overall dynamic aircraft behavior and requested for a robust data set, which covered all critical accelerations over the whole fuselage. The impact velocities for x- and y-directions have been defined individually based on acceleration time history data for critical envelope flight and landing cases provided by Loads & Aeroelastics domain teams in Germany and France (Figure 4 and Figure 5).

The time of these data have been multiplied by times 0.5 up to 1.5 (see Figure 4). These frequency variations resulted in robust acceleration time history data sets and covered all possible aircraft responses due to flight and ground cases.

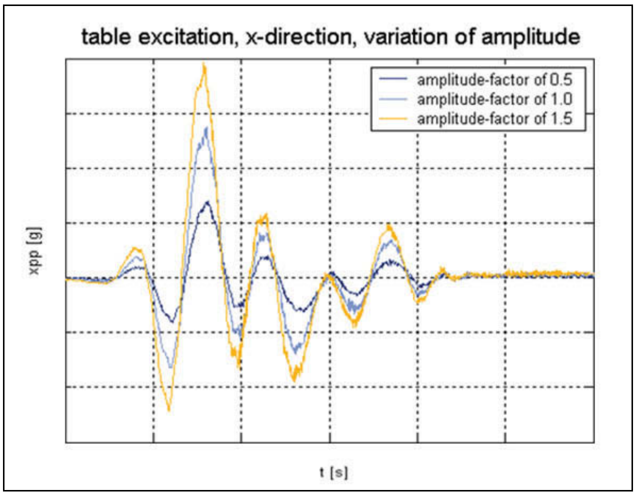

Figure 4: Variation of amplitude of an acceleration time history example

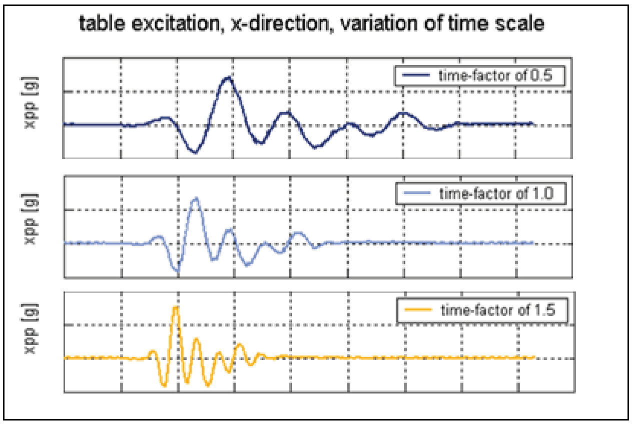

Figure 5: Variation of frequency of an acceleration time history example

Containers and pallets were located on standard floor roller tracks and fixed by latches. The roller tracks have been mounted onto the shaker table via a stiff frame. Calibrated Piezo-Electric (PE) load sensors have been used as measurement devices as shown in Figure 6. These sensors were integrated in individual measurement latches. ULD impact velocities have been derived from deflections based on history data integrations measured by optical sensors.

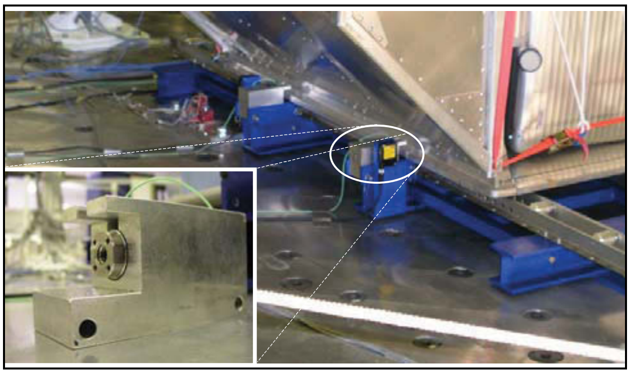

Figure 6: Measurement devices, load and distance sensors

3.1.3. Test Results of the ULD shaker test campaign

The analysis of the high-speed movies confirmed the expected cargo-moving phenomenon for frangible cargo. Inertia masses of frangible cardboard boxes and static friction loads between several boxes reduced their relative movements to a minimum. Moreover, no deflection was detectable for freestanding boxes. In addition the test campaign also demonstrated the cargo-moving phenomenon for rigid cargo softly mounted with straps. The high-speed movies attested also relative movements for soft mounted cargo and their ULDs. The elongation of standard straps allowed small relative displacements between ULD and loading and resulted in two lower load peaks instead of one high load.

3.1.4. Physical effects

Objectives of the test campaign were to get a better understanding of the cargo behavior owing to floor excitations and to get measurement data allowing to identify all critical simulation parameters. All physical effects have to be represented by the simulation and are the basis for reliable loads. The load progression pictured in Figure 7 is separated into different phases during an ULD impact on a latch. One phase is owing to the ULD impact and the other is affected by the loading interaction. Scenario 1 shows the cargo with its specific impact speed just before the impact. The impact speed could be caused by flight or ground maneuvers or by handling during loading on ground.

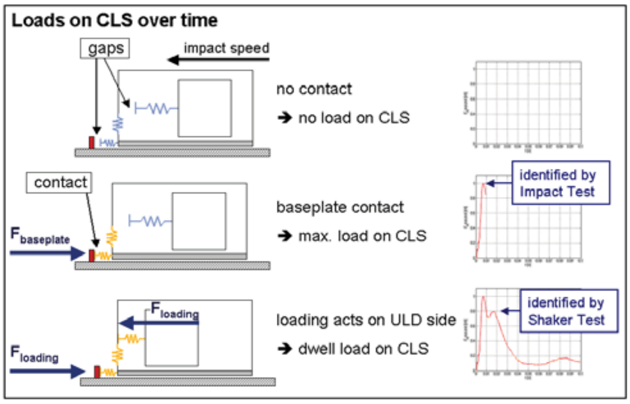

Figure 7: Different phases during an ULD impact on a latch

Scenario 2 pictures the first impact of the ULD onto the latch. Velocities between ULD and loading are significantly different now, the ULD strongly decelerates while the loading velocity is comparable to Scenario 1. Only the ULD interacts directly with the latch and affects a load highly depending from ULD stiffness and damping. Loading has no contact to the ULD at this time and takes only minor effect on the latch load via the friction between loading and base-plate. The load curve already exceeds its maximum level in that example. The monotony load decrease indicates a spring-back tendency of the ULD.

The ULD itself behaves like a very stiff spring. The energy absorption is low in this phase. Scenario 3 represents the last phase. The ULD spring-back tendency is abruptly stopped, when the loading reaches the ULD side and pushes the ULD back to the latch. ULD and loading take effect onto the latch load in equal measure. Their kinetic energies are absorbed over a longer duration time compared to the first phase. This longer duration time is represented by the corresponding load curve on the right lower figure side.

The analysis of the test data indicated, that dynamic loads on a cargo loading system differ significantly compared to the quasi-static load assumption. For standard cargo the dynamic loads are often lower than the static loads for typical flight and ground scenarios. Only really rarely flown rigid cargo, hardly mounted on ULDs like aircraft engines, rigidly fixed onto their pallets and could result in significantly higher dynamic loads compared to static ones. These high loads would be strongly affected by the stiffness and single mass characteristics of such hard mounted cargo. For standard cargo the measured loads seem to be always lower than the static equivalent loads. Additional investigations were launched to build up a simulation model to get optimized CLS design loads.

Figure 8 pictures the influence of ULD loading weight variations on dynamic CLS load levels. Tests and analysis show that empty ULDs significantly affect CLS load levels, effects owing to also much higher loading weights are low. In the given example the empty ULD with a tare weight (empty ULD weight) of 250kg affected the load levels up to approximately 75%. Multiplying the loading weight by twenty times the tare weight caused only 25% increase of the CLS load levels. This phenomenon is explained by the high stiffness characteristics of standard ULDs and was not considered in the traditional design process up to now.

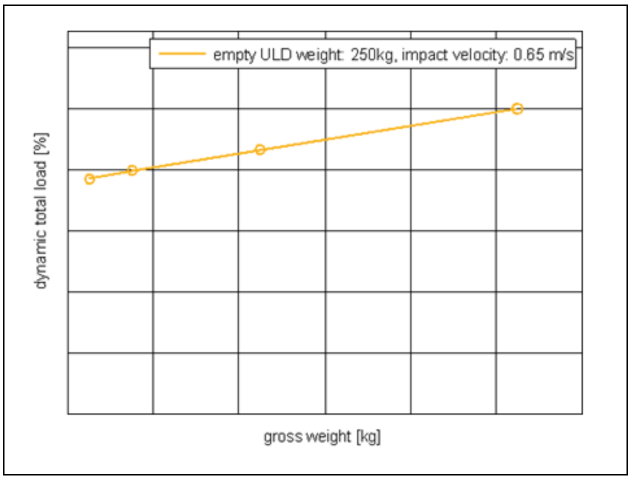

Figure 8: Influence of ULD loading weight on dynamic CLS load levels

Based on the above, the benefit of cargo weight limitation as often done in the past has a minor effect on the dynamic loads level. This phenomenon resulted in new cargo limitation philosophies. Although they can often be avoided, limitations for maximal ULD weights are necessary. It has been shown, that these ULD tare weight limitations are much higher than standard and also non-standard ULD tare weights for the most cases. These minor limitations are accepted by airlines.

3.1.5. Optimized dynamic design loads for CLS

The next step aimed at building up a theoretical model based on the investigated effects. Critical parameters were identified based on measurement data and validated by the simulation model. The simulation model should consider all identified physical effects to provide reliable dynamic CLS loads. Justification of a Cargo Loading System has to cover all relevant loads as quasi-static loads, dynamic loads, handling loads and failure cases. Handling loads are also driven by dynamic impact loads and are a subgroup of them based on different initial parameters.

The traditional CLS design process did not separate between static and dynamic load factors and considered the envelope load factors only in a static approach. This method covered also all critical loads but provided very conservative loads. This process led to a heavy design and payload limitations. The new dynamic approach requested an envelope data separation of static and dynamic load factors compared to the traditional process as given in Figure 9. It allowed to calculate static and dynamic loads in different manners and yielded reasonable loads for an optimized CLS design.

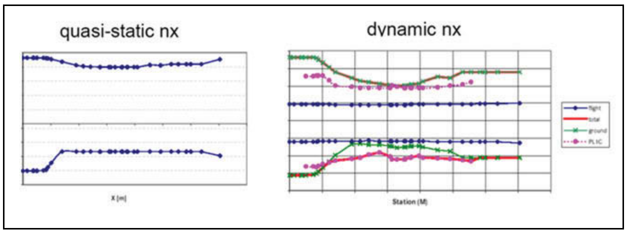

Figure 9: Example of an envelope separated into static and dynamic load factors

Figure 10 shows the reduced-order simulation model. It basically consists of a module-oriented five mass-spring-damper system. Two different sub-models for frangible and rigid cargo characterize the loading model. These sub-models assume the same critical cargo configurations as used for the ULD shaker test. Different stiffness and damping characteristics have been identified by specific tests, the floor parameters are based on an FEM Nastran model data. The results are validated by different tests shown in Figure 9.

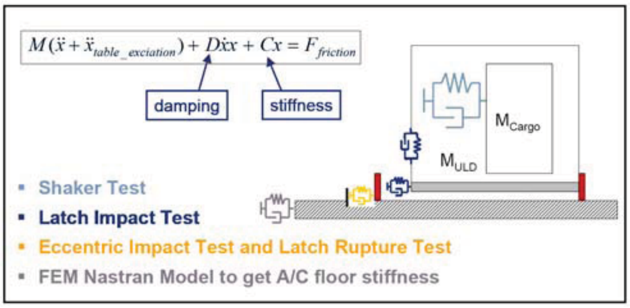

Figure 10: Reduced order simulation model for CLS – cargo interaction (color coding of the symbols correspond to the spring and damper resp.)

The simulation is based on the ordinary differential equation (ODE) for nonlinear, plastic system behavior and has been implemented in Matlab/Simulink with a focus on module-oriented and user-friendly structures. Energy dissipations for ULD and loading are hysteresis processes due to yielding or plastic straining of materials. A rational approach to represent such damping characteristics is defined by the product of deformation speeds and elastic deformations, which is an extension of the classical ordinary damping term of the ODE. In addition the ODE extension provides more realistic damping load increases during the first time steps for impact simulations.

Figure 11 shows the implementation of such differential equation in Simulink. The program structure is similar to an analog ODE solver with a module-oriented flexible description. The advantage of this description is in particular the transfer of specific physically based equations in clear Matlab command code instead of equation breakdown in many graphical Simulink blocks and particularly the determining the degree-of-freedom. This flexible implementation is valid for all kinds of technical problems, which can be described by ODEs, from one spring-mass model through highly complex and fully nonlinear models.

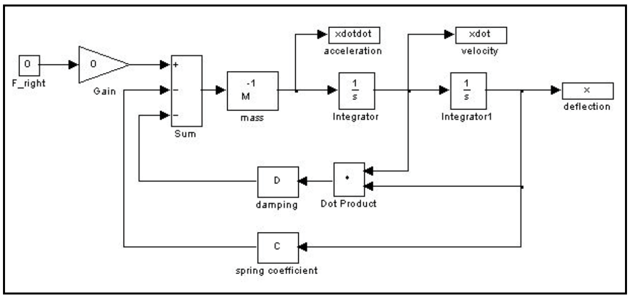

Figure 5: Matlab / Simulink implementation of an analog differentiator

The simulation model is excited by the individual cargo impact speed introduced by initial simulation conditions and states. Impact velocities for x- and y-directions have been defined individually for different fuselage locations. CLS design loads have to cover all critical dynamic loads and requested for a robust initial data set. This request has been accomplished by varying amplitude and frequency of the acceleration histories already described in the ULD Shaker Test Chapter above.

Different impact velocities for x- and ydirections and also for the different cargo compartment sections in the aircraft led to more reasonable and reduced CLS load levels. Figure 12 provides an example for individual impact velocities for the two compartments separated by aircraft center section. The lowest impact velocity is limited by the maximum Power Drive Unit (PDU) velocity for automatic cargo loadmanagement in a freighter.

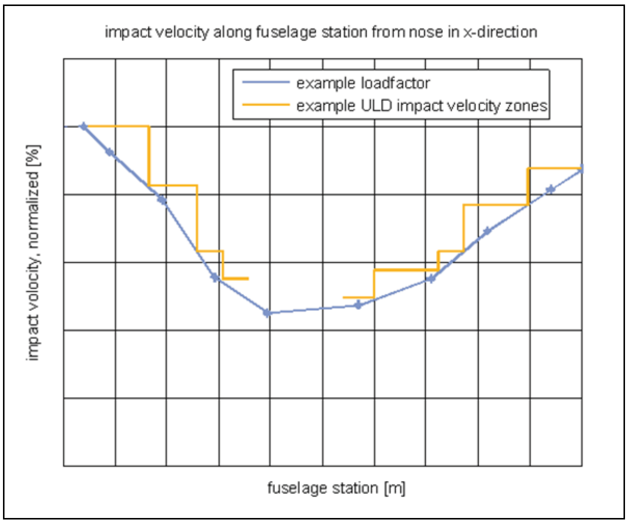

Figure 12: Typical impact velocities along the fuselage for the two cargo compartments

Hundreds of different measurement data sets for several different ULD types and payloads have been collected during the different test campaigns. The simulation model has been validated for the most critical one and provided for most cases very reasonable results within a 10% tolerance level. Simulated load levels for initial conditions outside of typical working points are mostly higher than the measured loads to be conservative in any case. Figure 13 pictures two comparisons between measured and simulated loads for different ULD types. The tolerances of these examples are quite good and represented typical deviations for typical impact velocity levels based on flight and ground scenarios and ULD handling. The validation of the simulation model confirms the reliability of load levels for an optimized CLS design.

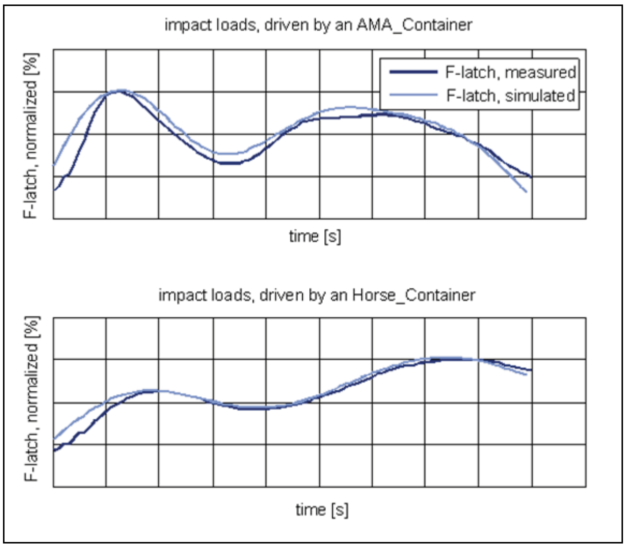

Figure 13: Example for impact load comparison for two different container types

4. CONCLUSION AND OUTLOOK

The ULD Shaker Test results showed that all kinds of ULDs specified in NAS3610 (National Aerospace Standard) cover significantly higher dynamic load factors in the critical frequency range than the static load factors they are certified for. The investigation into the dynamic properties of the Cargo Loading System substantially improved the understanding regarding the physical effects of cargo movement inside an aircraft.

A simulation model was built up that includes all identified physical effects and critical parameters and validated the simulation based on test data. The main benefits of the new dynamic CLS approach are an increase of revenue by avoiding payload limitations for the airlines as well as the reduced CLS latch loads resulting into weight savings. Minor critical limitations of ULD tare weight as well as hard mounted cargo are accepted by airlines.

The combined dynamic simulation and test approach has been set up in such a manner that it can be easily extended to other substructures of an aircraft barrel.

5. ACKNOWLEDGEMENT

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6. REFERENCES

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