

# Fluid Structure Interaction Simulation on the F/A-18 Vertical Tail

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For the Swiss F/A-18 Aircraft, the Boeing Company performed an Aircraft Structural Integrity Study (ASIP) to analyze the structural integrity of the entire airframe based on the Swiss design spectrum. To validate this study a full scale fatigue test was carried out at RUAG. By setting up the test facility and preparing the fatigue test loads using data from the F/A-18 Original Equipment manufacturer (OEM) RUAG met some difficulties due to the sparse documentation. This situation pushes RUAG to search for methods to generate aerodynamic loads for the F/A-18 on its own. As a result a large investment is made in the development and implementation of Computational Fluid Dynamics (CFD). The Center Aerodynamics of RUAG employs the Navier Stokes Multi Block (NSMB) computational fluid dynamics (CFD) code which is developed in an international collaboration. The CFD code was validated by comparing results of calculations with wind tunnel results, and literature cases. The F/A-18 CFD model was validated with loads data from the Boeing flight loads data base. For selected load cases unsteady calculations are carried out. The fluctuating loads at the vertical tail due to the buffeting induced by the vortices of the leading edge extension are up to 2.5 times higher than the averaged steady state value. Using the information of the CFD calculation a Swiss dynamic design spectrum is created and compared with the Boeing spectrum. Unsteady coupled results using CFD calculations for dynamic load analysis on the F/A-18 vertical tail are presented here. The use of novel unsteady aero-elastic simulation will improve the design of modern aero structures due to buffeting and flutter problems in an early design phase.

## Nomenclature

<i>ALE</i>	=	Arbitrary Lagrange Eulerian
<i>AoA</i>	=	Angle of Attack
<i>ASIP</i>	=	Aircraft-Structural-Integrity-Program
<i>BM</i>	=	bending moment
<i>CAD</i>	=	Computer Aided Design
<i>CFD</i>	=	Computational Fluid Dynamics
<i>CSM</i>	=	Computational Structural Model
<i>DES</i>	=	Detached Eddy Simulation

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<i>FEM</i>	=	Finite Element Model
<i>FSI</i>	=	Fluid Structure Interaction
<i>LC</i>	=	Loadcase
<i>LEX</i>	=	Leading Edge Extension
<i>MI</i>	=	Modul Integration
<i>MPI</i>	=	Message Passing Interface
<i>NSMB</i>	=	Navier Stokes Multi Block
<i>OEM</i>	=	Original Equipment Manufacturer
<i>Q</i>	=	Dynamic pressure
<i>RANS</i>	=	Reynolds averaged Navier Stokes
<i>SFH</i>	=	Service Flight Hour
<i>SH</i>	=	Single Program Multiple Data
<i>TEF</i>	=	Trailing Edge Flap
<i>TFI</i>	=	Trans Finite Interpolation
<i>TQ</i>	=	Torque or torsion moment
<i>VSI</i>	=	Volume Spline Interpolation

## I. Introduction

For the Swiss F/A-18 Aircraft, the Boeing Company performed an Aircraft Structural Integrity Study (ASIP) to analyze the structural integrity of the entire airframe based on the Swiss design spectrum. The Swiss maneuver spectrum is three times more severe in terms of maneuvers than the US Navy design spectrum, but the dynamic spectrum used for fatigue analysis is the same as the US Navy dynamic design spectrum. For the validation of the Swiss Redesign a Full Scale Fatigue Test was carried out at RUAG, Ref. [1]. Only few relevant fatigue load cases for the entire airplane are obtained from The Boeing Company in St. Louis, the F/A-18 Original Equipment Manufacturer (OEM).

This situation pushed RUAG to look for methods to generate aerodynamic loads for the F/A-18 and as a result a large investment was made in the development and implementation of steady and unsteady Computational Fluid Dynamics (CFD) calculations. To take the structural response into account a Fluid Structure Interaction (FSI) tool is developed. This effort provides RUAG with the ability to predict component loads to be applied on the structure for steady state and buffeting fatigue analysis. In addition, it is a tool which permits to better understand the complicated flow field over the entire F/A-18 full flight envelope and to check some of the load cases delivered by the OEM.

## II. Computational Fluid Dynamics Development with NSMB

### The NSMB Flow Solver

The calculations of the F/A-18 flow field are carried out using the NSMB Structured Multi Block Navier Stokes Solver. NSMB was developed from 1992 until 2003 in a consortium composed of four universities, namely EPFL (Lausanne), SERAM (Paris), IMFT (Toulouse) and KTH (Stockholm) and four industrial companies in particular Airbus France, EADS (Les Mureaux), CFS Engineering (Lausanne) and SAAB Aerospace (Linköping). Since 2004 NSMB is developed in a new consortium lead by CFS Engineering and composed of RUAG Aviation (Emmen), EPFL (Lausanne), EHTZ (Zürich), IMFT (Toulouse), IMFS (Strassbourg), the Technical University of Munich and the University of the Army in Munich.

NSMB employs the cell-centered Finite Volume method using multi block structured grids to discretize the flow field. Various space discretization schemes are available to approximate the inviscid fluxes, among them the 2nd and 4th order centered scheme with artificial dissipation, and 2nd, 3rd and 5th order upwind schemes.

The space discretization leads to a system of ordinary differential equations, which can be integrated in time using either the explicit Runge Kutta scheme or the semi-implicit LU-SGS scheme. To accelerate the convergence to steady state the following methods are available:

- local time stepping
- implicit residual smoothing (only with the Runge Kutta scheme)

- multigrid and full multi grid (grid sequencing)
- pre-conditioning for low Mach number
- artificial compressibility for incompressible flows

For unsteady flow calculations the 3rd order Runge Kutta scheme and the Dual Time Stepping method are available. Different turbulence models have been thoroughly tested and validated in NSMB:

- Baldwin-Lomax
- Spalart-Allmaras
- Chien  $k-\epsilon$
- Wilcox  $k-\omega$
- Menter Baseline and Shear stress  $k-\omega$
- DES

The ALE approach is available to simulate the flow on deforming grids. Recently a re-meshing algorithm was implemented in NSMB to permit the simulation of the flows on deforming grids, as found for example in Fluid Structure Interaction problems. NSMB has no limit on the number of blocks used in a calculation. Block interfaces do not need to be continuous since a sliding mesh block interface treatment is available.

### **The F/A-18 Mesh Generation**

The most time consuming process in a CFD simulation is the generation of the grid. This involves different steps. First (if required) the CAD surface needs to be cleaned up, then a multi block topology needs to be set-up, and finally the mesh is generated. The latest mesh for the F/A-18 fighter is generated by RUAG Center of Aerodynamics in collaboration with Mindware, using ANSYS ICEM CFD software. The half model mesh has 3377 blocks and 14.5 million cells see figure 1.

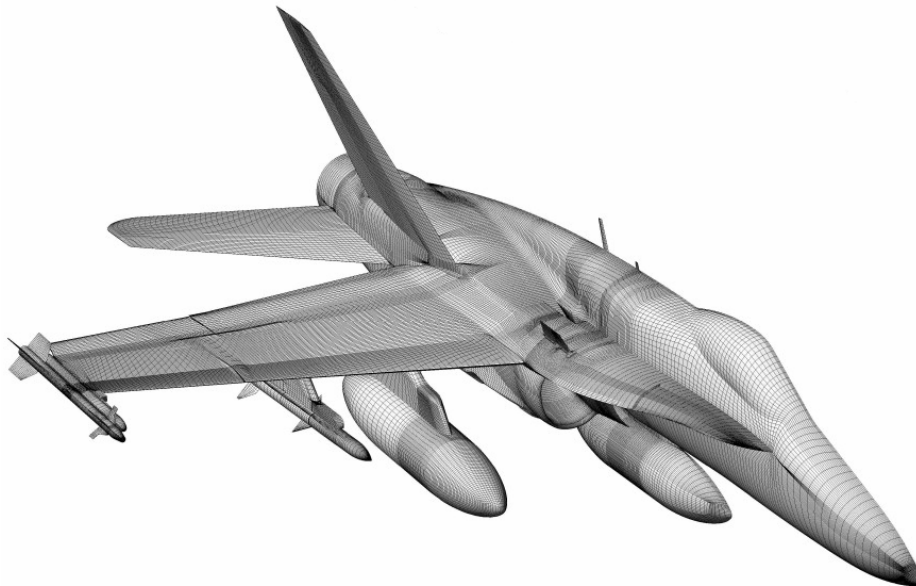


Figure 1: Detailed of the F/A-18 mesh (half model).

### **The aerodynamic Loads Extraction Method**

To permit the calculation of the aerodynamic loads on different aircraft a post processing program is developed that computes the aerodynamic loads on each aircraft component.

### III. The Steady State Calculation with NSMB

In all calculations discussed here it is assumed that the aircraft is perfectly symmetrical and only symmetrical load conditions are considered. Consequently only one half of the aircraft is used in the calculations.

The component loads in the F/A-18 US Navy F4 flight data base are based on reliable measurements and are used to validate the CFD calculation. 15 load cases are simulated with the half mesh model, taking into account the real control surface positions. Also 12 Swiss load cases from the ASIP study are calculated for comparison.

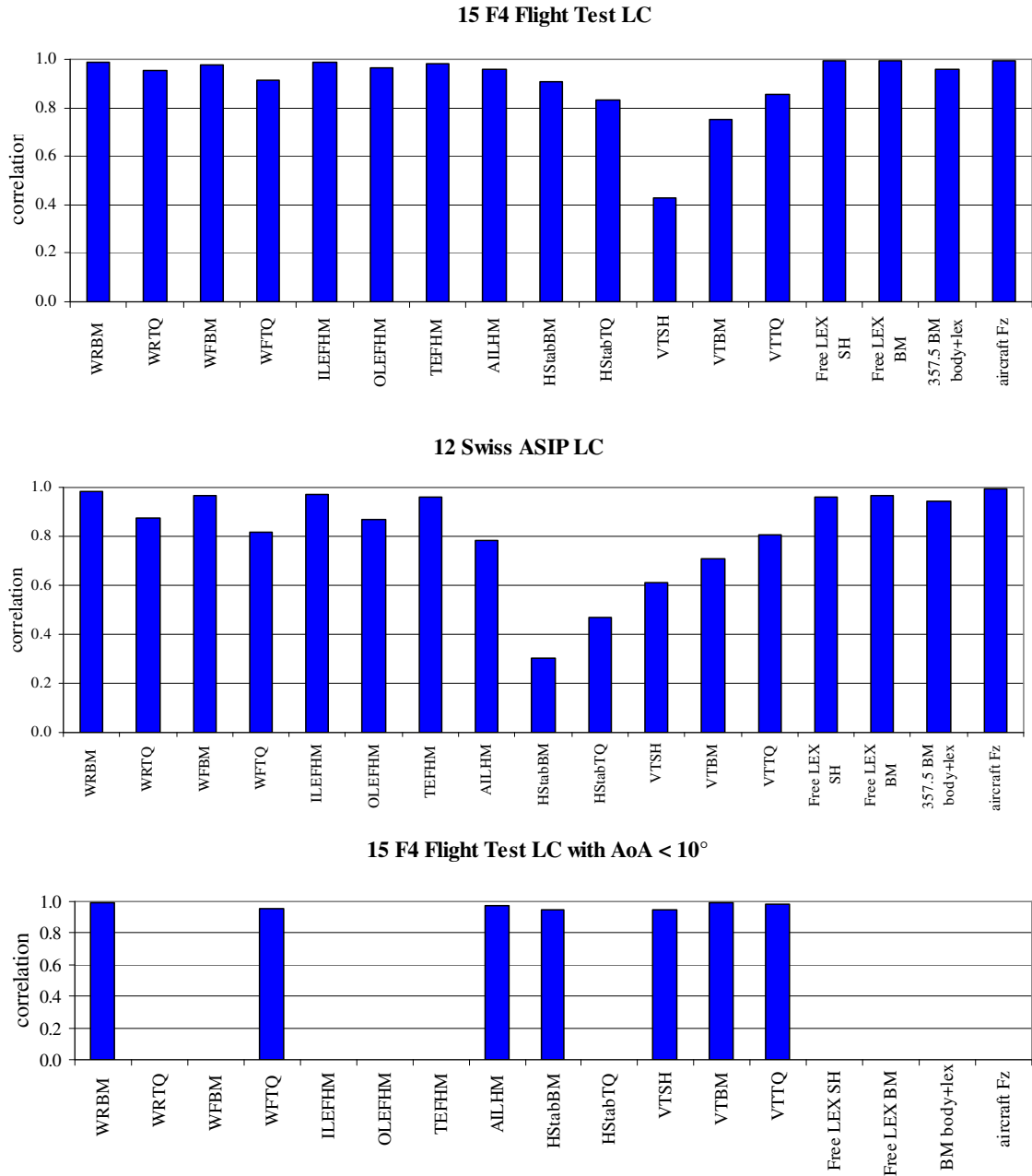


Figure 2: Comparison of CFD results with flight loads data and Swiss ASIP load cases

The CFD results for the F4 load cases (see figure 2) match very well compared to the flight test data. However for the ASIP load cases the CFD data shows less good agreement compared to the Boeing loads. This could be explained by the fact that the Swiss ASIP loads were inter- and extra-polated from the F4 database and therefore these loads do not represent real flight data.

If only loads with an AoA below  $10^\circ$  are considered the results match much better especially for the vertical tail compared to the F4 flight database. The vertical tail and the horizontal tail are influenced by unsteady loads which are not correctly treated by steady RANS calculation. In summary we can say that the NSMB solver predicts the F/A-18 US Navy flight data loads quite well using the RANS approach.

The Swiss load case C1S825 corresponds to an 8.25 g steady state manoeuvre at an angle of attack  $AoA = 15.9^\circ$ . At this condition the wing tip deforms due to the high loads up to 0.5m , and one can expect that this change in wing shape will influence the flow over the wing, and thus on the aerodynamic loads. To investigate this effect an iterative CFD calculation on a flexible F/A-18 wing (with control surfaces) is made. Four iteration steps are needed to reach the equilibrium between aerodynamic and structural forces. During this simulation the fuselage, horizontal stabilizer, vertical tail and rudder are considered as rigid.

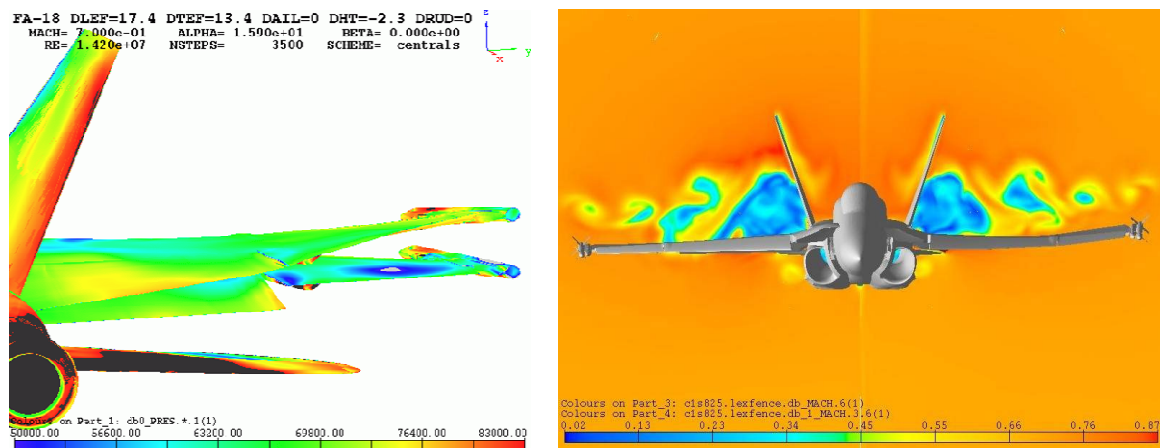


Figure 3: Deformed wing and comparison of mach contour

The deformed wing is shown in figure 3. Note that the missile remains almost parallel to itself; hence we are facing a more or less pure bending deformation mode. It can also be seen that the size of the gap between TEF and aileron is reduced by the deformation of the wing. The differences of the flow field due to the deformation of the wing is clearly visible in the Mach contour plot, see figure 3.

The first iteration produces a large deflection. The second and subsequent iterations bring only small corrections, and the third and fourth iterations are almost identical. The wing bending and the torque moment is calculated for the undeformed (no FSI) and the deformed (FSI) wing shape, see figure 4. The wing bending moment along the span for the flexible wing is reduced due to the redistribution of loads from the outer wing to the inner wing. As a consequence the torque moment is increased along the elastic axis which is explained by the change of twist angle (downward) under loading.

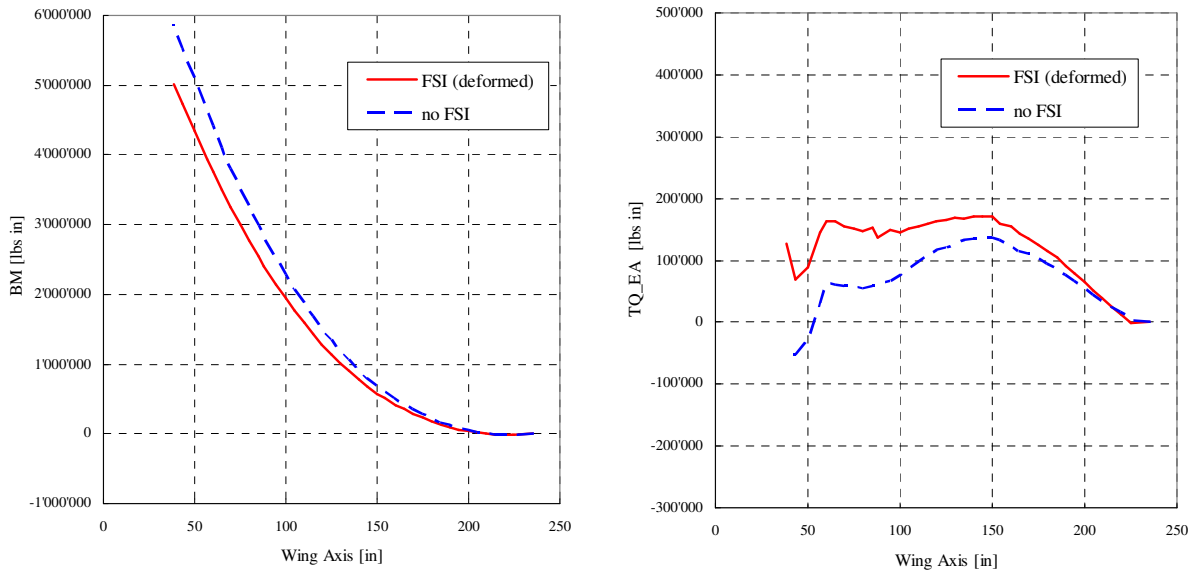


Figure 4: Wing bending moment and torque of undeformed and deformed structure

#### IV. The Unsteady Calculation with NSMB

##### First unsteady Calculation for C2S825 Swiss Load Case

Unsteady calculations are made for the Swiss design load case C2S825, which concerns a 8.25 g manoeuvre at Mach=0.7, Altitude 15'000 feet and angle of attack  $AoA = 26.6^\circ$ . Within the NSMB solver the Detached Eddy Simulation (DES) algorithm with the Spalart-Allmares turbulence model is applied. The dual time stepping approach is used with a constant outer time step of  $2.5 \cdot 10^{-4}$  seconds. Two thousand time steps are calculated, which results in 0.5 seconds of real time are simulated. In figure 5 you can see the different pressure loading at the aft fuselage at two time steps. The difference between steady and unsteady (averaged value) calculations is clearly visible in the total  $F_z$  load at the vertical tail. The pressures are saved each outer time step to permit the analysis of the unsteady aerodynamic loads on the aircraft. Comparison of the mean unsteady aerodynamic loads with the loads obtained using a steady calculation show significant differences in loads on the aft fuselage, vertical tail, rudder, trailing edge flap, aileron and horizontal stabilizer, indicating that unsteady flow effects are important on these components of the aircraft.

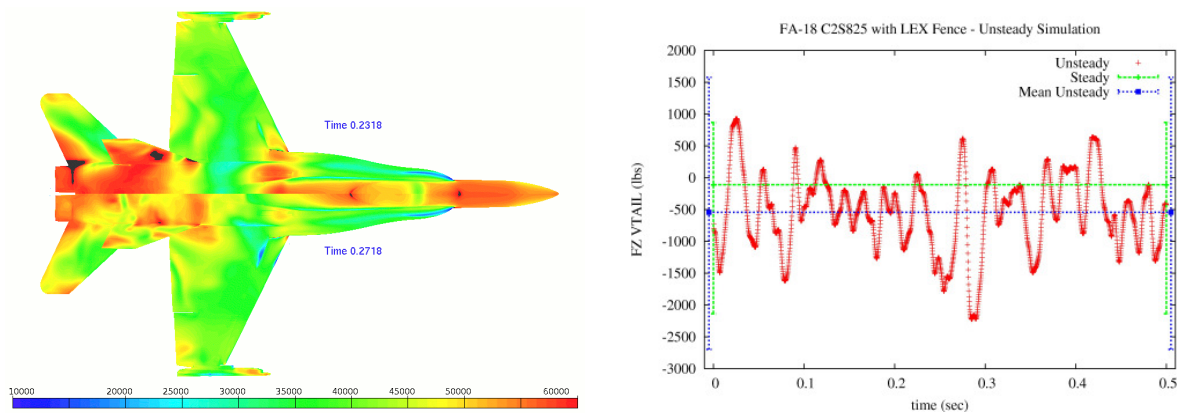


Figure 5: Unsteady CFD result at two time steps 0.2318 sec top and 0.2718 sec bottom, see the differences in pressure on the aft section, and fluctuation in total load  $F_z$  at the vertical tail.

## V. Unsteady aero-elastic coupling Development

To take into account the full structural response due to dynamic aerodynamic loads an unsteady aero-elastic simulation tool is required. RUAG started the development of such a tool in early 2005. Essential elements of this tool are:

- a CFD solver using the ALE formulation and which includes a re-meshing algorithm to regenerate the CFD volume mesh after the movement of the surface;
- a geometrical coupling tool which permits transfer of the aerodynamic loads from the CFD mesh to the CSM mesh, and transfers the structural displacement into the CFD surface geometry displacement;
- a CSM solver to compute the structural state. To reduce computational costs a linear structural model is used, which is further simplified by using a modal formulation. The time integration of the structural equations are computed using the Newmark method.

The CFD and CSM solvers are coupled through the geometric coupling tool (the so called segregated or partitioned approach). Within this approach different coupling schemes can be formulated and in a first step the so called Conventional Staggered Scheme (CSS) Ref. [2] is implemented. This may be sufficient for small deformations of the surface, but for larger deformations a stronger coupling approach may be needed Ref. [3].

### Validation of the unsteady coupling Procedure

To validate the unsteady aero-elastic simulation tool calculations are made for the AGARD 445.6 wing Ref. [4]. The AGARD445.6 wing, made of mahogany, has a 45° quarter chord sweep, a half span of 2.5 ft, a root chord of 1.833 ft and a constant NACA64A004 symmetric profile.

Flutter tests are carried out at the NASA Langley Transonic Dynamics Tunnel, are published in 1963 and re-published in 1987. Various wing models are tested (and broken) in air and Freon-12 for Mach numbers between 0.338 and 1.141. The case most often uses in the literature is the so called weakened model 3 at zero angle of attack in air. The model is weakened by holes drilled through the structure of the original model to reduce its stiffness.

The linear structural model is build by RUAG, with the material properties taken from Ref. [5]:

E1	3.15106 10 <sup>6</sup>	Pa
E2	4.16218 10 <sup>8</sup>	Pa
G	4.39218 10 <sup>8</sup>	Pa
ρ	381.98	kg/m3
v	0.31	-

Only the first four mode shapes are considered, consisting of two bending and two torsion modes. CFD calculations are made for the following free stream conditions:

Mach	0.95	-
ρ <sup>∞</sup>	0.061	kg/m3
α	0	°
Re	1.196 10 <sup>6</sup>	1/m
μ	234.93	-

using free stream pressures of respectively 3500, 4600 and 7000 Pa. Experimental data shows that flutter occurs at freestream pressure of 7000 Pa.

The coupled aero-elastic calculations are started from the steady CFD result for the same conditions. An initial modal displacement is given to the structure and the unsteady simulation was started. A structural damping of 2% is used in the CSM calculation. In the figure 6 one can observe that, conforming to the experimental case at 7000 Pa the deflections are growing, in the two other cases they are damped.

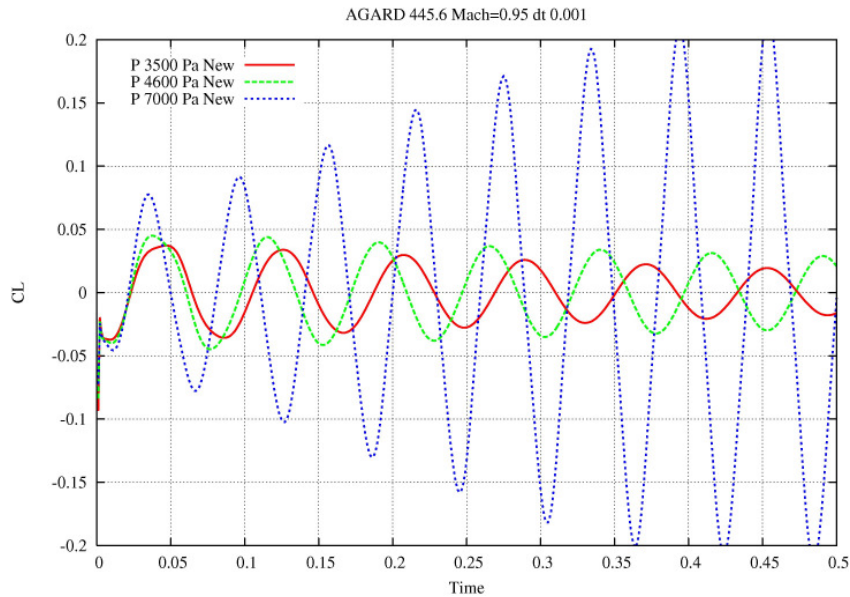


Figure 6: Lift forces for the 3 different pressures and a duration of 0.5 sec.

### Re-meshing Algorithm for complex Geometry

The NSMB flow solver includes a re-meshing procedure since 2004, which was improved in 2005 and 2006. The objective of the re-meshing procedure is to generate a new grid inside NSMB using the old coordinates as input together with the displacements of parts of the mesh (for example the deformation of the wing surface due to the aerodynamic loads). The initial re-meshing procedure is based on the Volume Spline Interpolation (VSI) method Ref. [6] and is carried out in two steps. In the first step information is collected on coordinates and their displacements, and a list of so called prescribed points is generated. A matrix of linear equations needs to be solved to compute the Volume Spline Coefficients. For the second step three methods are available:

1. generate the new volume mesh using the Volume Spline Interpolation method
2. generate the mesh on the block faces using the Volume Spline Interpolation method and use 3D Trans Finite Interpolation (TFI) to generate the new volume mesh
3. generate the mesh on the block edges using the Volume Spline Interpolation method, use 2D Trans Finite Interpolation to generate the mesh on block faces and use 3D (TFI) to generate the volume mesh

The main shortcoming of method 1 is the large computational requirements (CPU time and memory), in particular for complex geometries such as the F/A-18. As mentioned before, at the start of the re-meshing procedure a list of so called prescribed points is generated. If  $n$  is the number of prescribed points, then the memory requirements for the VSI coefficient calculation is proportional to  $\frac{1}{2} n^2$ , and CPU time requirements follow the same trend.

The simplest method to reduce memory and CPU time requirements is to reduce the number of prescribed points in the VSI coefficient calculation, and this can be done by using methods 2 and 3. When using the VSI method to generate the volume mesh one needs to ensure that the displacements of the surface are correctly transferred into the new volume mesh, and as a result many prescribed points are needed on the moving surface. When using VSI to generate the block faces (method 2), one only needs to select the block edges of the moving surface. The conservation of geometry is ensured automatically by setting the new coordinates of the moving block face as the sum of the un-deformed coordinates and their displacement. When using VSI to generate the block edges (method 3), one only takes the vertices on the moving surface as prescribed points. Although methods 2 and 3 look simple in practice several difficulties are encountered. The first problem is typical of multi block meshes, and is due to the fact that several blocks share the same edge. In this case one needs to ensure that all blocks which share an edge receive a moving edge before generating the mesh on the block face. The second problem is related to the TFI method. Many variants of TFI exist, and when the TFI method for the re-meshing algorithm is not exactly the same as the

TFI method used to generate the original mesh large movements of the mesh may be observed in regions where nothing should happen. Since the TFI method of the original mesh is a priory unknown, this results in problems. The breakthrough is to use the TFI method (in 2D and 3D) on the displacements instead of the coordinates. The advantage of this method is that if the displacement of the edges is close to zero, the displacement of the coordinates in the volume will be close to zero as well, and as a result the original coordinates are unchanged. The second advantage of this procedure is that it is independent of the method used to generate the original coordinates. The re-meshing method used for the F/A-18 studies can now be summarized as:

- compute the displacements of block edges using Volume Spline Interpolation
- use 2D Trans Finite Interpolation to generate the displacements of the coordinates on the block faces
- use 3D Trans Finite Interpolation to generate the displacements of the coordinates in the volume

## VI. Unsteady coupled Calculations for the F/A-18 Vertical Tail

### Simulation Parameters

Unsteady simulations are made for the F/A-18 fighter using different aircraft configurations and free stream conditions. All calculations are carried out using the dual time stepping method, in which the outer loop is used for the advancement in time, while in the inner loop a pseudo time stepping method (time marching) is used to solve the equations at each outer time step. The Detached Eddy Simulation (DES) variant of the  $k-\omega$  Menter Shear Stress turbulence model is used to model the unsteady turbulence. All unsteady calculations are started from a converged steady state calculation for the same free stream conditions. An outer time step of  $2.5 \cdot 10^{-4}$  seconds is used, and the pressure and deformation vector were saved each outer time step. For the aero-elastic calculations the fluid structure coupling is executed each inner time step corresponding to a square number (inner step 1, 2, 4, 9, ...). Initial tests show that this is sufficient and computationally less expensive compared to carrying out the coupling each inner time step.

A simple structural model of the Vertical Tail used for the aero-elastic calculations was prepared by RUAG. For the F/A-18 vertical tail only the first 4 or 5 mode shapes are important (bending and torsion moments), and it was decided to use only the first 5 modes in the coupled calculations.

Three different F/A-18 conditions/load cases are computed, a transonic case, a Swiss design load case C2S825, a subsonic case for which experimental data were reported in the literature.

### Transonic Load Case

The definition of this configuration and the free stream conditions are summarized in Table 1.

Mach	Alt [feet]	AoA [deg]	LEF [deg]	TEF [deg]	HSTAB [deg]
0.9	5'000	0.0	0.0	0.0	0.0

Table 1: specification of the transonic load case

This load case is not in the buffeting environment and therefore an initial perturbation has to be used. The coupled CFD-FSI calculation is computationally twice as expensive as the uncoupled calculation.

To analyze the movement of the vertical tail, 5 points are selected. Points 1 and 2 are on the top of the vertical tail, points 3 and 4 near the gap between rudder and vertical tail and the last point is near the trailing edge, for details see Figure 7.

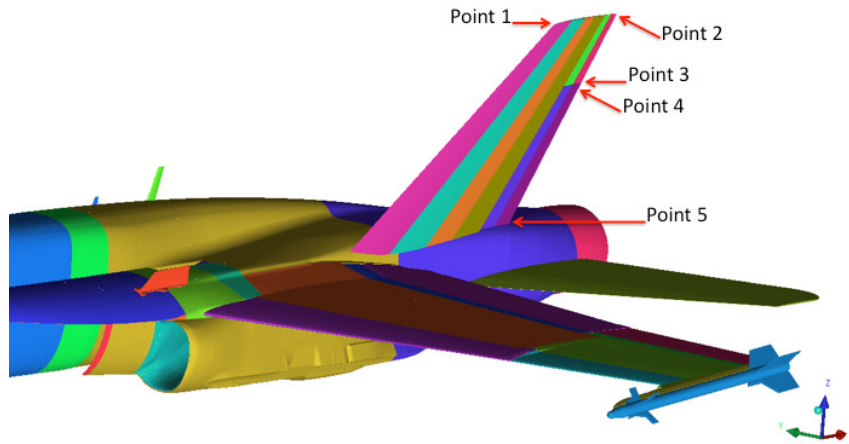


Figure 7: Five selected points which were used for dynamic data analysis.

Figure 8 shows the movement in Y-direction (outboard/inboard) of the five points. Most dominant is the movement on the top of the vertical tail (points 1 and 2), where the initial perturbation is clearly visible when starting the coupled calculation. This initial perturbation is followed by an oscillatory movement of the vertical tail, which is damped out in time.

The unsteady simulation without FSI coupling for this load case shows a steady flow on the vertical tail, which is confirmed by the fully coupled calculation. The initial perturbation at the start of the coupled simulation is damped out in time, indicating that there is no mechanism which maintains an unsteady flow behavior.

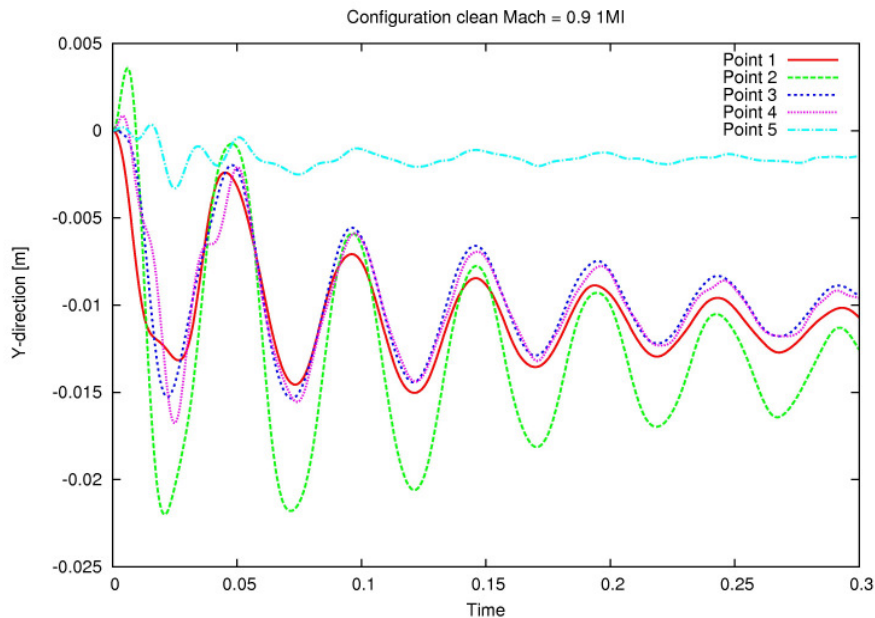


Figure 8: Movement in Y direction for the 5 selected points for 0.3 sec.

### Swiss Design Load Case C2S825

The Swiss design load case C2S825 (Boeing data from Swiss ASIP) is affected by severe buffeting at the vertical tail. This case is characterized by the following parameters, see Table 2:

Mach	Alt [feet]	AoA [deg]	LEF [deg]	TEF [deg]	HSTAB [deg]
0.9	15'000	26.6	26.0	0.0	-6.1

Table 2: Specification of the Swiss design load case C2S825.

This load case corresponds to an 8.25 g manoeuvre at Mach=0.7. The calculation without FSI coupling shows significant differences in the averaged unsteady aerodynamic loads compared to the loads obtained using a steady calculation, in particular on aft fuselage, vertical tail, rudder, trailing edge flap, aileron and horizontal stabilizer. This is a clear indication that unsteady flow effects are important on these components of the aircraft.

A first coupled simulation is made for this load case running up to 0.5 seconds real time. As for the transonic load case 5 points are selected to show the movement of the vertical tail, see figure 9. Compared to the transonic load case the movement of the vertical tail is much more prominent, up to 13 cm in Y-direction compared to a little more than 2 cm.

To compare data transformed from the time domain to the frequency domain the simulation of 0.5 seconds is not enough. Therefore a second coupled calculation is made running up to 4 seconds real time, which is later used for fatigue spectrum data.

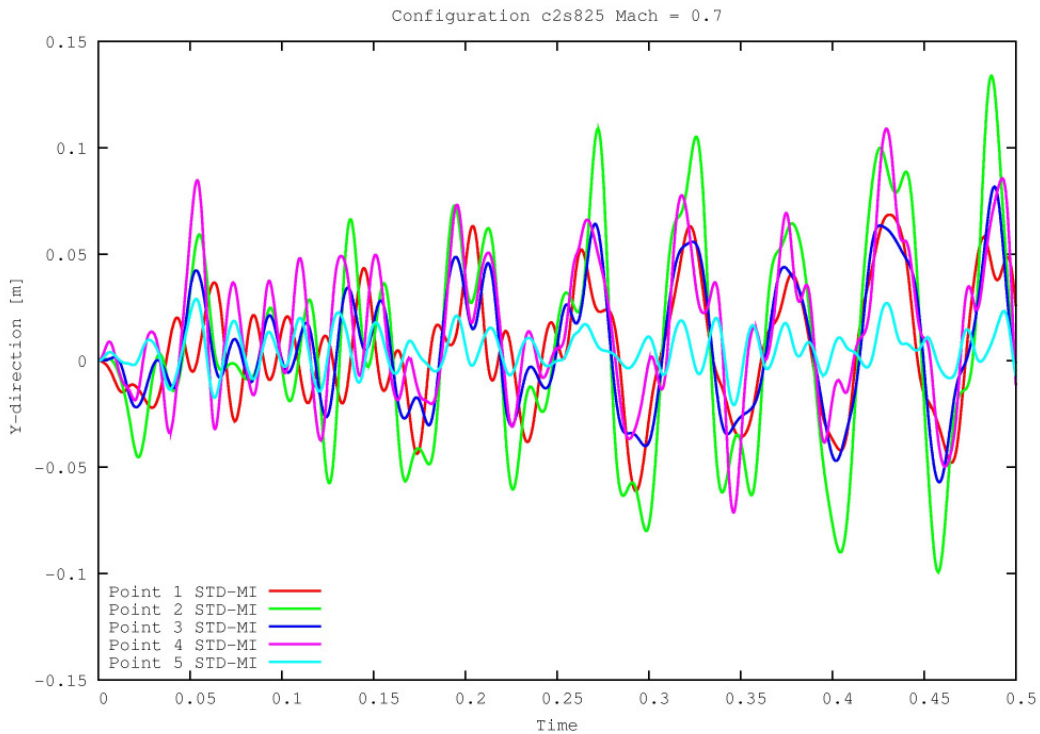


Figure 9: Movement in Y direction for the 5 selected points for 0.5 sec.

### Subsonic Load Case

L. A. Meyn published in 1996 results of buffeting measurements on a Full Scale F/A-18 in the wind tunnel at NASA Ames Research Center Ref. [7]. The test conditions were Mach=0.15, SL at different angles of attack, the following data was analyzed, see table 3.

Mach	Alt [feet]	AoA [deg]	LEF [deg]	TEF [deg]	HSTAB [deg]
0.15	0	var	0.0	0.0	0.0

Table 3: Specification of the subsonic load case.

Interesting results can be found in the Ref. [8], where the RMS-Pressure Coefficient (1) on the 45% chord, 60% span of the vertical tail from CFD-computations, wind tunnel test and flight tests are published. Figure 10 shows the result of our CFD calculation.

$$\text{RMS-Pressure Coefficient} = \frac{1}{Q} \sqrt{\frac{1}{N} \sum_1^N (p_i - \bar{p})^2} \quad (1)$$

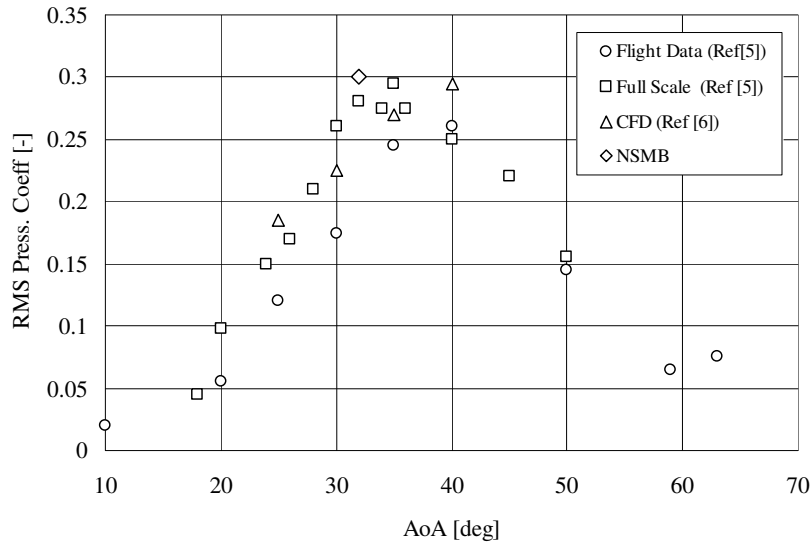


Figure10: RMS pressure coefficient at 45% chord and 60% span of the vertical tail.

## VII. Fatigue Analysis for Vertical Tail Buffeting

### Buffeting Loads Calculation

To determine the buffeting loads at the vertical tail root at FS557 stub location an engineering approach is used. In order to quantitatively take profit of the results of the CFD-FSI-calculation on the F/A-18 the vertical tail surface is divided into 54 panels and the pressure and the motion at each panel centroid is extracted (see figure 11). The differential pressure  $p_i$  over the 54 panels as well as their displacement in time gives us the ability to determine the dynamic loading of the connection between the vertical tail and the fuselage (2).

$$\vec{M}(t) = (BM(t), PM(t), TQ(t)) = \sum_1^{54} \vec{r}_i x (A_i \vec{p}_i(t) - m_i \vec{a}_i(t)) \quad (2)$$

With BM, PM and TQ the bending, pitch and torsion moment at the root of the vertical tail,  $A_i$  the panel surface,  $p_i$  panel pressure,  $m_i$  lumped mass and  $a_i$  the acceleration. The most interesting aspect for RUAG is the fatigue damage caused by the vertical tail buffeting. In order to check the plausibility and the feasibility of a fatigue calculation based on the F/A-18 CFD-FSI, the peak-valley sequence in a structural location of the stub 557.5, which is the forward connection beam vertical tail to fuselage, has been calculated.

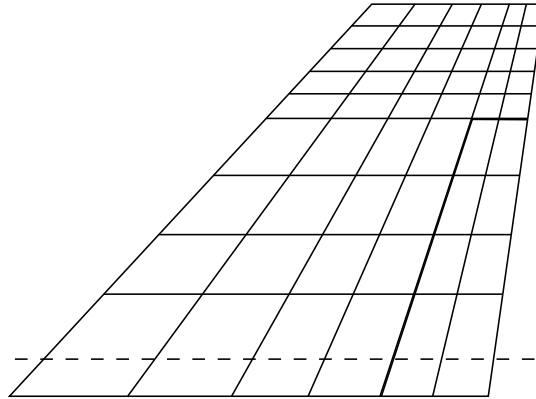


Figure 11: Vertical tail with 54 panels used for analysis.

The strain survey measurements accomplished during the Swiss F/A-18 Full Scale Fatigue test delivered us the coefficient A and B of equation (3) and on this way the relation between the strain at gauge position SF6001 (see figure 12) and the moments BM and TQ.

$$\varepsilon_c(t) = A \cdot BM(t) + B \cdot TQ(t) \quad (3)$$

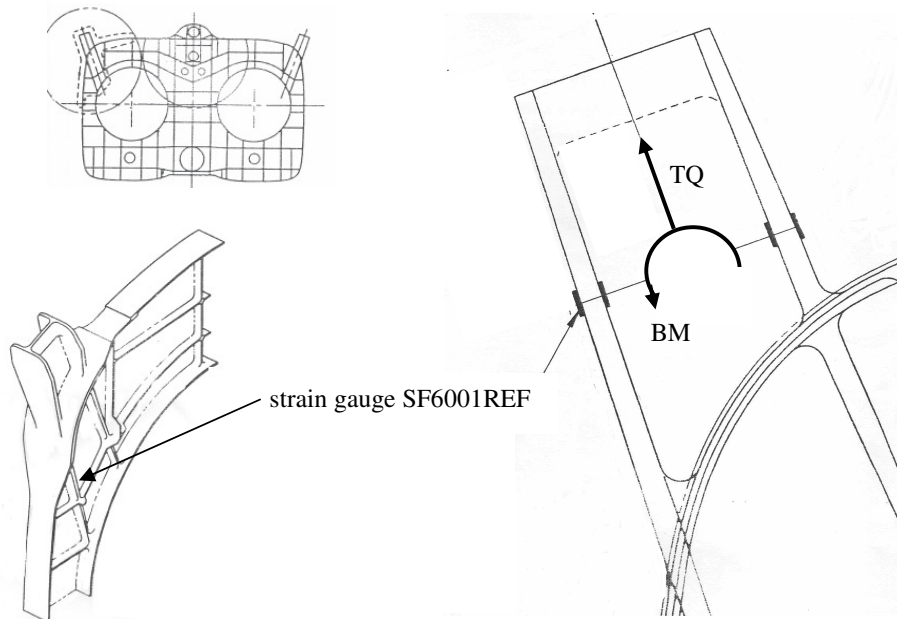


Figure 12: Gauge position at the vertical tail stub at FS557 (first stub out of 6).

A part of the  $\epsilon_c(t)$ -function (3) for the buffeting peak valley sampling can be seen in the figure 13. In order to evaluate the buffeting effect on the global fatigue damage this peak-valley sequence has been inserted in the test spectrum called MES used for the Full Scale Fatigue Test, considering that buffeting occurs when the angle of attack AoA exceeds a limit value of  $20^\circ$ . Such a mixed spectrum of manoeuvre and buffeting loads is presented in figure 14.

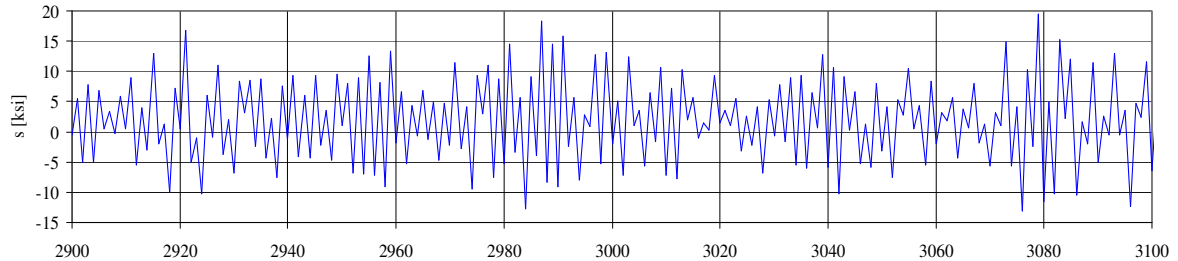


Figure 13: A sample of the  $\epsilon_c(t)$ -function for the buffeting peak valley sampling for 2.5 sec.

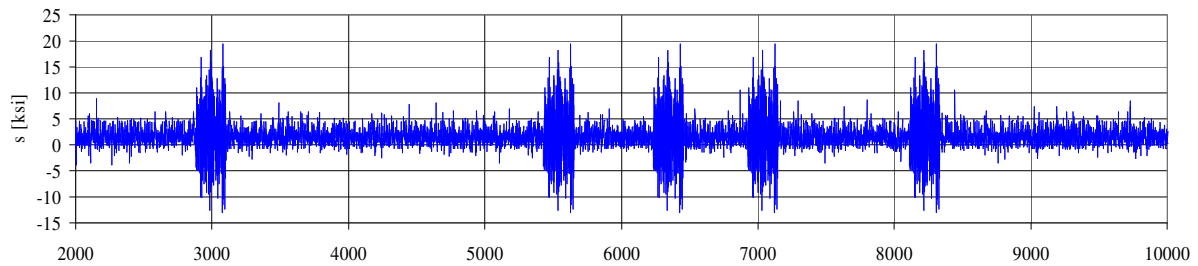


Figure 14: Mixed Spectrum with AoA limit for buffeting above  $20^\circ$ .

### Fatigue Life Calculation

This set of spectrum has been used for the crack initiation life calculation (Boeing CI89 software) in order to evaluate the effect of the buffeting on the stub at F.S.557. To produce realistic conditions the following parameters have been chosen for this calculation:

- Neuber Notch Approach
- Material: AL7050-T74
- Flight Hours Number for Spectrum 200
- No Prestain Material Data
- Equiv. Strain Equation Smith-Watson-Topper

In figure 15 the Fatigue life curves for the onset of buffeting above AoA of  $20^\circ$  (green line) is compared with the no buffeting data (blue line / direct Swiss Full Scale Fatigue Test data). The fatigue life for buffeting cycles at the stress level of KtDLS 60 Ksi can be reduced by a factor of 30. The red line represents the fatigue curve due to the buffeting sequence only without manoeuvre loads, which occurs every 20 hours or 10 time in the Swiss design spectrum (sequence of 200 flight hours).

**Crack Initiation Life**  
**SG\_SF6001, Y557.5 Bulkhead, Vertical Tail Attachment Stub, Outer Leg - IB side, Ref Stress 7.11 KSI,**  
**Mat 7075-T73, Kc/Kt=1**

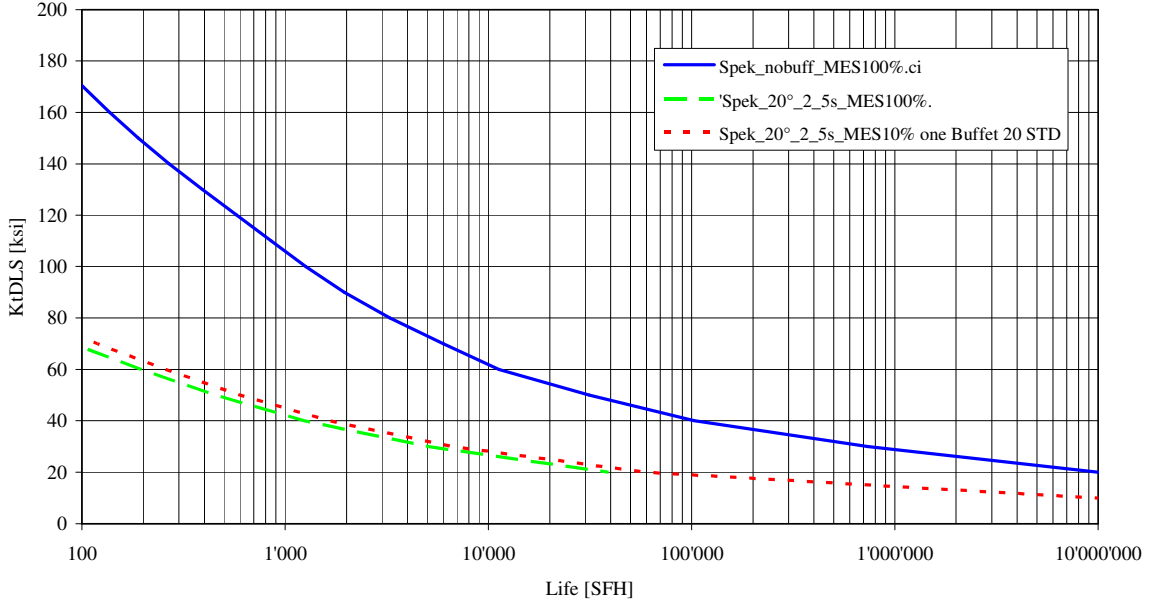


Fig. 15: Fatigue life curves for MES and MES plus buffeting

In a more detailed study the fatigue damage rate of the buffeting cycles is more carefully analyzed (see figure 16). The fatigue damage is based on the cumulative Miner rule using strain life material data. The investigation is done for the stress level KtDLS of 40 Ksi and 60 Ksi. The fatigue damage is mainly caused by the buffeting cycles only. Significant damage accumulation occurs at a peak/valley amplitude higher then 40 Ksi which belongs purely to buffeting loads. So the fatigue damage is primarily caused by the buffeting cycles.

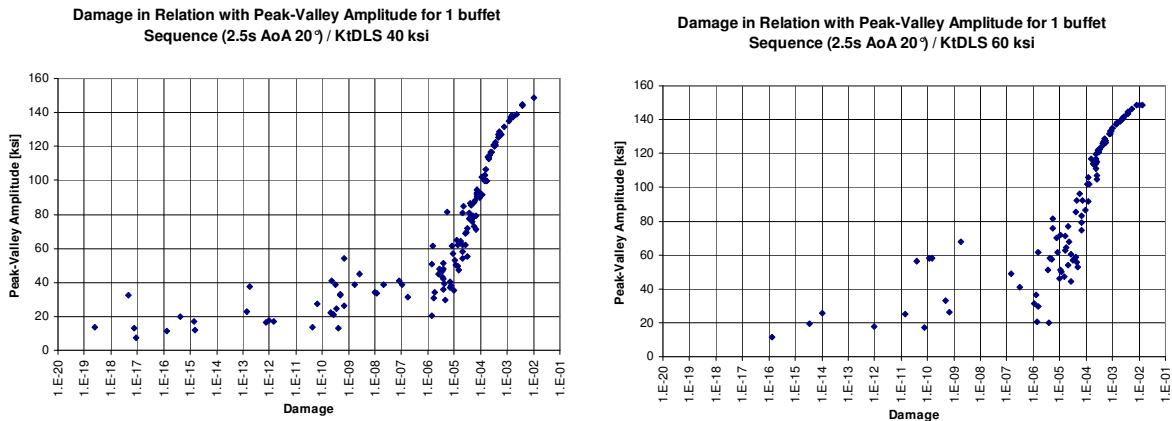


Fig. 16: Damages of the buffeting sequence

Miner Damage sum of 40 Ksi for maneuver spectrum (200 SFH) = 2/1000  
 Miner Damage sum of 60 Ksi for maneuver spectrum (200 SFH) = 17/1000

Miner Damage sum of 40 Ksi for buffeting cycles (200 SFH) = 120/1000  
Miner Damage sum of 60 Ksi for buffeting cycles (200 SFH) = 780/1000

The Miner damage sum for the buffeting cycles at 40 Ksi and 60 Ksi is at least an order of magnitude higher as for the maneuver cycles. This clearly demonstrates the severity of fatigue life due to buffeting.

The above simple method will allow a dynamic analysis using buffeting loads for the Swiss usage spectrum. With the help of FSI/MI unsteady coupling tool buffeting load cycles can be calculated to generate a full dynamic spectrum for fatigue analysis.

## VIII. Conclusion

The interaction of the aerodynamic loads on structural stiffness is important and must be considered for the loads calculation using fluid structure interaction. With today's computer performance an unsteady CFD calculation brings more information into buffeting and flutter behavior of modern airplanes. With the NSMB unsteady capabilities flow field for up to 4 seconds over the F/A-18 were processed and analyzed.

To obtain the full information an unsteady fluid structure interaction analysis is necessary. The buffeting impact for the F/A-18 vertical tail is simulated using unsteady aero-elastic coupling algorithm. An efficient re-meshing procedure within the flow solver is important for complex geometries such as the F/A-18 fighter. The required CPU time and memory is still very high but can be managed with today's computer capacity.

The unsteady coupled CFD results may be used to develop a fatigue spectrum for the Swiss F/A-18 usage under buffeting environment condition to assess the structural integrity in more detail.

The buffeting and flutter should be addressed in an early design phase of a modern airplane or be of help later. RUAG CFD dynamic fluid structure interaction tool may provide a good answer to these problems.

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