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Aircraft Weapon Integration
A Structural View

Wolfgang Luber[1]
wgl-dynamics
Munich, Germany

ABSTRACT

The approach to prove structural integrity on military aircraft with external and internal stores focus on the understanding of the fundamental structural mechanisms – dynamic and static loads - involved and the identification of boundaries for all potential store loading up to the design limit of the aircraft. The integration of a store or weapon with a combat aircraft brings up a complex system engineering problem, which have to be described in an integration process.

This report gives an overview to the subject of weapons compatibility and integration, primarily from the viewpoint of mechanical integration, and explores the structure system integration.

A structured top-down approach is essential for proving store compatibility. However, for weapons integration, the requirements of structural dynamics (aeroelasticity, aeroservoelasticity), aeromechanical and loads aspects must be included. In particular these are carriage life, desired release envelope, the number of weapons that can be carried, influences of other stores and store types in captive flight and separation to be carried on the same sortie, and so on. The report outlines the basic engineering process employed in a typical weapons integration program. This includes the definition of a set of requirements to the route of qualification and certification. The required analytical work and the required tests for verification are described; and the route to certification is discussed

INTRODUCTION

The integration process in general is used to transform components of the design into the desired end products through assembly and integration of lower level components and engineering fields. Each engineering field will have undergone its own proving programme to ensure that it meets its specification. This is likely to include software testing, structural analysis and ground as well as flight testing. Ground and flight testing includes also a level of environmental testing to ensure the aircraft and the integrated store structure e.g. its full specified temperature range. At the end the integration testing has to ensure that the component software and hardware operates as required.

The layout of military aircraft structures is strongly influenced by dynamic and static loads from the early development phase onwards up to final design and clearance phase. Different dynamic and static loads have to be considered, namely manoeuvre loads, dynamic gust loads, buffet loads on wing, fin, fuselage also buffet loads from airbrakes, cavities and blisters, gunfire loads mainly at attachment frames and panels, Hammer shock loads for air intake, bird strike and ammunition impact, acoustic loads for outer air intake and missile bays. Also dynamic loads from landing, jettison, brake chute and rough runway induced loads as well as induced loads due to wake penetration of flying behind an aircraft, may be designing the aircraft structure. Dynamic loads resulting from flight test

[1]Former Chiefengineer at Airbus Defence and Space,Lecturer for Aeroelasticity at Technical University Munich
Email: wolfgang.luber@live.de

excitation like bunker input, stick jerks and control surface sweeps also have to be considered and static loads due to manoeuvre of the Aircraft.

For some of the designing loads examples are given to explain their derivation and significance both for design of aircraft structural parts and related clearance aspects. Methods to derive design loads for different application by using analytical and experimental tools will be discussed.

Validation methods for various design loads using different dynamic model test results, wind tunnel model and flight test results are mentioned.

Main purpose of this presentation is to indicate where dynamic and static loads would be dimensioning structures of high performance combat airplanes with external stores and how to approach the problem of integrating all aspects into the airworthiness and clearance process.

For instants, flutter and aeroservoelastic certification of an aircraft which is required to carry many different types of external stores is general a highly complex and tedious task. The most aircraft operate in the transonic flight regime and carry large under wing and fuselage stores. Due to store separation during aircraft flying a sortie, the clearance of the aircraft must also include asymmetric store configurations.

In aircraft development a limited number of specific stores (baseline configuration) and of additional store loading (key-configuration) will be certificate to the aircraft weapon system specification. At the ends of the program development phase or when the Aircraft is in service an additional loading (follow-on stores) must be cleared with minimally engineering resources and in the presence of minimum cost normally in a constraint time.

The table 1 below shows the different source of loading and the affected components. The component affected is divided into external store itself and in the Aircraft structure. As we can see most of the different loadings influence the Aircraft structure and the external store structure and both together. In this report mainly the loading cases explained for the consideration of the Aircraft with external stores. In case of store release during a sortie the aircraft will have in some cases an asymmetric weapon carriage. For landing impact asymmetric landing with or without cross wind is in most cases a real challenge. The Structure department must analyze each of these cases for save handling of the aircraft on ground and airborne.

	Store			**Aircraft Structure**				
Components affected / **Source of Loading**	**Store**	**Pylon**	**Attachment**	**Wing**	**Fin**	**Foreplane / Tailplane**	**Fuselage**	**Pilot**
Atmospheric Turbulence Gust	X	X	X	X	X	X	X	X
Buffet / Buffeting / Buzz	X	X	X	X	X	X	X	X
Landing impact, Ground Operations	X	X	X	X	X	X	X	X
Bird strike	X	X	X	X	X	X	X	
Store Release & Jettison		X	X	X			X	
Missile Firing		X	X	X				
Flight Manoeuvre	X	X	X	X	X	X	X	X

Table 1: Source of loading vs component affected

METHOD

The generic terms of any mission payload carried on an external pylon or an internal bay on a non-permanent basis is a “store”. The family of stores includes weapons, fuel tanks, countermeasure pods, chaff flare pods, missiles and so on. Whilst many of the stores would only be released (jettisoned) from aircraft under emergency conditions (e.g. in the event of engine failure during flight or take off, for fast escaping an enemy aircraft …), weapons are designed to be released as a matter of course.

For all different stores and combinations, the aircraft with external and internal stores need a structural Clearance, a route to certification. In the next flowchart, figure 1, in principal a typical Loads clearance document tree is depicted. This is a loads top-down approach for the route to airworthiness. Similar tries for other involved engineering disciplines have to written in view of external store integration on combat aircraft. It is important that the System Requirements and the Methods of Qualification are clearly defined.

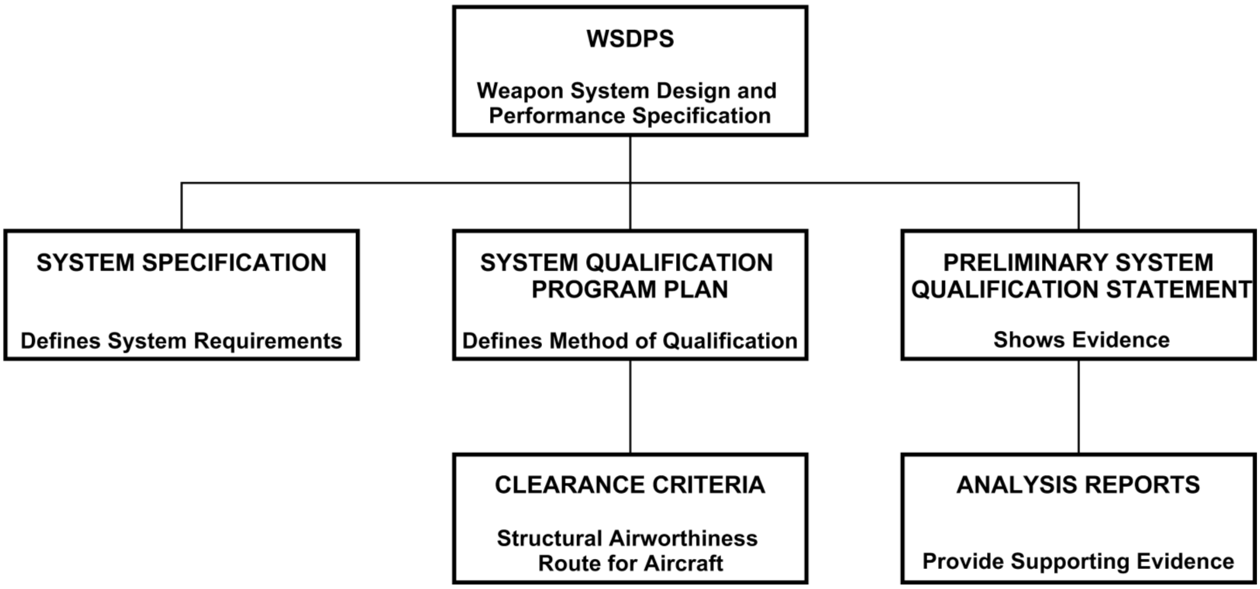

Fig. 1: Loads Clearance Document Tree

During the integration of a weapon system with a combat aircraft Preliminary and Critical Design Reviews shall be held. To ensure that the integrated elements are tested against the specification a Test Readiness Review shall be recommended.

For a complex integration program there will be hundreds of requirements which must be integrated into soft and hardware of the Aircraft System. It is important to understand the implications of every requirement which is derived from Weapon System Specification. Each requirement has an associated cost and time schedule. In the world of system engineering a V-diagram has been developed to understand more the complexity of the integration and to show the mutual dependence of the integration process. Figure 2 shows a general V-diagram, for system integration.

In principal the right hand side of the V-diagram shows the requirements which are needed and have to prove for a successful integration program. The left hand side of the v-diagram shows the methods of proving the compatibility of the aircraft and weapon system and to show evidence against the requirements of the different components.

For each engineering disciplines a detailed clearance procedure, including analysis work as well as testing have to be established. In the next chapter the requirements for aeroelastic and aeroservoelastic will be discussed. For all other engineering fields during the integration process a detailed list of requirements and description of the integration process as well as the certification procedure have to produce.

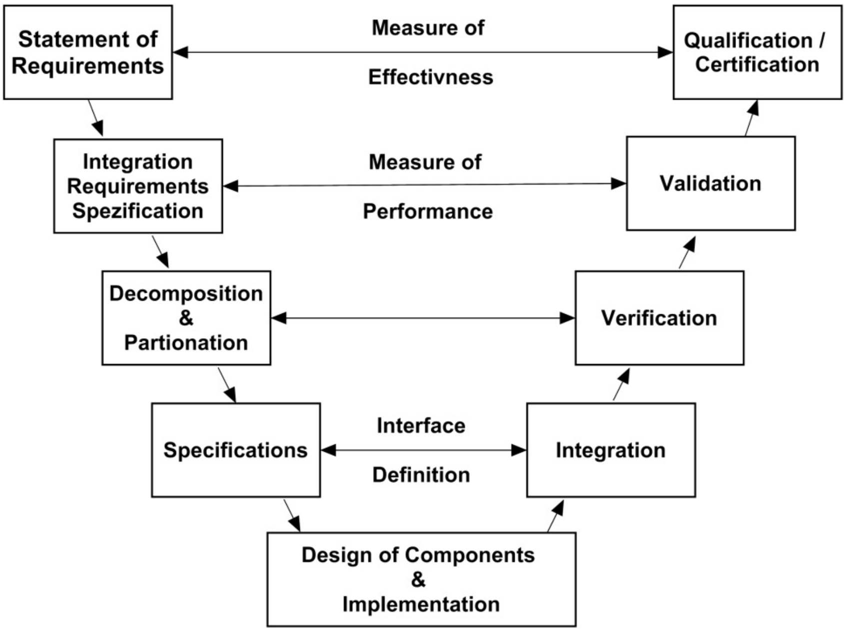

Fig. 2: V-Diagram for system integration process

Aeroelastic Requirements

The flutter requirements are derived from U.S.–Military-Specifications (Mil-Spec) and British Defense Standards (DEF-STAN) documents as well as from national Specifications. From these documents specific requirements for airspeed margins, damping, aeroelastic and aeroservoelastic stability requirements can be derived.

Therefore the aircraft shall meet the following stability design requirements for both normal and emergency conditions.

- Margin:
  Fifteen percent equivalent airspeed margin on the applicable design limit speed envelope, both at constant altitude and constant Mach number.

- Clean Aircraft Damping:
  The damping coefficient g (structural damping) for any critical flutter mode or for any significant dynamic response mode shall be at least three percent for all altitudes on flight speeds up to design limit speed.

- Aircraft with Stores Damping:
  Critical flutter modes whose zero airspeed damping is less than 3% ‘g’, the damping coefficient ‘g’ need only be greater than the zero airspeed damping coefficient in that mode.

The full requirements of the specification are subjected to the MIL-A-8870C, Airplane Strength and Rigidity Vibration, Flutter, and Divergence, a graphical presentation of the most important criteria is shown in Fig. 3.

For first flight clearance: The clean aircraft shall be allowed to fly up to half calculated flutter speed but not higher than 75% of the design speed of the vehicle for any critical flutter mode. The aircraft with stores shall be allowed to fly up to the minimum of half calculated flutter airspeed and half required airspeed.

It should be mentioned that the calculated flutter airspeed includes validation of the theoretical model by ground testing. After first flight the expansion of the flight envelope is based on theoretical analysis updated with flight flutter test results.

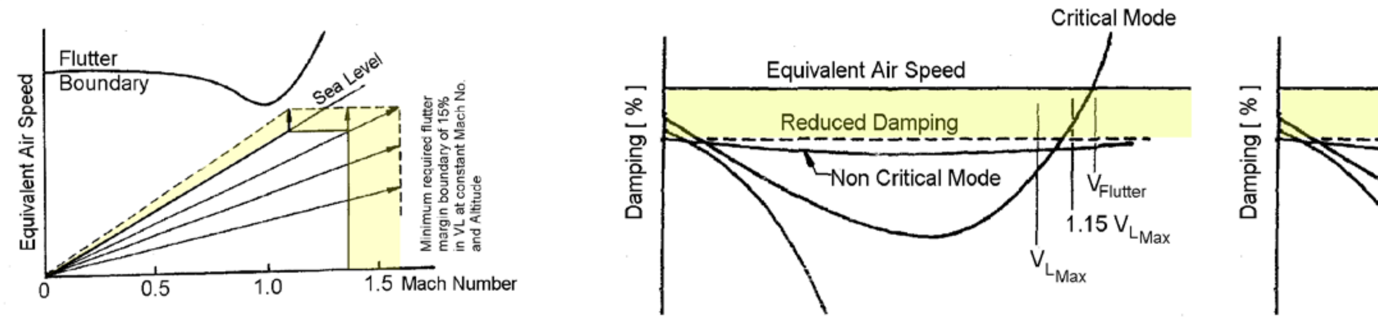

Fig. 3: Graphical Representation of the Flutter Requirement MIL-A-8870

Aeroservoelastic Stability Requirements

Interaction of the control system with aircraft elastic modes shall be controlled to preclude any structural coupling. Structural coupling is a phenomenon associated with the introduction of the closed loop control system into flexible aircraft structure.
The equivalent airspeed margin and damping requirements shall be met with the FCS open and closed loop. In addition, the stability margin of the flutter system shall respect the structural frequency stability margins in the flight control system requirements.

The aeroservoelastic design requirements are primarily stability requirements for all flight control rigid/flexible aircraft modes. The stability is achieved by the introduction of notch filters. The open loop frequency response requirements are demonstrated in Figure 3, which describes gain and phase margins for production aircraft for configurations which are flight tested on prototypes including structural coupling flight tests. In contrary to the production criteria a more conservative clearance requirement was established for the prototype aircraft, Figure 4. For the initial phases of the prototype program the decision was made to a 9 dB stability margin requirement for all structural mode frequencies. The first frequencies of the low flexible modes are phase stabilized and higher frequency flexible modes are gain stabilized.

The Military Specification MIL-F-9490D for FCS requirements shall be met the design boundaries, which include rigid aircraft motion, structural elastic modes and system modes.

For aeroservoelastic stability assessments of an aircraft with Flight Control System (FCS) criteria from the following MIL Specifications have to be applied:

- Flight Control System MIL-F-9490D
- Airplane Strength and Rigidity, Vibration, Flutter and Divergence MIL-A-8870

The military specifications for aircraft with FCS contain gain and phase margin requirements for the open loop frequency responses. For the rigid dynamics in the frequency range of the modes M from $0.06 < f_M <$ first aeroelastic mode which are in the range of minimum to maximum operational speed 6 dB gain and 45 degree phase margin and at limit airspeed V_L 4.5 dB gain and 30 degree phase margin. MIL-F-9490D requires for the mode frequencies $f_M >$ first elastic mode 8 dB and 60 degrees phase margin in the operational range and 6 dB and 45 degrees phase margin for V_L. The requirements are summarized in Table 2.

Special requirements for mode frequencies $f_M >$ first elastic mode may be formulated which take into account uncertainties in the prediction of unsteady aerodynamic forces at extreme flight conditions. Especially if actively controlled configurations are concerned, which are unstable? For these configurations the flight clearance has to be based upon prediction for open loop response functions.

The aeroservoelastic stability requirements defined for flutter in MIL-A-8870B shall be met as well. A minimum required flutter margin boundary of 15% in V_D at constant altitudes and Mach numbers is defined there. The damping coefficient g for any flutter mode shall be at least three percent.
The damping requirements are demonstrated in Figure 4.

Airspeed Mode Frequency	Below V_{0min}	V_{0min} to V_{0max}	At limit speed V_L	Above $1.15V_L$
$f_M<0.06$	GM=6.0 No PM below V_{0min}	GM=±4.5 PM=±30	GM=±3.0 PM=±20	GM=0. PM=0. stable nominal phase and gain
$.06 \le f_M<1$ st ASEM		GM=±6.0 PM=±45	GM=±4.5 PM=±30	
$f_M>1$st ASEM		GM=±8.0 PM=±60	GM=±6.0 PM=±45	

Table 2: MIL-F-9490D minimum gain and phase margin requirements

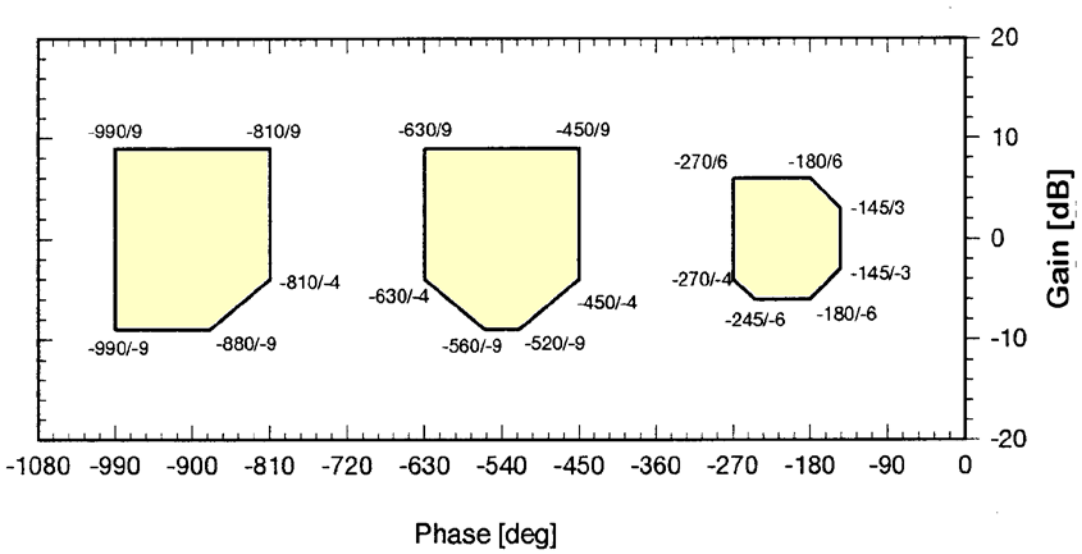

Fig. 4: MIL-F-09490 Stability Margin Criteria for Open Loop Frequency Response Function

Vibration/Dynamic Loads Requirements
In addition to the stability requirements for the structural coupling unacceptable vibration levels must be avoided including noise levels. The vibration levels induced by structural coupling might create high fatigue loads to actuators and to aircraft structure. The notch filters together with noise filters have to be designed to meet the specific vibration requirements.

Backlash Requirements
Aircraft backlash ground tests are required on all control surfaces to meet the flutter MIL-SPEC Requirements:

Flaperon: Outboard 0.0022 Radians (pitch)
Inboard 0.0200 Radians (pitch)

Taileron: 0.0006 Radians (Pitch)

Rudder: 0.0022 Radians (yaw)

For normal operation and during steady flight, the flight control system induced aircraft residual oscillations at the crew station shall not exceed 0.04 g`s vertical acceleration. For a typical unstable aircraft configuration the FCS backlash requirement for the tailplane is 0.0006 Radians.

EXAMPLES FOR EXPLAINING THE METHOD (Analysis and Route to Clearance)

INFLUENCE OF ACOUSTIC LOADING ON SUPERSONIC FUEL TANK

The supersonic fuel Tank is mounted on the centre wing or the centre fuselage station on combat Aircraft. Cracks were detected on the flat panels of the integrated pylon, Figure 5. Additionally internal cracks on flanges were identified and equipment fittings failed. The probable reason of these damages is the dynamic stimulation by high acoustic loading of the flat panels and the subsequent severe vibration.
Aerodynamic noise from the wing, fuselage and tank and cavity noise from the main undercarriage bays can be responsible for these kinds of damages.

Fig. 5: Cracks between tank and pylon and on integrated pylon panels (tried to repair by tape)

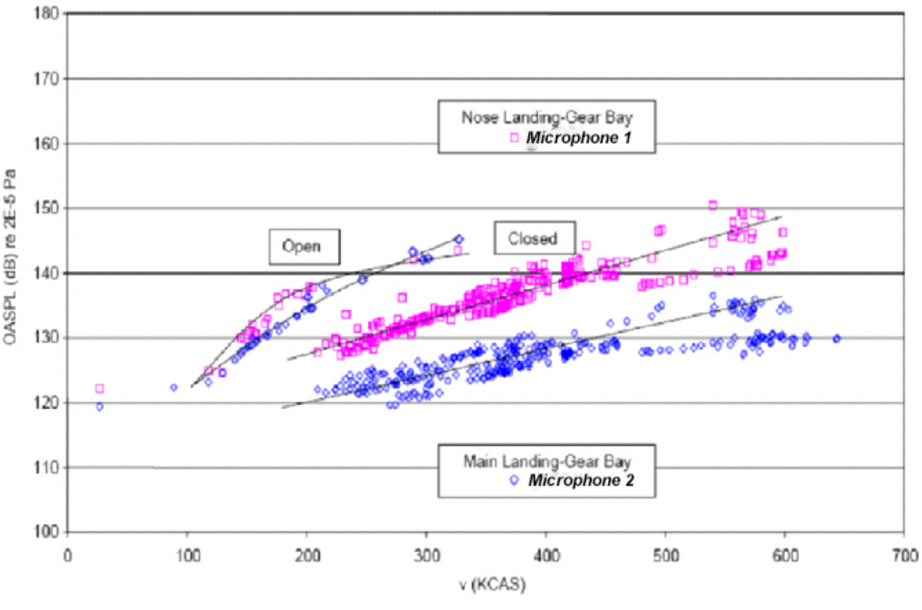

Fig. 6: OASPL in opened and closed nose and main undercarriage bays in relation to velocity

Cavity noise has been measured in the Combat Military Aircraft main undercarriage bays on different Airplanes, with one microphone. Flight test measurements were evaluated to demonstrate the influence of extended and retracted undercarriage on the Overall Sound Pressure Level (OASPL) in relation to velocity, the result is shown in Figure 6. Due to cavity noise the OASPL´s in the opened main undercarriage bay increase significantly up to 145 dB with maximum allowable velocity. The maximum velocities of the operating and extended undercarriage are defined in the "Structural Design Criteria Production":

LOADS on PYLON INTERFACE

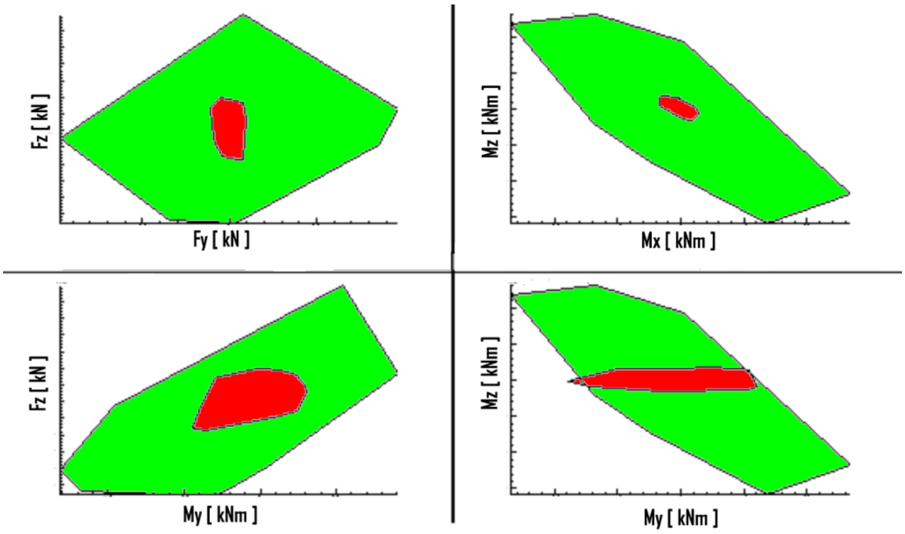

Fig. 7: Load Envelopes at pylon interface

Using flight test results to update dynamic model and transform ground or axle loads from main landing gear wheel to attachment points of the gear. With this input a dynamic response analysis will be performed. Figure 7 shows the result of a store integration analysis. The calculated loads (red area) are compared with the allowable load envelopes (Ale's – green area). This example discusses the loads on the interface of a pylon with a heavy store mounted. As it can be seen in Figure 7 the Mx versus My exceeds the allowable load envelope. In this particular case the sink rate for this external store configuration must be restricted or the store must be tuned to keep the loads inside the allowable loads envelope.

FLUTTER OF ASYMMETRIC AND ASYMMETRIC STORE CARRIAGE ON INBOARD PYLON

In Fig. 8 the flutter speeds for symmetric and antisymmetric store configuration are drawn versus radius of gyration of the inboard store for wing sweep angle at 25°. Comparing the frequencies of the different configurations one can see that the symmetrical store pitch frequency is below the asymmetrical wing bending frequency. This leads to a milder flutter case than that of the symmetrical configuration where the store pitch frequency is above the wing bending frequency. For this reason the flutter speed is higher for the asymmetric configuration. For $\rho/\rho_{Ref.}$ = 0.7 to $\rho/\rho_{Ref.}$ = 0.9 the wing bending-store pitch flutter is de-tuned and a mode coupling between store pitch and store roll come in. It should be mentioned that in case of store pitch and store roll mode have the same frequency at $\rho/\rho_{Ref.}$ = 0.6 the lowest flutter speed for this typical coupling occurs. This proves that the different behavior of the symmetrical and asymmetrical configurations is explained by different mode frequencies of these configurations.

This flutter mechanism can only be investigated with a total aircraft flutter models. Asymmetrical store configurations are possible for aircraft carrying tanks and missiles.

The favorable or unfavorable effect of asymmetry, depends on the fact whether additional stores are carried on outboard wing station, because this can be explained by the decrease of the wing bending mode frequency due to additional mass on outboard station For symmetrical full tank, only on inboard station and no store on outboard station, the effect of asymmetrical carriage is fundamental, because the store pitch frequency de-tunes the wing bending mode, whereas the asymmetrical tank carriage are tuned by the wing bending mode. That means that in the asymmetric configuration the wing bending mode frequency is below the store pitch frequency which creates the capability of severe flutter.

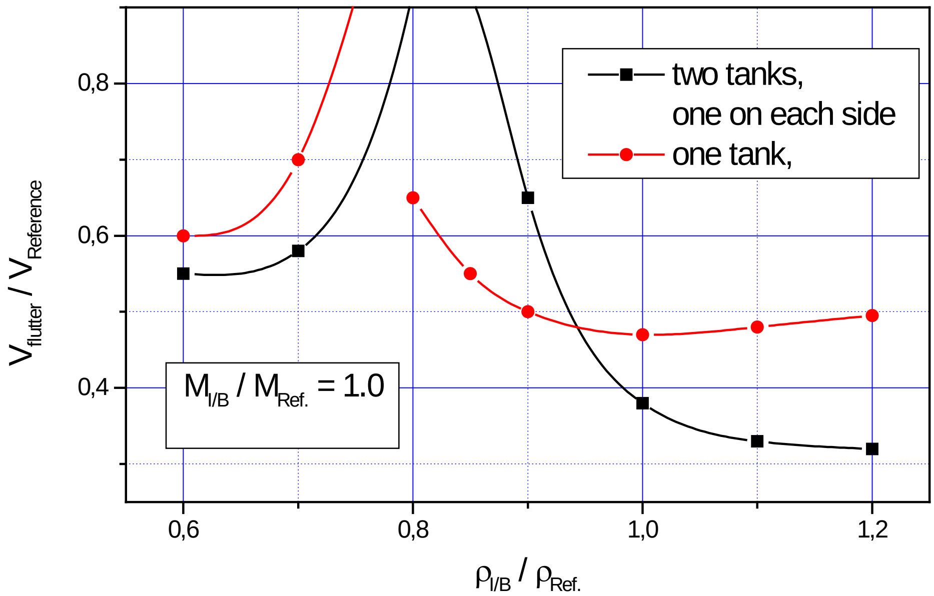

Fig. 8: Flutter speed versus symmetric and asymmetric carriage, with radius of gyration variation

Change of flutter speed by Asymmetric Carriage of inboard stores

The following example illustrates the asymmetrical flutter of an inboard wing store attached by adapter or launcher which reduces the stiffness of the pylon itself. Due to this reduction in stiffness the considered store radius of gyration for pitch $\rho/\rho_{Ref.}$ = 0.97 can be expected to result in the minimum flutter speed in case of asymmetrical carriage at the wing in the forward most position.
The flutter behavior is shown in Fig. 9 for asymmetric carriage for different wing sweep angles. At 25° sweep angle the flutter onset shows a considerably low flutter speed for the asymmetrical configuration. This figure also demonstrates the fundamental influence of the wing sweep angle on asymmetric flutter. From this figure it can be concluded, that above 35° wing sweep angle asymmetrical flutter is not important.

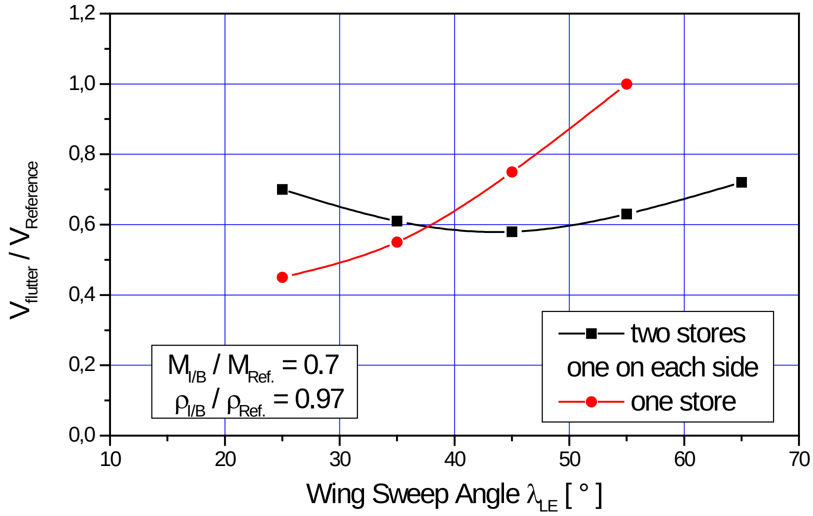

Fig. 9: Flutter speed versus wing sweep angle symmetric and asymmetric carriage

Fig. 10 shows the possibility of increase or decrease of flutter speed versus sweep angle for symmetric store configurations compared with asymmetrical store configurations of different radii of gyrations at constant mass value. Compared with Fig. 9 the results show that the increase of mass on the inboard store changes the flutter mechanism to higher flutter speed at high wing sweep angle. With decrease of radius of gyration the flutter speed of the asymmetric store configuration changes to a more critical case compared to the symmetric carriage.
A different coupling of the lowest three vibration modes, - first wing bending, store pitch, and store roll, -are possible in the asymmetric configuration. Considering the mode shape a small change is recognized between symmetric and asymmetric configurations, but the frequency of the two configurations are very different.

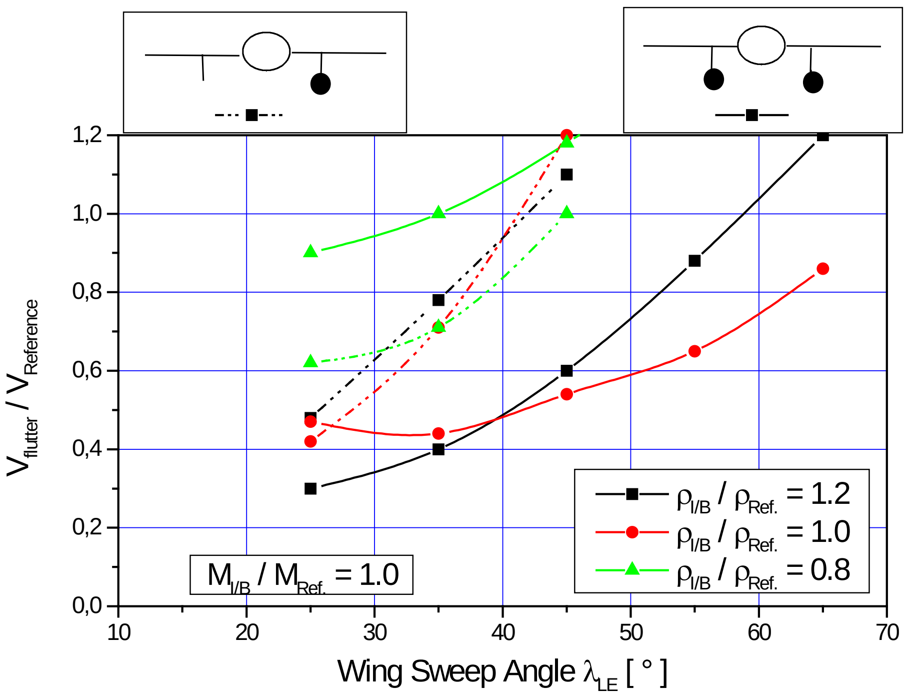

Fig. 10: Flutter speed versus wing sweep angle radius of gyration variation

SELECTION OF REPRESENTATIVE CONFIGS BY COMPARISON TO MAX MASS C. G. BOUNDARIES

The structural coupling criticality of external stores is not only influenced by the mass and inertia properties, moreover the criticality depends in addition on the FCS control law gains. The maximum control law gains and control law filters define the maximum amplitudes of the flexible aircraft frequency response functions. A first indication of a situation of maximum gains might be derived from the mass c. g. diagram as schematically shown in figure 11, which summarizes important information:

- Overall boundaries
- cg moving window for selected configuration
- dry mass/cg box for selected configuration

In detail:

- Line **Ad** represents the dry mass and dry cg box which are the physical limits for a given configuration

- Lines **C1**(FWD), **C2**(AFT) represents the extreme cg ranges for a given configuration, including all subsets.
- Lines **B1**(FWD) and **B2**(AFT) represents the cg moving window to the selected configuration.

Area **A** dry Mass/cg box contains the following characteristics points:

- **A1➔** Min Mass
- **A2➔** Max Mass
- **A3min➔** corresponding to most AFT cg (A3) maximum tolerances
- **A3max➔** corresponding to most AFT cg (A3) minimum tolerances
- **F1➔** corresponding to most FWD cg (F1)

All the other points comprised along and within the lines Ad represents the subsets of the selected configuration

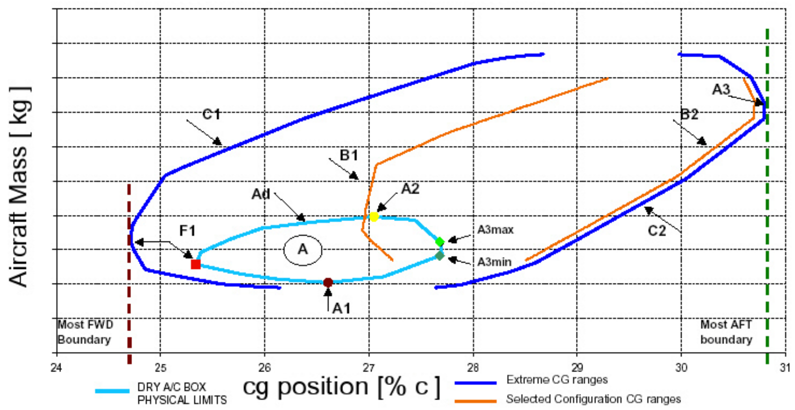

Figure 11: Mass – c.g. diagram

Maximum gains will be present for the pitch control of an unstable aircraft configuration mainly for the maximum aft c. g. boundaries.

These boundaries are a function of the store groups for which different control laws are valid. The corresponding structural coupling criticality of different store groups might be found through attributing the structural coupling critical configurations derived from figure 11 to the store groups and combination with the corresponding maximum control law gains. Mass and c. g. position of selected configurations for structural coupling should be in line with the characteristics of store group definitions installed in the FCS control laws.

The definition of representative selected configurations for structural coupling from these considerations needs to be confirmed by analytical calculations with the flexible aircraft model using control law gains for both maximum aft and forward c. g. positions by application of the updated model from ground structural coupling testing and comparisons of calculated frequency responses to the results of structural coupling tests.

CONCLUSIONS

The paper presented the guideline of the Integration of Aircraft/weapon system for a combat aircraft. Due to the complexity of the integration the process have to be divided in two main parts, the structural integration and the system integration. The focus in this paper is on the structural integration. A clearance tree for Load and flutter is shown. Beside this also the aeroacoustics load and landing impact loads are discussed. It is important that for structural Integration a clear time table with all the different disciplines must be established to show that the clearance can be achieved in time of the project. Also important is the planning of the flight test. It should be mentioned that not only symmetric carriage must be investigated, also asymmetric carriage must be analyzed.

The fundamental mechanism of store flutter is characterized by the aerodynamic coupling of store pitch mode (producing large wing torsional motion) with wing bending mode. Two modes with large wing bending motions are existent which are defined by the in-phase and out of phase coupling with lateral motions. According to this, two different flutter cases had to be considered which are able to generate low flutter speeds at very large or very small values of store inertia about the pitch axis. For intermediate values of store inertia the influence of asymmetric carriage is less important because reasonable high flutter speeds are expected for this range.

Knowing the flutter mechanism it is quite clear that changes of flutter parameters, like store weight, wing sweep position, different pylon stiffness, shifting the center of gravity in more rearward position and also the carriage of additional stores on outboard wing pylon which influence the wing bending frequency, and or the store pitch frequency will change both the symmetrical and asymmetrical flutter behavior considerably.

In the sense of parametric approach to the flutter clearance it is recommended to establish flutter trends by variation of important parameters to the actual store configuration analysis. It is easier to find out the regions with possible low flutter speeds of symmetrical and asymmetrical store configurations. Once the region of possible low flutter speeds is defined, those configurations need a more detailed investigation.

It has been shown by this analysis that asymmetrical store carriage or asymmetrical stiffness distribution results in a change of the wing bending frequency and the wing nodal line position of the store mode, which generate either lower or higher flutter speeds. For store configurations with values of pylon stiffness and store inertia close to the minimum flutter speed condition the change by asymmetries can be most effective, caused by a different coupling of the involved modes.

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