Flutter Clearance of Aircraft with External Store

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ABSTRACT

The approach to flutter clearance of aircraft with external stores focus on the understanding of the fundamental flutter mechanisms involved and the identification of flutter boundaries for all potential store loading up to the design limit of the aircraft.

A finite element model is required which will be updated with ground test results. The basic for the analytical investigation can be a branch mode model which is derived from finite element component model. The advantage of the branch mode model is that stiffness trend investigations can be easily performed by introducing a generalized factor to the in the flutter mechanism involved modes. From selected assumed mode a set of generalized unsteady aerodynamic matrices will be calculated. To analyze real conditions, aerodynamic interference of different surfaces is investigated. The analytical calculations were verified by low speed wind tunnel tests and flight flutter tests. Different excitation methods were used to excite the aircraft in a symmetric or antisymmetric case.

Flutter diagrams for different store configurations on investigated aircraft are presented. The procedure how to find for a new follow on store the uncritical clearance speed is discussed. Flutter diagrams as the result of analytical investigation are the basics for the flutter clearance work.

During design phase, the aircraft is completely engineered with regard to external store carriage capability. The residual follow-on store certification can be accomplished by analogy or minimal flutter analysis.

1.0 INTRODUCTION

Flutter 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 stores.

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.

During development phase the aircraft will be investigated applying the state of the art aeroelastic analysis, flutter model tests, ground vibration and structural coupling tests and flutter test to safe clearance speed can be confidently established.

The complete information gathered during the design of the aircraft and if necessary additional analysis with imaginary stores will be used as the basic of the parametric approach.

This lecture seeks to show how the problem can be realistically approached and how problem magnitude can be reduced to manage able proportions by physical insight into mechanisms involved. Basically the following aeroelastic problem areas must be considered in a new aircraft/store configuration:

- Divergence: The potentially of this problem can be recognized and it can generally be analysed fairly easily. The divergence is primly a problem for large stores mounted forward on flexible suspension system.
- Flutter of a store itself on a flexible pylon. This is mainly a problem for small stores with large aerodynamic surfaces mounted on a flexible pylon. This instability can be recognized very easily by simple analysis.
- Classical flutter of bare wing modes which occur due to modification of the mass inertia as provided by a new store/pylon suspension system.
- A new flutter mode occur due to the addition of a store to the wing that means a new flutter mode is introduced because of effectively new boundary conditions created by the store: for instants, a stiff pylon carrying a heavy tank on inboard pylon, which introduces an outer wing bending-torsion flutter.
- Aeroservoelastic instability effects where the store is mounted artificial unstable, because for improvement of handling, performance or aerodynamic reasons. That means the originally designed FCS does not cover this kind of frequency shift. Therefore a structural coupling with the wing bending mode can occur.

Most external stores aeroelastic problems occur either where an existing wing flutter mode is modified where a new flutter mode is introduced to new store carriage. These are therefore the ones which will be investigated in more detail during this parametric approach. In general, the occurrence of each type of flutter and how it behave is very much a function of aircraft configuration and store location relative to the aircraft and store/attachment system, mass and elastic characteristics.

In some cases it would be practically impossible to provide a flutter clearance with design charts via available parameters. Therefore it will only be shown, by examples, how the problem can be approached and interpreted in a manner which is sufficient to come to a flutter clearance.

Fighter airplanes like the variable sweep wing combat aircraft TORNADO using high power control and automatic control systems, which basically are designed to maneuver the aircraft and to provide sufficient damping for the rigid body modes. The airplane, Fig. 1 in this study is controlled by a triplex analogue fly-by-wire flight control system, mechanical emergency control and automatic stabilization. The primary flight control systems provides pitch, roll and yaw control by means of wing mounted spoilers limited to low speed conditions, an all moving taileron and a conventional rudder.

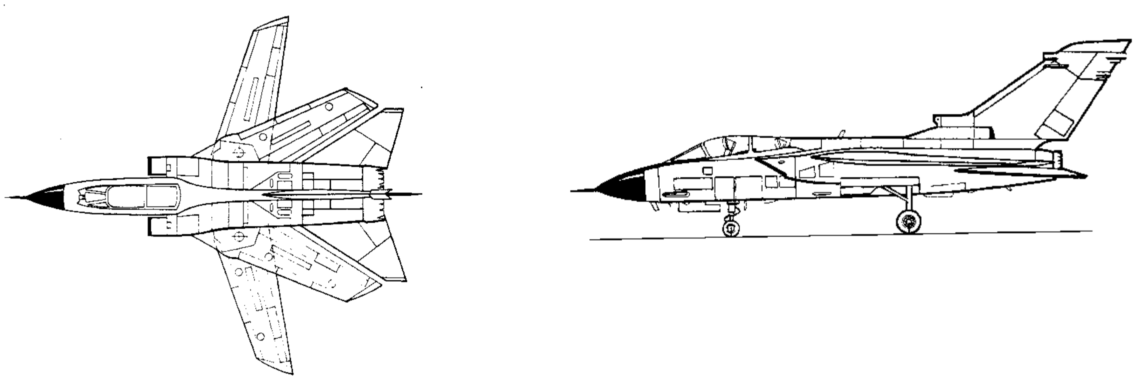

Figure 1: Two side view of the Aircraft.

The airplane has two under wing stations for carriage external stores. The heavy stores are carriage on inboard pylons, whereas light store are carried on outboard station.

2.0 AEROELASTIC DESIGN REQUIREMENTS, DESIGN CRITERIA, PHILOSOPHY TO GET CERTIFICATION

2.1 Structural Design Requirements

Analyses, wind tunnel tests, and airplane ground and flight tests up to design limit speeds shall demonstrate that flutter, buzz, divergence and other related aeroelastic or aeroservoelastic instability boundaries occur outside the 1.15 times design limit speed envelope.

Fig. 2 summarizes the requirements and evidence required for qualification and certification of a typical military aircraft.

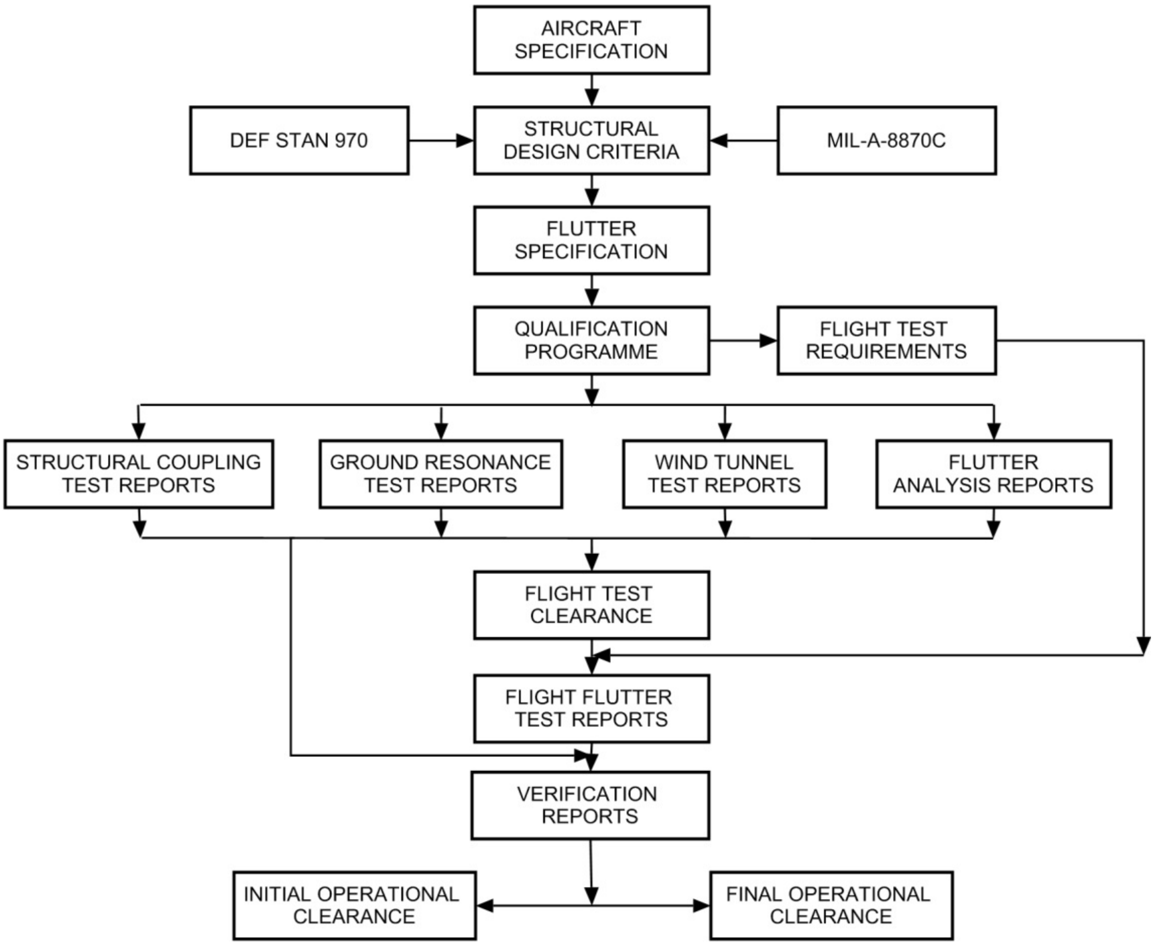

Figure 2: Requirement for Qualification.

2.1.1 Flutter 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.

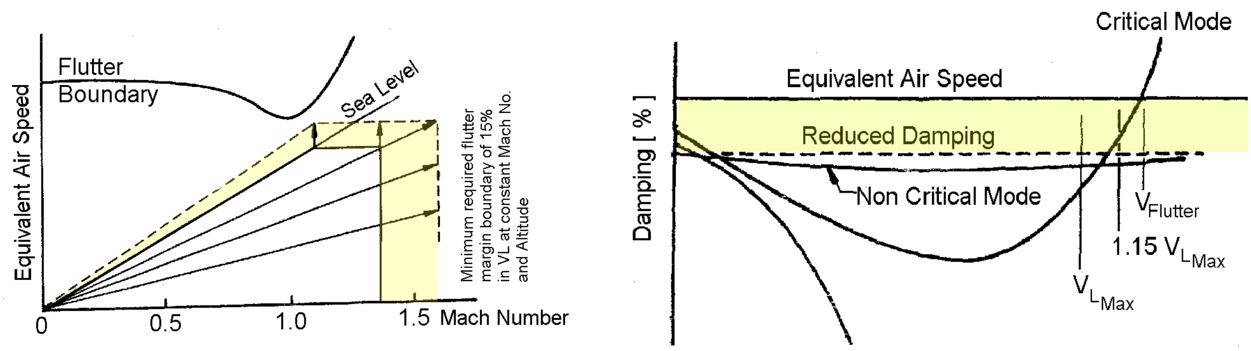

Figure 3: Graphical Representation of the Flutter Requirement MIL-A-8870.

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.

2.1.2 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-9490 D 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 1.

Table 1: MIL-F-9490D minimum gain and phase margin requirements.

<table>
<tr><th>Airspeed
Mode
Frequency</th><th>Below
V_{0min}</th><th>V_{0min}
to
V_{0max}</th><th>At limit
speed V_L</th><th>Above
$1.15V_L$</th></tr>
<tr><td>$f_M<0.06$</td><td rowspan="3">GM=6.0
No PM
below
V_{0min}</td><td>GM=±4.5
PM=±30</td><td>GM=±3.0
PM=±20</td><td rowspan="3">GM=0.
PM=0.
stable
nominal
phase and gain</td></tr>
<tr><td>$.06 \le f_M < 1$
st ASEM</td><td>GM=±6.0
PM=±45</td><td>GM=±4.5
PM=±30</td></tr>
<tr><td>$f_M>$1st ASEM</td><td>GM=±8.0
PM=±60</td><td>GM=±6.0
PM=±45</td></tr>
</table>

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 Fig. 4.

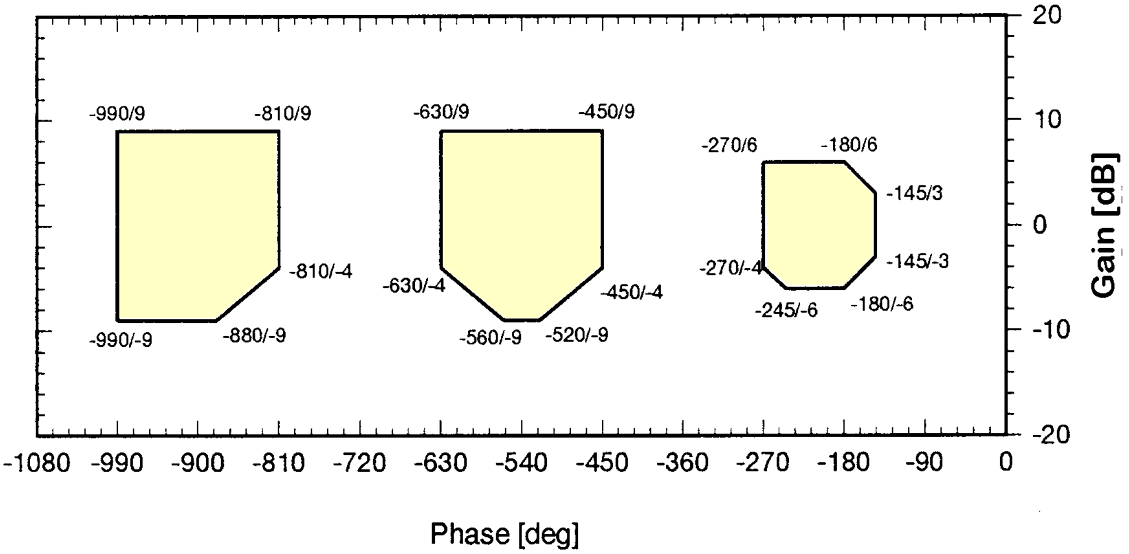

Figure 4: MIL-F-09490 Stability Margin Criteria for Open Loop Frequency Response Function.

2.1.3 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.

2.1.4 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.

2.2 Design Considerations

In the early design stages as well as during service of an aircraft, the flutter analyst is always confronted with providing configuration trade-off information necessary to arrive at an optimum overall design. Generally, these decisions must be made on the basis of small analysis and test information in early design. This problem is even more involved in a design, as might be in the case in an attack aircraft. The following comments can be made regarding the principle desirable directions to be followed in the design of a weapon system which may potentially carry many different external store configurations:

- Try to obtain as high the wing flutter speed as is possible, that mean a large distance between wing bending mode to the wing torsion mode frequency. This should be accomplished by stiffness rather than by mass balance.
- Keep all heavy stores as close to the fuselage as possible.
- Try to minimize the possible mass/inertia variations at outboard store stations.

2.3 Qualification and Certification

For flutter and structural modes coupling stability it is required to provide evidence of Qualification to prove that the aircraft is free from structural instabilities and to ensure safe flight, necessary for the flight testing task and verification against the specification.

As mentioned before, qualification is to demonstrate that the aircraft shall be free from flutter and aeroservoelastic instabilities at speed up to 1.15 times the maximum airspeed and the maximum Mach number for all flight conditions.

Flutter and Aeroservoelastic qualification is achieved by:

- Theoretical calculations – Flutter and Aeroservoelasticity:

  The analysis must include the characteristics of the Flight Control System for all possible configurations (clean and with external stores) as well as failure cases.

Supported by:

- Ground Tests:

  Ground vibration tests on aircraft components, ground resonance tests on completed aircraft, structural mode coupling tests, actuator impedance tests, static stiffness tests and free play tests.

- Wind tunnel Tests:

  Flexible and rigid model testing, with dynamic similar models.

- Flight Tests:

  Vibration and flutter flight tests and in-flight structural mode coupling tests.

Fig. 5 shows in principle the aeroelastic stability qualification route to flight clearance. During this process the flutter engineer has to handle many different models, they are described below.

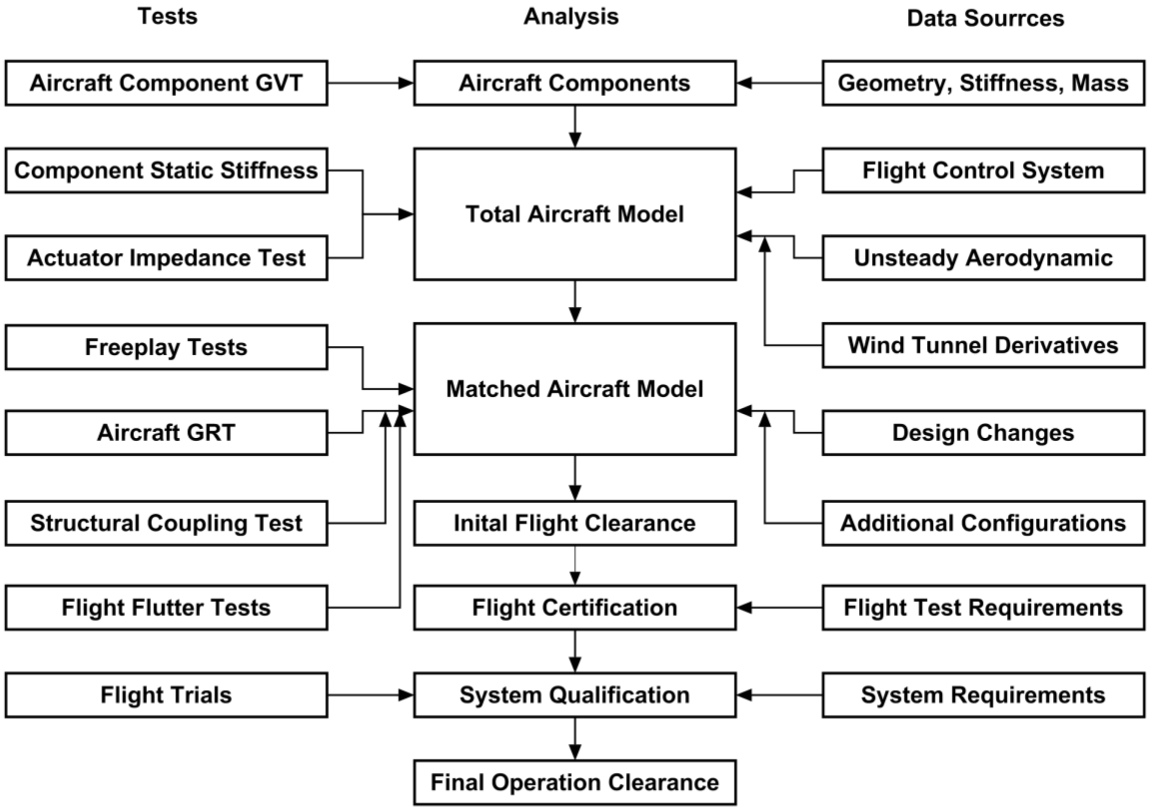

Figure 5: Flight Certification Route.

2.3.1 Theoretical Models

The aeroelastic and aeroservoelastic models are based on a theoretical finite element model representative of the stiffness and mass characteristics of the actual aircraft, by means of dynamic assembly. The complete flutter model is assembled using the dynamic model by components and includes unsteady aerodynamic forces to analyze the aeroelastic stability characteristics of the aircraft. Sensitivity studies are performed to investigate parameter and failure variations (e.g. store and fuel mass, attachment stiffness and FCS configurations).

2.3.2 Validation of Models by Ground Testing

Stiffness and mass data of the theoretical aircraft model will be validated by component and total aircraft ground vibration tests. Ground vibration testing is performed on components, like wing, fin, foreplane, pylons and on fully assembled aircraft a ground resonance test (including hydraulic system) is performed.

Static stiffness testing is performed on selected combinations of pylon and store configurations and impedance actuator testing covering single and dual hydraulic system working as well as failure cases. Where any definite differences exist between the tests and predictions derived from the theoretical models, the models are updated to account for the results of the ground testing.

In general, the result of ground testing will be a validated aeroelastic model which is the basis for predicting flutter characteristics for selected key configurations.

2.3.3 Validation of Models by Flight Testing

The main validation of the flutter model is made with flight flutter testing, and this model is used to derive clearances up to the required 115% of the design speed envelope. The flight flutter tested key configurations establish measured data, which are compared with the theoretical results. Where any differences reveal, the models will be adjusted to account for the results of the measurements. The flight envelope expansion is done by a Mach number/airspeed survey. In the beginning phase of flight flutter testing, the test will be concentrated on areas with high flutter stability. When the measurement of frequency and damping shows a more conservative flutter onset or confirms the predicted flutter point, the test in of more critical points will be performed. In case of fundamental differences to the predictions, the test will be interrupted and the differences are investigated and the models are updated.

3.0 METHOD AND STRUCTURAL MODEL

Modified branch mode techniques are used to solve the problem of different stores carriage on aircraft. By this approach the frequencies and mode shapes of the coupled system are obtained by superposition of limited number of clean wing normal modes and so called junction or direct link modes, which are employed in order to improve the convergence of the results related to the number of cantilevered bare wing normal modes. The procedure, using modified branch mode techniques for total airplane representation and cross checking the solution of ground vibration and flutter calculations with total airplane model test results is considered to be the most efficient approach for obtaining reliable flutter results. After verifying these methods it is the basic for the described parametric approach. During the verification phase it turned out that only free-free dynamically scaled total aircraft models give good correlation when tuning effects occur.

3.1 Structural Representation

For the representation of total airplane dynamics the following sets of finally retained generalized coordinates are considered for flutter and vibration analysis:

- Rigid Aircraft body modes.
- Fixed fuselage normal modes.
- Fixed taileron normal modes and taileron attachment modes.
- Fixed fin/ruder normal modes and fin/rudder attachment modes.
- Wing external store junction modes.
- Fixed external store normal modes and pylon attachment modes.

All airplane components are represented by finite element models to describe the complexity of the structure. For the cantilevered component modes distinctions between primary modes for the main structure as for the wing and secondary modes for substructures as for example an external store. Attachment modes, which are rigid body modes for components, are used to vary the connection stiffness of main structures with substructures. One attachment mode for each external store has been introduced to establish a yaw degree of freedom corresponding to the flexibility of the pylon control rod, which provides constant stream wise direction of the pylon for all wing sweep positions. The single point pylon attachment with free motion of the pylon in yaw relatively to the wing, prove wing modes do not contribute to the pylon yaw displacements.

4.0 RESULTS OF FLUTTER INVESTIGATION

As already mentioned there is a huge variety of configurations, arising from the attachment of stores, as well as from the large differences of mass and inertia to the aircraft with variable wing sweep.

4.1 Inboard Store Only: Symmetric and Asymmetric Carriage

4.1.1 Influence of Different Sweep Angle on Flutter Speed: Symmetric Carriage

Fig. 6 shows flutter speed as a function of wing sweep angle for a store with constant weight and variable radius of gyration. The increments of flutter speed with wing sweep change with store radius of gyration. The minimum flutter speed occurs at different sweep angles and changes with radius of gyration. (Compare the slopes of $\rho/\rho_{ref.}$ = 1.0 and 1.2). It should be mentioned that the flutter behavior may look completely different for a store having another mass and radius of gyration that is depicted in Fig. 6. To use the parameter approach many different stores have to be investigated.

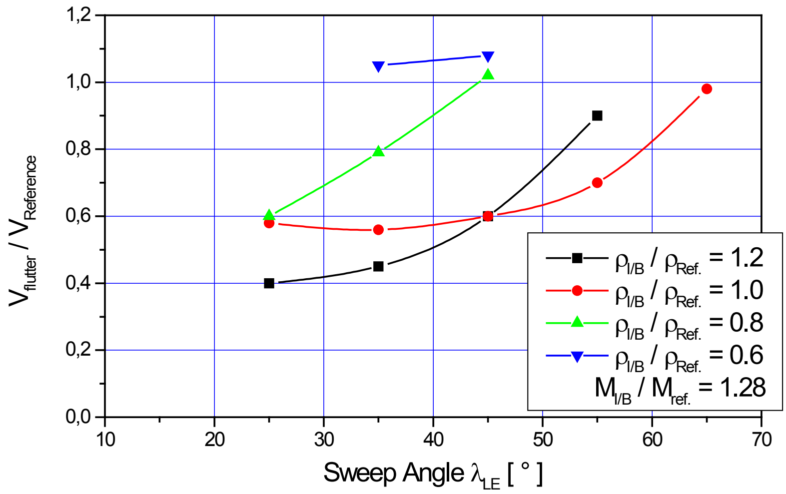

Figure 6: Flutter Speed versus Sweep Angle for different Radii of Gyration.

4.1.2 Influence of Model Suspension System on Flutter Speed: Symmetric Carriage

In some cases we used wind tunnel test results to verify the mathematical model and to measure the flutter onset. Most of the flutter cases, experienced during the wind tunnel tests were more symmetrical than antisymmetrical flutter cases. The test turned out that there can be a strong influence of fuselage tuning effects upon the store flutter case, mainly in a symmetric mode. For these reasons it is recommended to use a freely suspended wind tunnel model and therefore a total mathematical model for wing store flutter investigation. The next figure depicts the effect of boundary conditions on the flutter speed for wing store configurations.

Fig. 7 shows the difference in flutter speed for varying boundary conditions as a function of pylon pitch stiffness. The fixed wing curve depicts how the flutter speed of a fixed wing with external store varies with pylon stiffness. Considering the mode shapes of the flutter points a qualitative assessment of the flutter behavior can be made. At 100% pylon pitch stiffness the nodal line of the important mode shape is at about three quarter wing chord. Both nodal lines for 50% and 200 % pylon pitch stiffness are further forward on the wing chord, which produce a higher flutter speed. The free-free aircraft has a different flutter behavior versus the pylon pitch stiffness. The basic mode shape of this flutter mode shows a forward nodal line for 100% pylon pitch stiffness. Due to the influences of the elastic fuselage, the nodal line changes with increasing of pylon pitch stiffness. Just for comparison the third curve shows the flutter behavior with the aircraft fixed in the heave direction. The calculated cases prove that the in heave restricted aircraft shows similar flutter speeds as the cantilevered wing. For the parametric approach it is essential to use the total aircraft model without constrains to analyze real flutter speeds. The flutter speed can be largely underestimated with cantilevered wing models for certain pylon pitch stiffness.

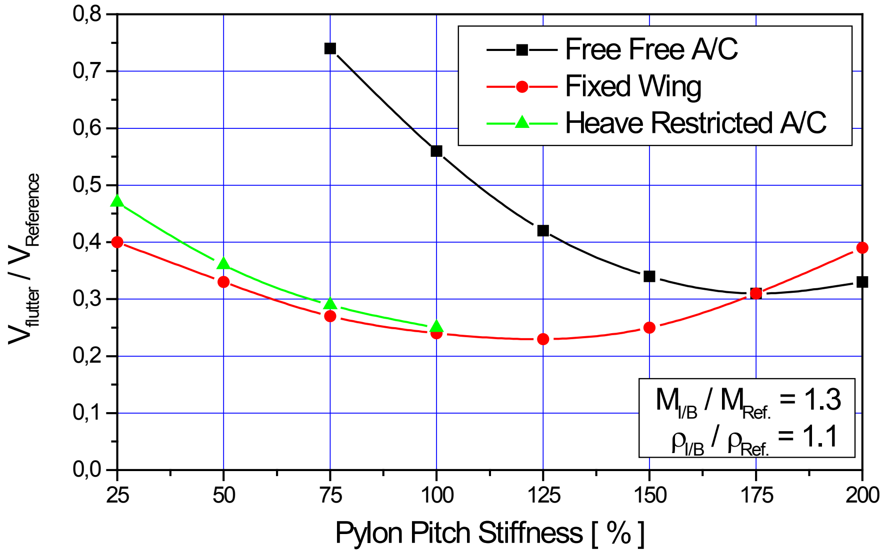

Figure 7: Flutter speed versus pylon pitch stiffness for free-free and restricted Aircraft.

4.1.3 Change of Flutter Speed Due to Variation of Radius of Gyration

An explanation of the flutter mechanism is given in Fig. 8 for the inboard store configuration. This figure shows clearly the two mode which are involved in this flutter case due to the variation of the radius of gyration. The right hand slope produces the lowest flutter speed which is a coupling of store pitch with the wing bending. The second part (lower) of this figure presents the change of frequency of the different modes with radius of gyration.

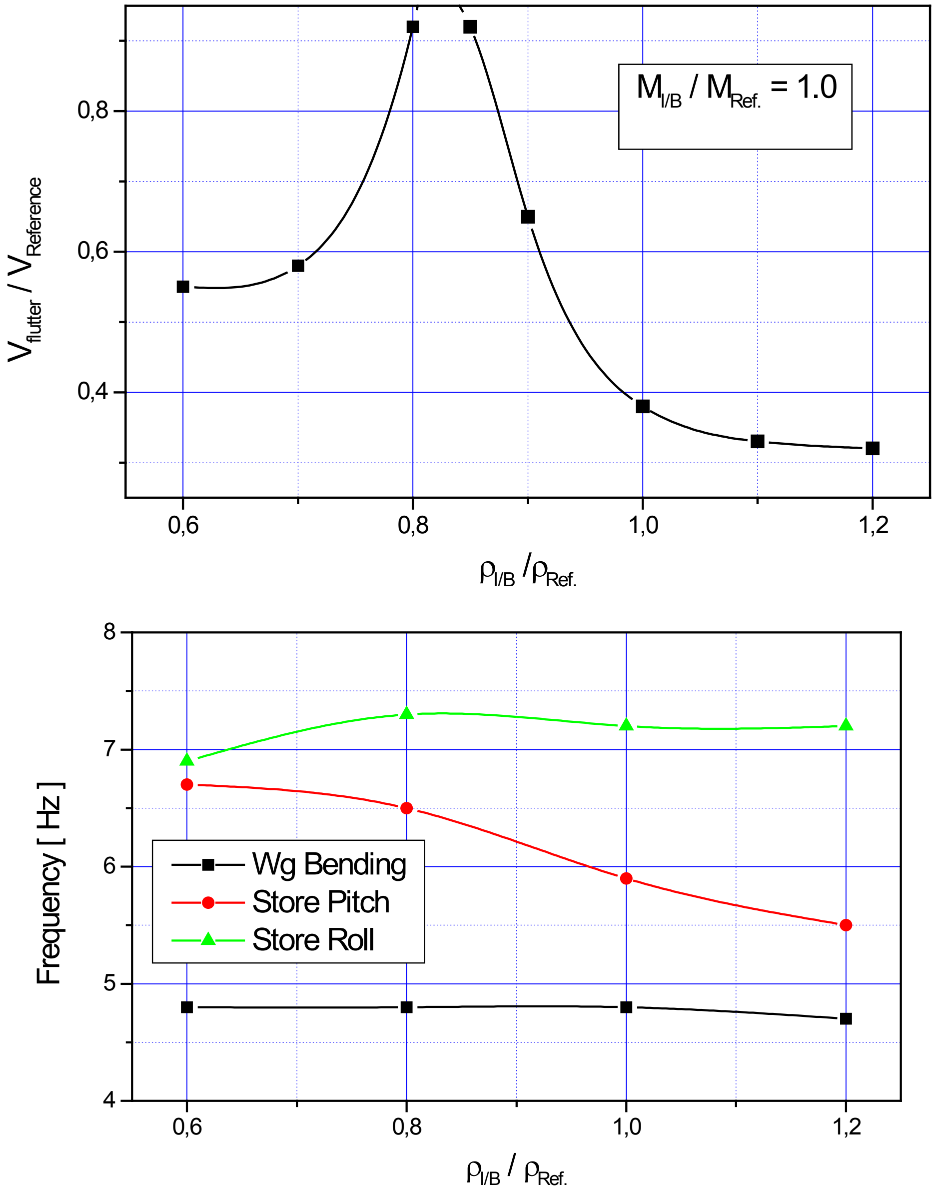

Figure 8: Flutter Speed and Modal Frequencies versus Radius of Gyration.

The flutter speed on the left hand curve is higher because there is couplings between the store pitch and roll mode. With increasing the radius of gyration the coupling of the roll and pitch mode will be separated due to decrease of the store pitch mode frequency which avoid an increase of store roll frequency.

It should be mentioned that this figure represents only the flutter behavior for a tank with constant mass value and different radius of gyration at 25° wing sweep angle. For increase of the sweep angle in principal the same flutter behavior is expected on increased flutter point. During the analysis it was recognized that the variation of mass has no fundamental influence of changing the flutter mechanism.

4.1.4 Change of flutter Speed During Fuel Emptying

The following Fig. 9 explains the change of flutter speed by symmetrical emptying of both tanks by symmetrical carriage. During emptying of the tanks there is one critical area between 10% fuel and 35% fuel of each tank where the flutter speed drops down to very low level. It can be seen from this figure that the lowest flutter speed is at that point when the center and intermediate compartments are empty.

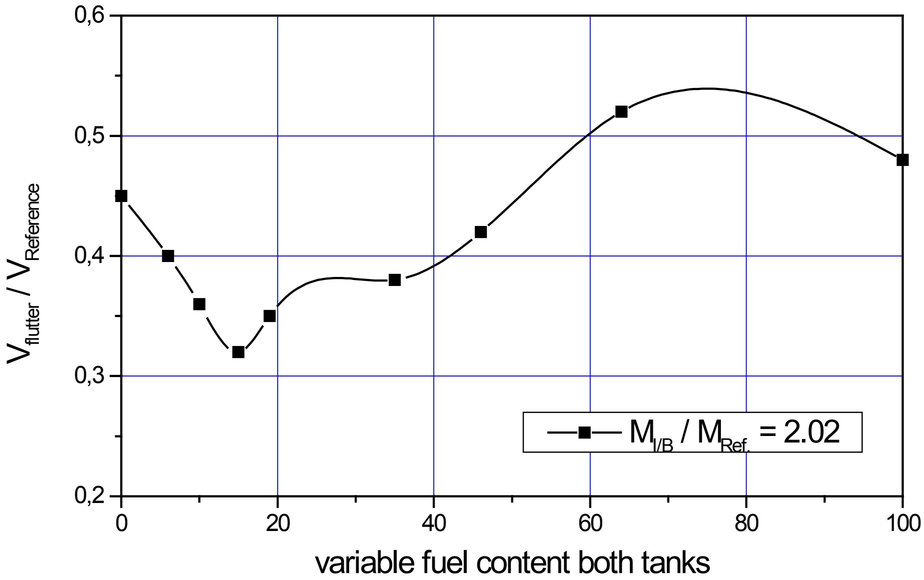

Figure 9: Flutter speed versus symmetrical tank emptying.

The example in Fig. 10 shown here is a very large tank mounted on the inboard pylon. The design philosophy of this tank was to avoid a flutter critical coupling of modes by separating store pitch mode from fundamental wing bending mode over a wide range during fuel emptying of the full tank. This is reached by scheduling the compartments of the tank in such a way as to maintain high tank pitch inertia as long as possible to keep store pitch frequency below wing bending frequency and to avoid frequency coincidence condition up to lower fuel states. Therefore fuel emptying takes place in three stages, beginning in the center compartment via the intermediate to the end compartments. The critical points are 64% fuel where the center compartment is empty and also 19% fuel where the intermediate compartments are empty. The radius of gyration varies from minimum $\rho/\rho_{Ref.} = 1.5$ up to 2.11 and the center of gravity migrates from 4.3 cm in the full condition up to 35.6 cm in the empty condition.

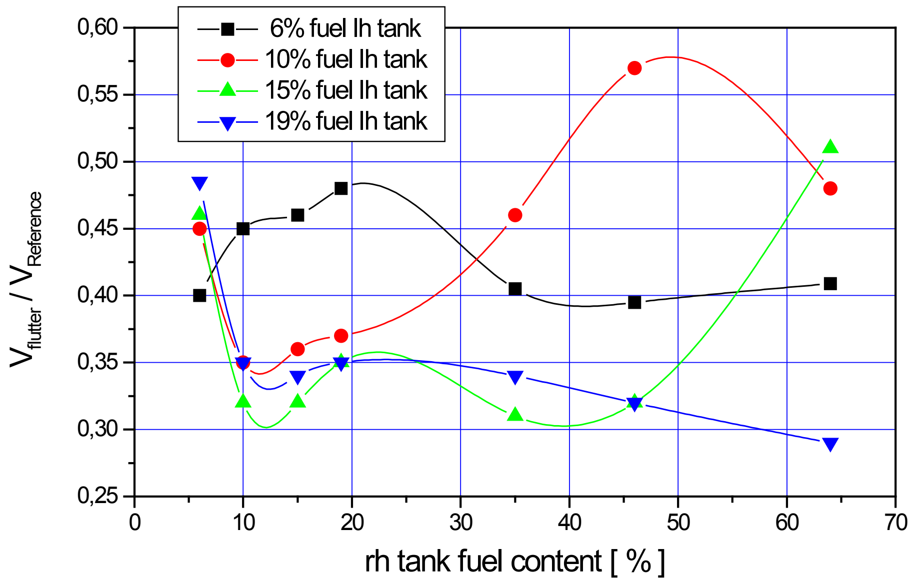

Figure 10: Flutter speed versus asymmetrical tank emptying.

The Fig. 10 shows that the flutter behavior for asymmetrical filled tanks is lower than in the symmetric case. Therefore greater asymmetric fuel states should be avoided.

In general, multiple numbers of combinations bears to much different flutter mechanisms and the flutter speed changes rapidly. In case of symmetric emptying of the tanks, the flutter a mechanism is stable and do not change so fast.

4.1.5 Influence of Pylon Stiffness on Flutter Speed

Fig. 11 demonstrates the effect of asymmetric pylon on the flutter speed. Two different inboard stores conditions are investigated. For the first store group a radius of gyration was assumed which matches the minimum flutter speed conditions for symmetrical store carriage and results to higher flutter speed if only one store is being carried. The second store is attached to the pylon with an adapter. The radius of gyration $\rho/\rho_{Ref.} = 0.97$ was chosen to meet the minimum flutter speed condition in case of asymmetrically carriage. In this case the more critical flutter speed was found for the asymmetrical configuration with one store only. In Fig. 11 the flutter speed is plotted versus stiffness of the right hand pylon, whereas the left hand pylon stiffness ids kept at 100%. (The reduction of the stiffness was made by factorizing the complete pylon matrix with the corresponding factor). Both slopes indicate a change of the critical flutter mode when the stiffness of one pylon decreases to about 90% of the nominal value.

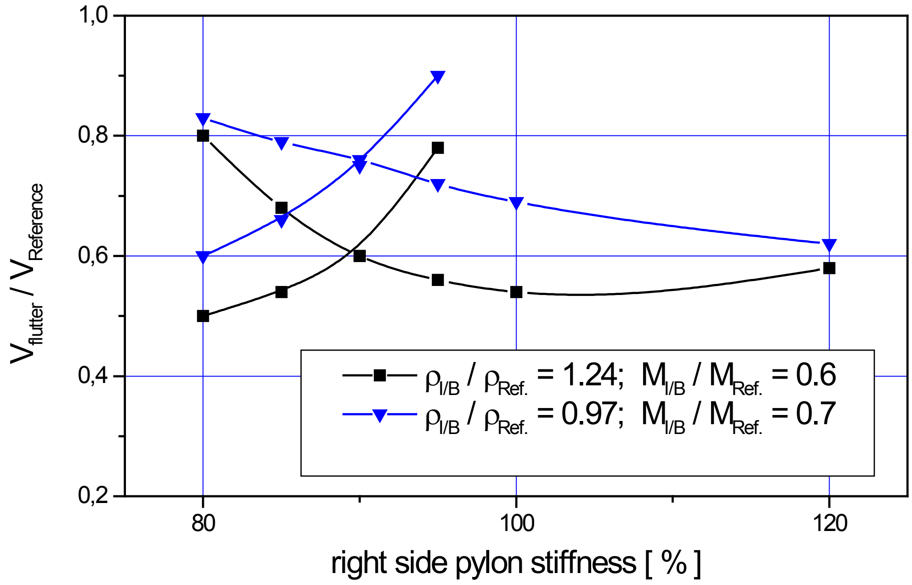

Figure 11: Flutter speed versus pylon stiffness.

When the stiffness of one pylon is increased to 120% a further flutter mode was found at a very high flutter speed outside the range of the diagrams. It can be concluded that each wing side creates is corresponding flutter case, each having a minimum flutter speed defined values of pylon stiffness. For the $\rho/\rho_{Ref.} = 1.24$ curve the min flutter speed is reached at 100% stiffness corresponding to the ρ value which already matches the minimum flutter speed condition at nominal stiffness. On the other curve ($\rho/\rho_{Ref.} = 1.24$ the flutter mode do not reach the minimum, which is reflected by the decreasing flutter speed when the stiffness of one pylon is being increased. Both curves indicate that the flutter speed, related to smaller stiffness is still decreasing for further reduction of the stiffness.

The result of this calculations demonstrate that asymmetry of pylon stiffness can be very important for values of store inertia and pylon stiffness, which are close to the minimum flutter speed condition. For the cases considered here the influence is reduced, if structural damping is taken into account. For final judgement this phenomenon needs to be further investigated, especially in view of store having intermediate and smaller radii of gyration.

Differences in pylon stiffness inside the usual range of small tolerances seems to be less important for flutter but can create considerable problems during the evaluation of flight test data, caused by closely spaced frequencies, which may result to misleading high damping values. In this case a verification of test results by flutter calculations is even more important and it may be necessary to provide the flutter clearance of store configurations with marginal flutter speeds rather by analysis than by flight test.

4.1.6 Change of Flutter Speed by Asymmetric Carriage of Inboard Stores

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.

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. 12 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.

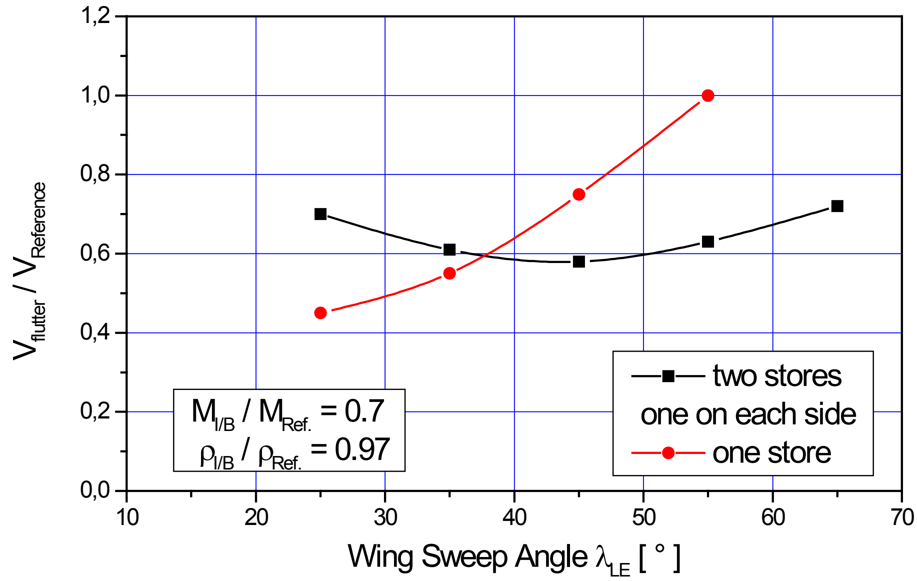

Figure 12: Flutter speed versus wing sweep angle symmetric and asymmetric carriage.

Fig. 13 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. 12 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.

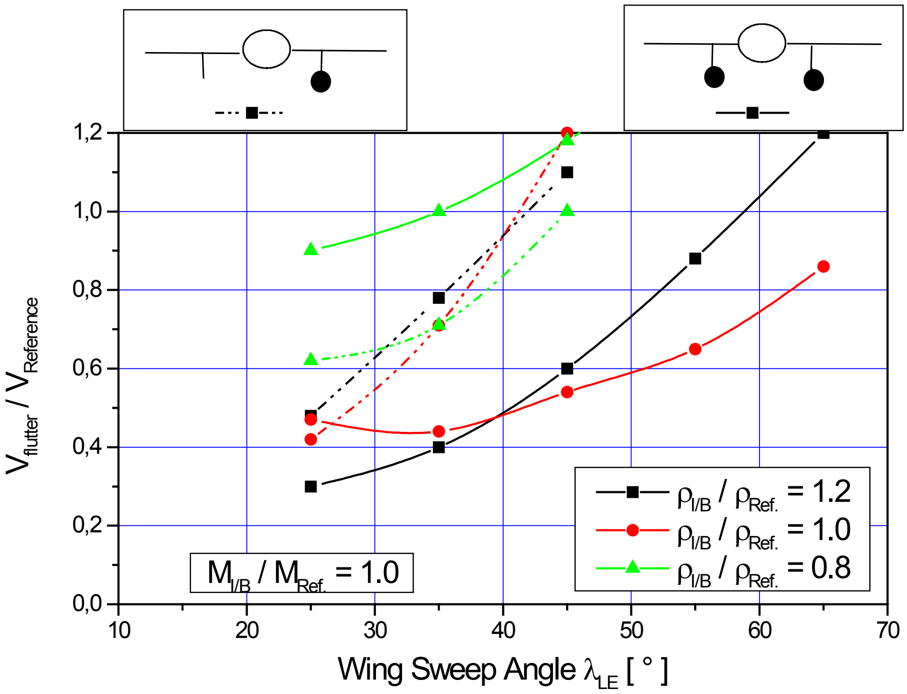

Figure 13: Flutter speed versus wing sweep angle radius of gyration variation.

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.

In Fig. 14 the flutter speeds for symmetric and antisymmetric store configuration are drawn versus radius of gyration of the inboard store for constant 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.

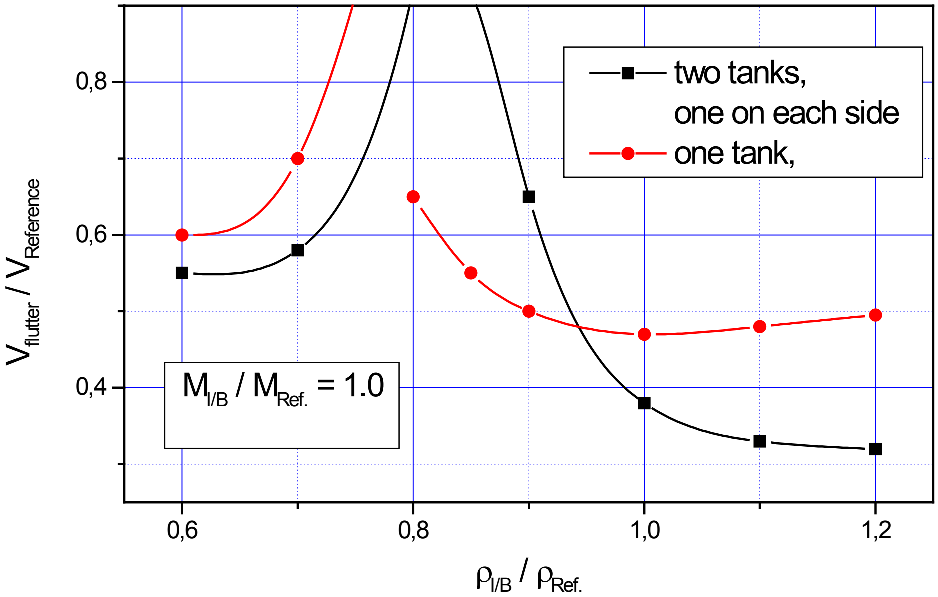

Figure 14: Flutter speed versus symmetric and asymmetric carriage, with radius of gyration variation.

In Figure 14 the flutter speeds for symmetric and antisymmetric store configuration are drawn versus radius of gyration of the inboard store for constant 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.

4.2 Outboard Store Only

In principal the same method must be applied for the outboard store carriage as described by the previous chapter. For the parametric approach many different configurations have to be considered. In this lecture notes only on two distinguish cases will be shown.

4.2.1 Influence of Wing Pivot Yaw Stiffness on Outboard Flutter

Fig. 15 depicts the influence of wing pivot yaw stiffness for a subsonic case at Mach = 0.9. Due to the possibility of this aircraft to fly with variable wing sweeps the chordwise bending have an important part on the outboard store flutter mechanism in both load cases, symmetric and antisymmetric. Two outboard store modes are involved in the flutter mechanism, the first mode exists at about 6 Hz and the second mode at about 8 Hz, exhibiting large store pitch motions coupling with “in phase” and “out of phase” wing fore and aft motions (chordwise bending) The reduction of wing pivot yaw stiffness is possible through to different states of the backlash inside the wing bearings. This is mainly an analytical investigation, because at 100% wing pivot yaw stiffness this missile has a sufficient flutter boundary, but it shows the trend in flutter.

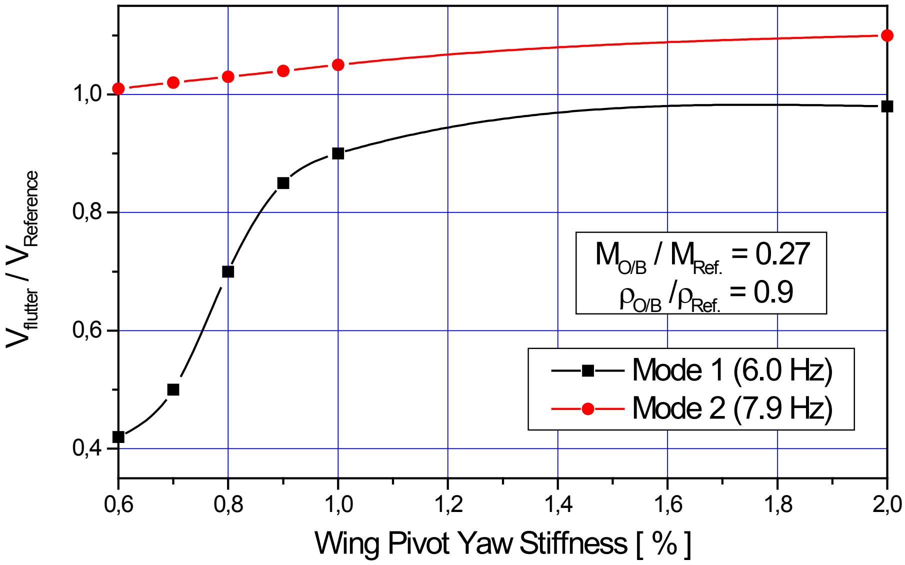

Figure 15: Flutter speed versus wing pivot yaw stiffness.

4.2.2 Influence of Store Center of Gravity Migration on Outboard Store Flutter

In Fig. 16 the influence of center of gravity movement is depicted for two different Mach Numbers and two different pylons on outboard station. In the subsonic case the worst condition is found by the most rearward center of gravity position, because the flutter speed decreases dramatically. The worst condition in supersonic flight is calculated by the most forward position of the center of gravity of the missile. This trend is in contrary with the subsonic results. Anyway the change in flutter speed during supersonic flight for this configuration is very small. It is interesting to note, that no more increase in flutter speed can be expected by shifting the center of gravity further forward than 0.12 m because another flutter mode (2^{nd} mode) arising from detrimental coupling of the store yaw mode crosses over.

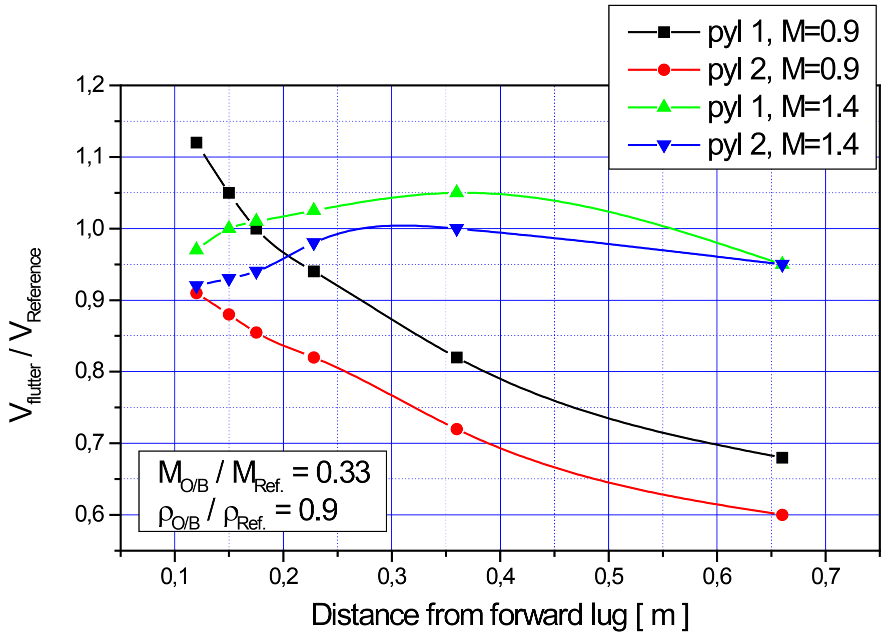

Figure 16: Flutter speed versus outboard store center of gravity shifting.

Due to the fact that on outboard station many different stores can be attached a large number of calculations have to be performed. The outboard store mass and radius of gyration changes are huge and therefore many parameters have to be produced. Changes of Mass distribution and center of gravity on outboard stores are not as common as on inboard stores. But during service of the aircraft it turned out that on outboard station a symmetric carriage is very seldom, therefore the asymmetric configurations have to be investigated in more detail.

4.3 Outboard and Inboard Store Carriage

In this chapter only two examples will be shown. From previous analysis the critical corner points of single carriage are known. The combination of these cases has to be investigated as well as configurations which are becoming critical through to new couplings between inboard and outboard masses and stiffness'.

4.3.1 Influence of Fuel Emptying of Inboard Store

In Fig. 17 the results are presented which have been achieved for two different wing sweep positions. One external tank is assumed to be full and the other tank varies from zero to 100% fuel state. For the 25 ° wing sweep angle the highest flutter speed was calculated for symmetrical full/full condition. Emptying one tank only the flutter speed is decreasing and reaches the lowest value at the empty/full condition. This behavior is not changed if a relatively large value of 2.5% structural damping is considered, which proves that the damping gradient in the flutter point is comparable for symmetric and antisymmetric fuel conditions.

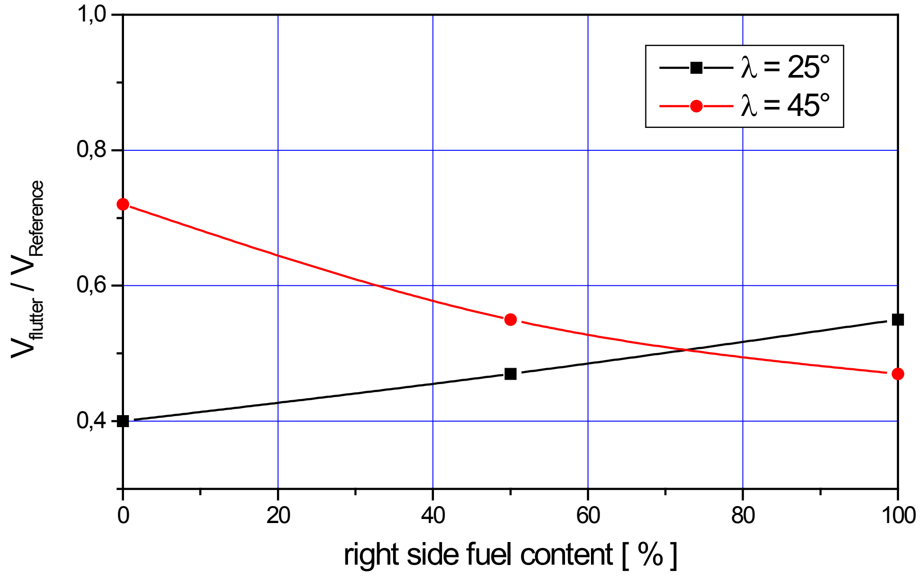

Figure 17: Flutter speed versus asymmetrical fuel emptying of Inboard tanks with symmetrical outboard stores.

The flutter trend changes to the opposite if the wing is swept in more rearward position. In this case the symmetric full/full condition represents the worst condition and would clear also the asymmetrical fuel states. At higher speed the second flutter mode occurs at about 6.0 Hz which is not important for flutter because it indicates higher flutter speeds for all fuel states (2nd flutter mode not shown in this figure).

Fig. 18 shows the same flutter speeds as resulted for the same configuration if one tank is being kept in the 50% fuel condition. For 25 ° wing sweep angle the results are similar to those obtained for the tank configuration without outboard stores.

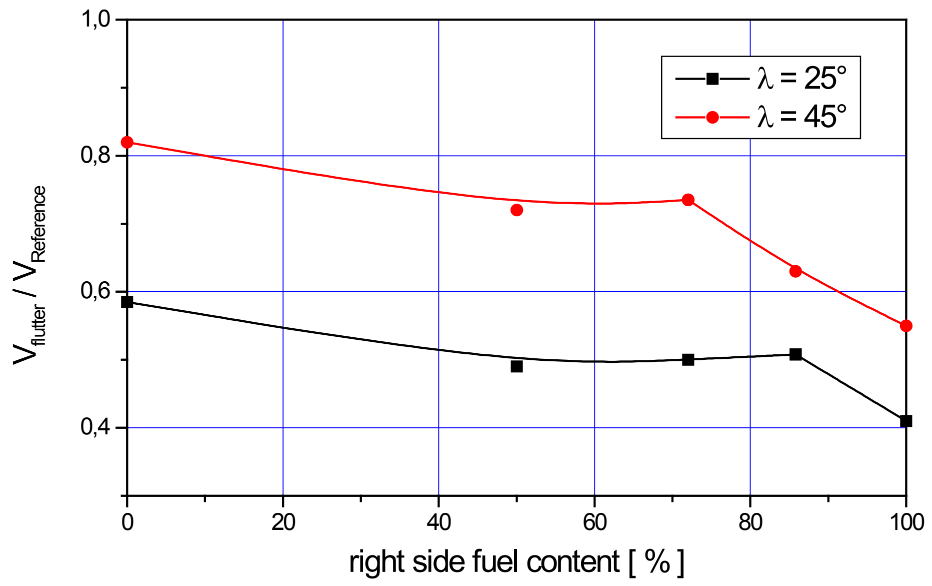

Figure 18: Flutter speed versus asymmetrical fuel emptying of Inboard tanks with symmetrical outboard stores.

At 45 ° wing sweep angle the lowest flutter speed is achieved for the 50/100 % fuel condition. It is striking that all results obtained for the tank fuel emptying reveal only little effect of asymmetries on the second flutter mode which is dominated by the store pitch mode of the tank with 50% fuel, coupling with the wing bending mode at a frequency of about 6 Hz. This is also evident from the flutter speed/damping curves for the inboard carriage only.

5.0 CONCLUSION

All results are demonstrated here have been obtained for wing pylons with single point attachments, due to the requirement of sweepable wings. The results are pure theoretical without structural damping. In some cases structural damping changes the flutter behavior. For a parameter investigation the pure tend is important and therefore only results without structural damping are considered. The pylons are connected via a control rod to sweep each store in the streamline position after sweeping the wing. For other pylon attachments changes of the critical flutter conditions by asymmetrical store carriage may be different.

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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