Vibration-induced fatigue life estimation of the Vertical Tail of the F/A-18 aircraft using virtual sensing

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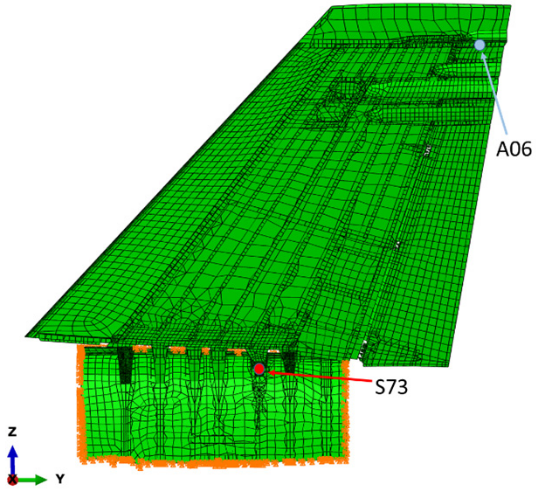
Introduction

Virtual sensing:

- Monitoring and estimation of operational unmeasured quantities (strains in this case) of the structure by indirect measurements (acceleration in this case)
- Hybrid modelling method based on sparse (minimum) measurements and the numerical model of the structure
- Enables fatigue monitoring anywhere in the structural component under question



Research question: Applicability of local/component FE-models for virtual sensing instead of global FE-model

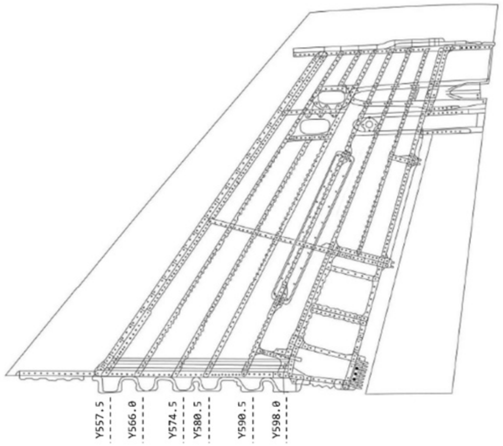
- Modelling effort for the component or subassembly of the structure only smaller compared with the global model of the whole assembly
- Limitations of the method when applying only a local/component FE-model and only one acceleration sensor
  - Estimation error evaluation
- Verification by operational measurements

- Application case: Vertical Tail (VT) of the F/A-18 Hornet aircraft

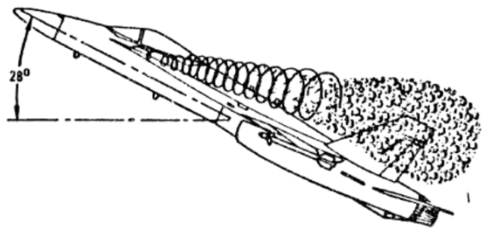
Dynamic loading environment of the F/A-18 Vertical Tail structure

VTT

- High-energy vortices from inner wing leading edge extensions induce severe cyclic loading to the downstream structure
  - Excites the resonance frequencies of the empennage
  - Induced broad band dynamic loads, i.e., buffet loads contribute to the fatigue of the Vertical Tails
  - Occurs especially when flying at high angles-of-attack
- Excited first bending and torsional mode has dominant impact on the fatigue life of the VT structure
  - First bending mode has dominant impact the lower aft root region; especially fuselage to the VT attachment frames
  - First torsion mode predominantly affects the upper region of the structure



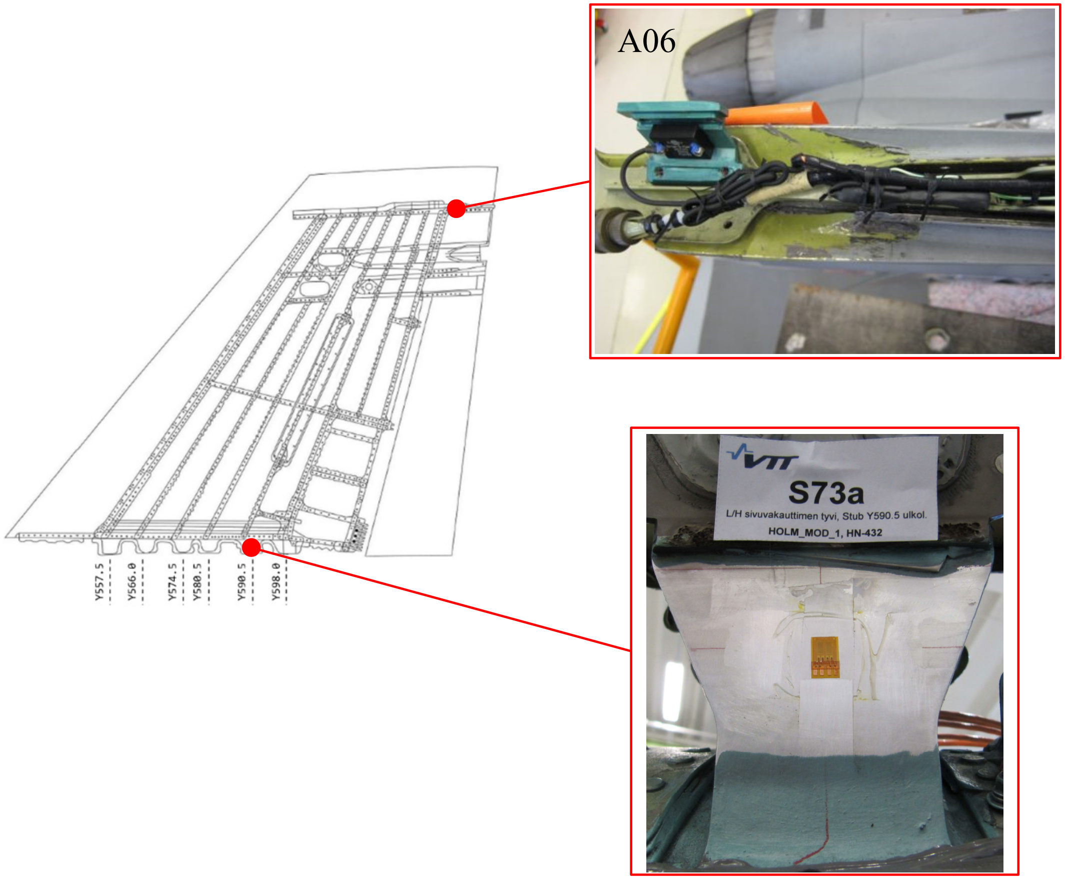
Vertical Tails Excited in 16°-42° AoA range
- Mode I: 1^{st} Bending Mode, peak levels at 32°-36°
- Mode II: 1^{st} Torsion Mode, peak levels at 24°-28°



- Extrinsic signs of fatigue in the VT; black smears from the fasteners and loose fasteners are due to fretting

Hornet Operational Loads Measurement

- The Finnish Air Force has been running the Hornet Operational Loads Measurement (HOLM) program since 2006
  - Quantification the effects of operational usage on the structure of the F/A-18 aircraft
  - Supporting the aircraft structural integrity management efforts
- Onboard instrumentation on globally and locally significant structural locations:
  - 44 strain sensors
  - 4 acceleration transducers
  - In addition, more than 250 flight parameters
- In this study, two of the sensor data have been utilized:
  - Accelerometer A06 at the tip of the VT for virtual sensing
  - For validation reference only: strain gauge S73a at lower aft root region of the VT stub



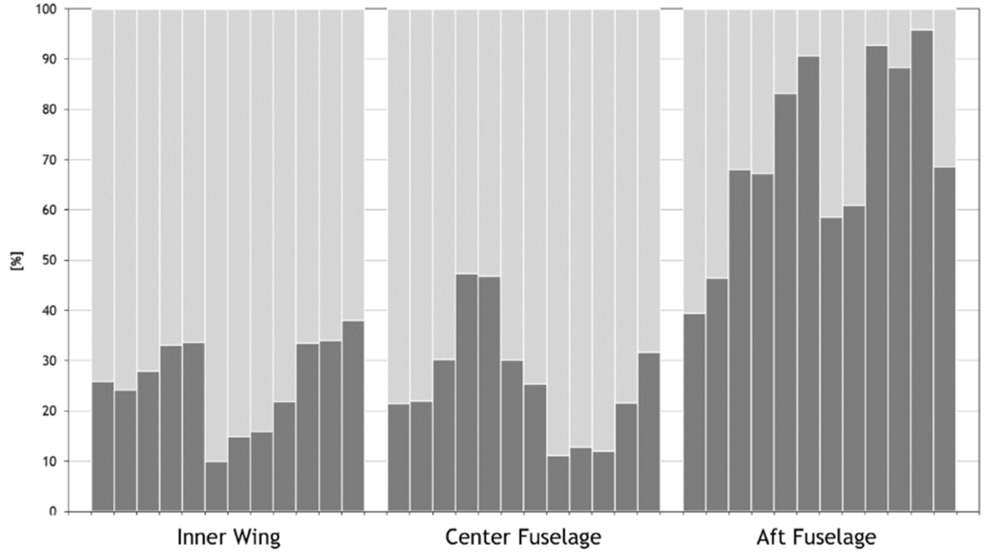
Hornet Operational Loads Measurement

Summary of measured HOLM data including results from numerous flights:

- Breakdown of the calculated fatigue damage divided into two main sources:
  - maneuver-induced quasi-static loading
  - buffeting-induced stochastic loading
- Fatigue damage proportion from the buffet loading is relatively high in the aft fuselage, up to 96 %

⇒ Fatigue monitoring based on acceleration only should be feasible for VT structure
  - Effect of quasi-static loadings should be limited

- Maneuver-induced quasi-static loading: light bars
- Buffeting-induced stochastic loading: dark bars



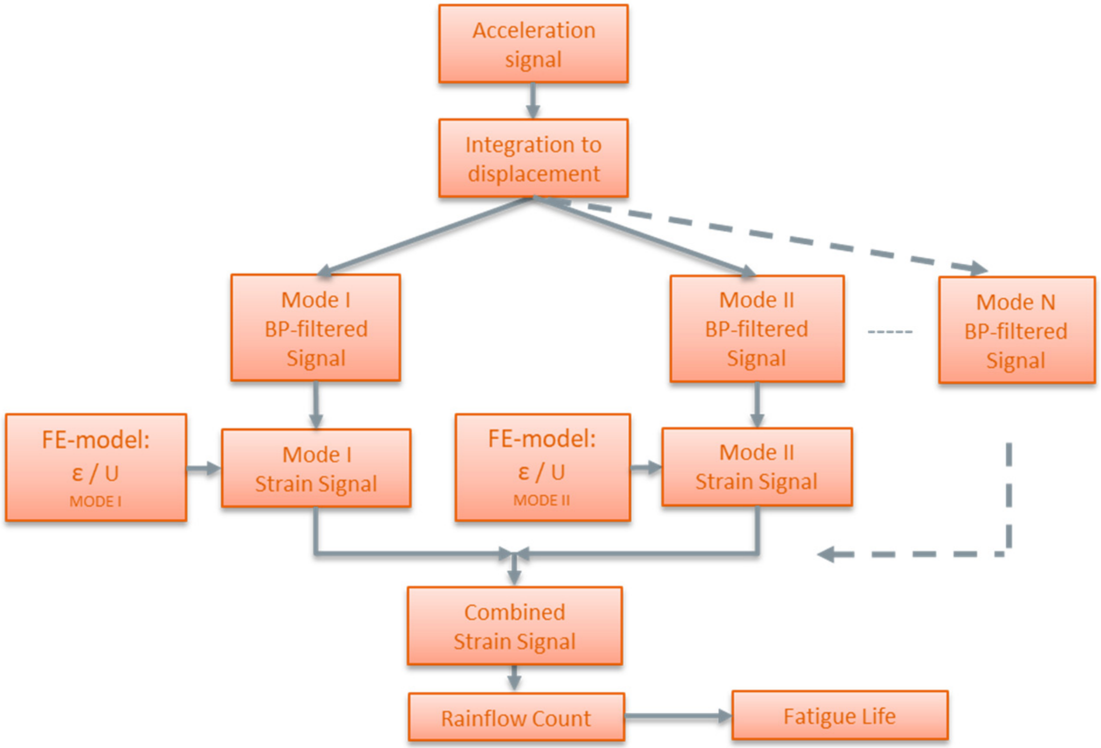
Modal expansion approach

Virtual sensing based on mode-specific bandpass filtering:

- Can be applied in cases where dominant modes are well separated in frequency range of interest
- Enables application of only one sensor

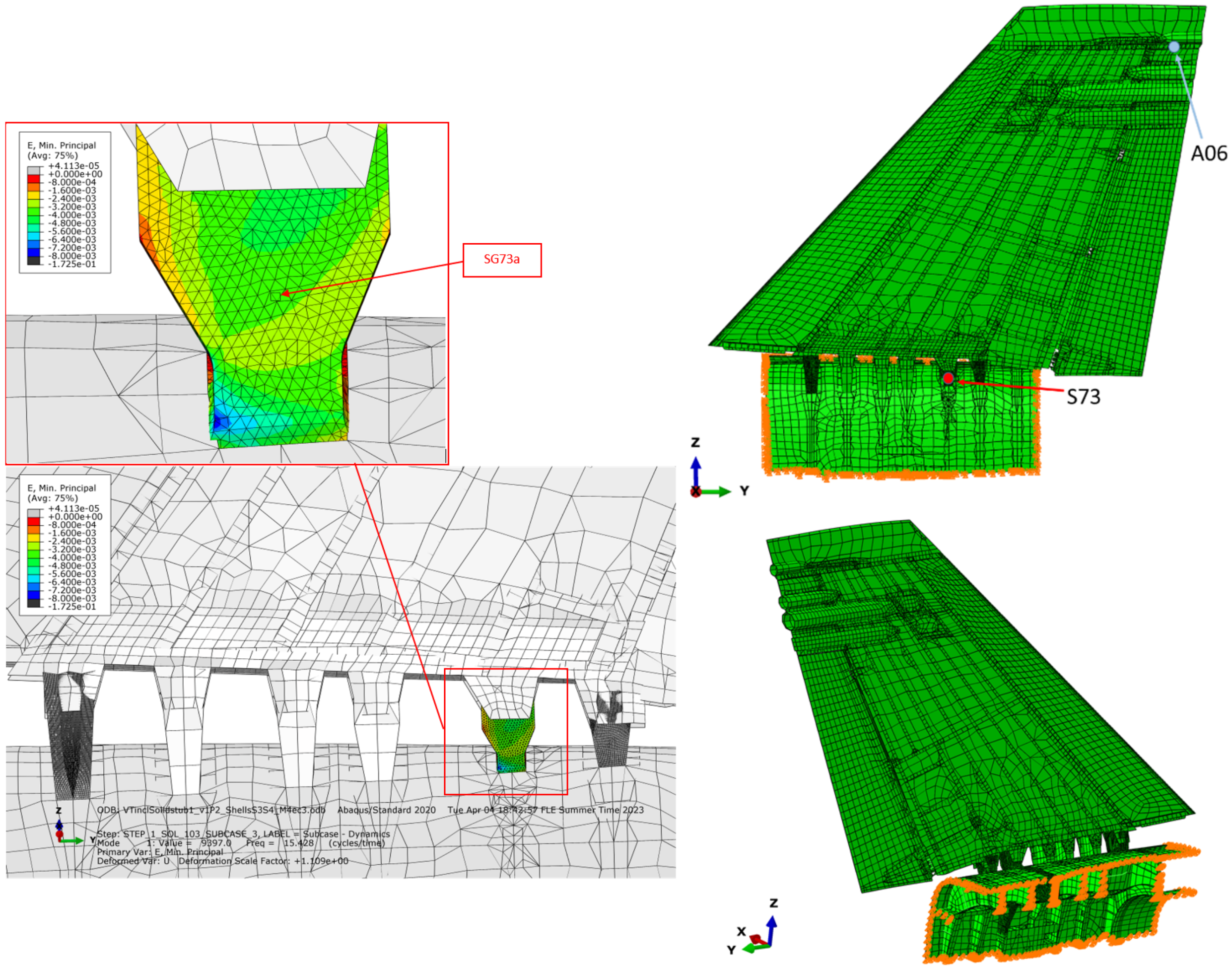
Analysis process:

1. Conversion of acceleration signal into displacement by time domain integration
2. Bandpass filtering the integrated signal into modal-specific responses
3. Mode shape specific displacement-to-strain conversion factors provided by the FE-model for the critical locations of interest will be used to convert the BP-filtered displacement signals into virtual strain signals
4. Summing up modal-specific virtual strains, a combined virtual strain time history is obtained
5. Fatigue damage analysis



FE-model of the VT structure

- Model includes VT and part of the left aft fuselage
  - FE-model mainly consisted of linear shell elements
  - Face sheets are carbon fiber-reinforced polymer composite laminates
  - VT structure is connected to the aft fuselage by six attachment frames, so called stubs
  - The instrumented stub was modeled by parabolic solid elements
  - FE-model provided originally by Patria
- Totally about 295 000 nodes and 199 000 elements



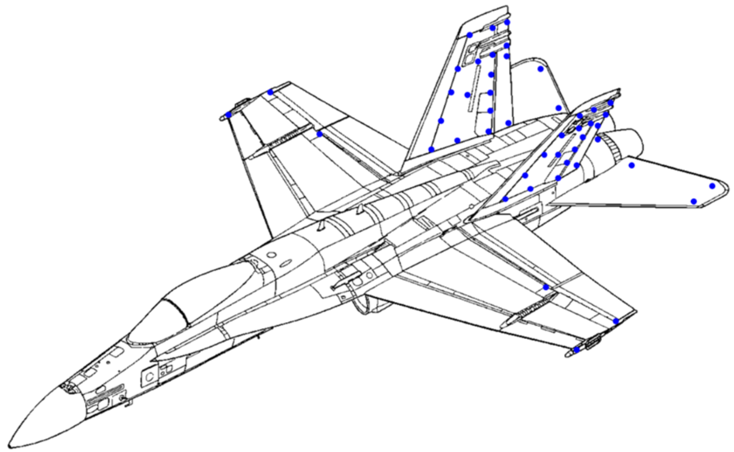
Experimental modal analysis

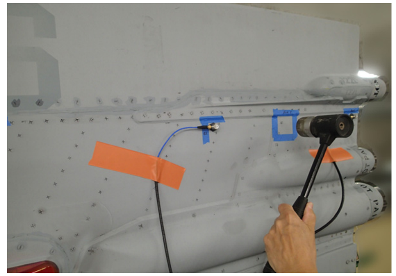
To validate the FE-model, dominant elastic natural modes of the VT and aft fuselage were identified experimentally by impact testing:

- ➢ LH and RH Vertical Tails were excited separately by an instrumented impact hammer having a soft plastic tip
- ➢ A total of 50 response points were measured by triaxial accelerometers

1. Traditional impact testing
   - Frequency Response Functions (FRFs) were calculated between measured excitation force and acceleration responses ⇒ modal parameter estimation
2. To identify also closely spaced double modes, a special measurements were conducted for Operational Modal Analysis (OMA):
   - Both VTs were excited by random multi-impact excitation (MIMO analysis) ⇒ response-only modal parameter estimation
   - Very closely spaced modes can not be identified reliably by traditional impact testing

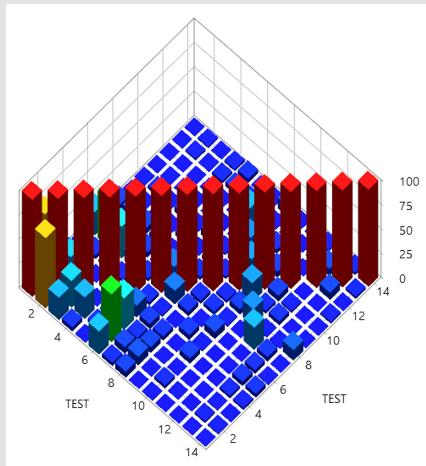
(ICAF2023 Poster#85: Modal testing of vertical tail of F/A-18 Hornet)





Mode no	Freq [Hz]	Modal Damping [%]	Description
1	8.96	1.0	Global torsional
2	9.65	2.4	Global torsional+roll
3	13.75	1.9	HT bending, out of phase
4	**15.15**	**1.3**	**First VT+HT bending, antimetric, VTs in phase**
5	**15.66**	**0.5**	**First VT bending, symmetric, VTs out of phase**
6	22.13	3.1	Tail twisting
7	23.80	17.2	RH Rudder rotation
8	30.93	8.1	LH Rudder rotation
9	**45.91**	**1.2**	**VT torsion, symmetric**
10	**45.95**	**0.8**	**VT torsion, antimetric**
11	62.15	4.1	LH VT 2. bending
12	62.92	4.9	RH VT 2. bending
13	84.41	2.9	RH Rudder torsion
14	86.24	2.5	LH Rudder torsion

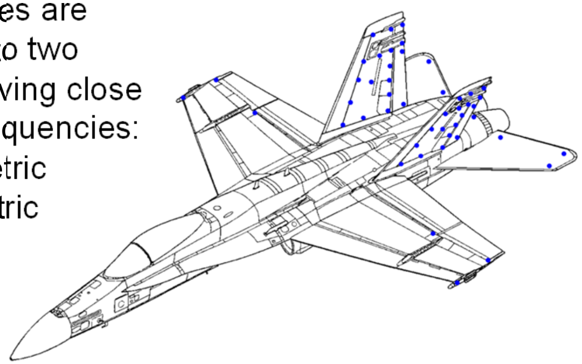
AutoMAC

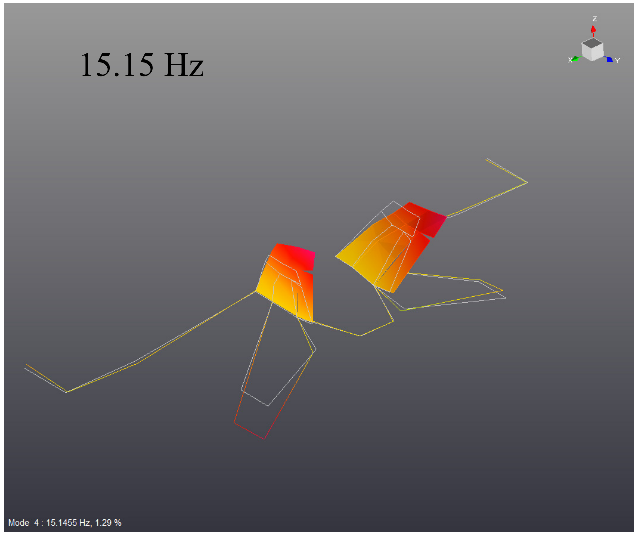


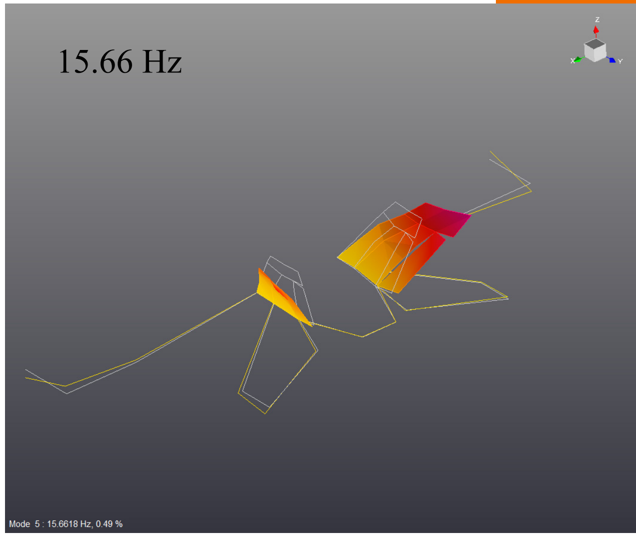
(MAC is a measure of correlation; orthogonality or independency of two modal vectors)

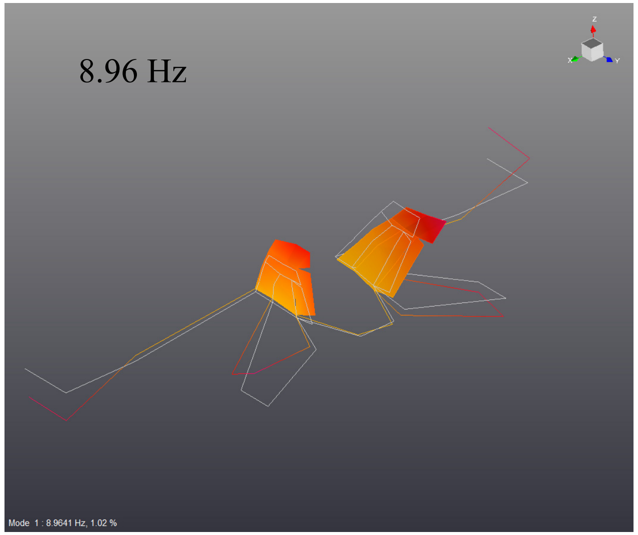
Experimental modal analysis

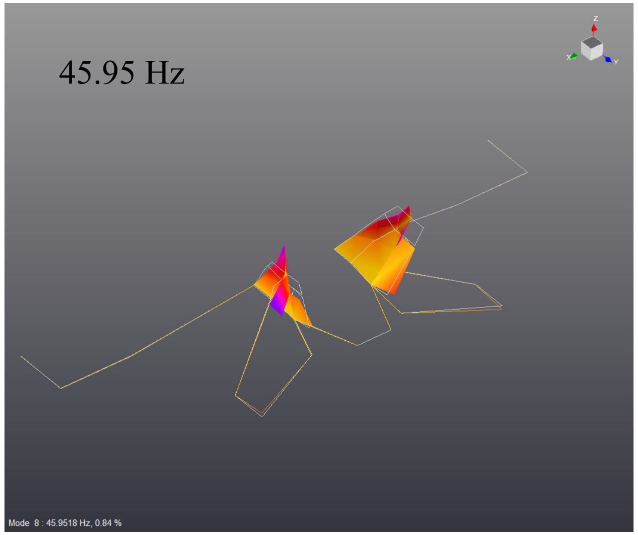
- Due to symmetry, main modes are divided into two modes having close natural frequencies:
  - symmetric
  - antimetric

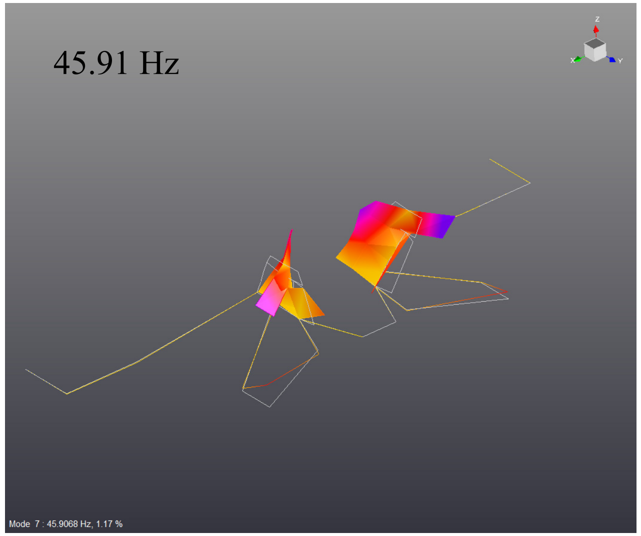












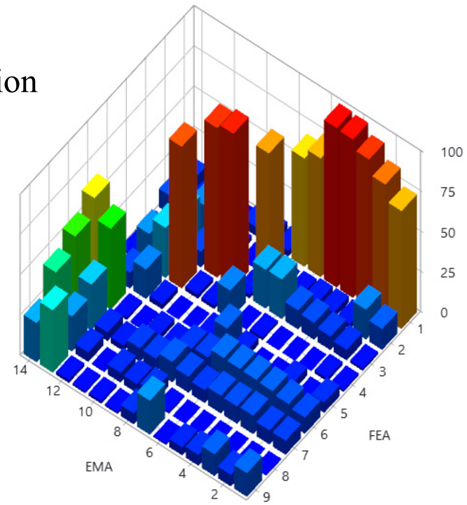
FE-model validation

Correlation between numerical (FEA) and experimental (EMA) modes:

- FE-model predicts relatively acceptable the dominant 1st bending and 1st torsional modes (symmetric)
- Calculated 1st VT bending mode has high MAC values also with several other experimental modes
  - ➢ Spatial aliasing; this is due to limitation of the FE-model (includes VT only)
  - ➢ Component model cannot simulate global modes of the aircraft
- Correlation of the other higher modes than 1st bending and torsional are worse

MAC correlation

$$MAC_{jk} = \frac{(\phi_j{}^T \phi_k)^2}{(\phi_j{}^T \phi_j)(\phi_k{}^T \phi_k)}$$

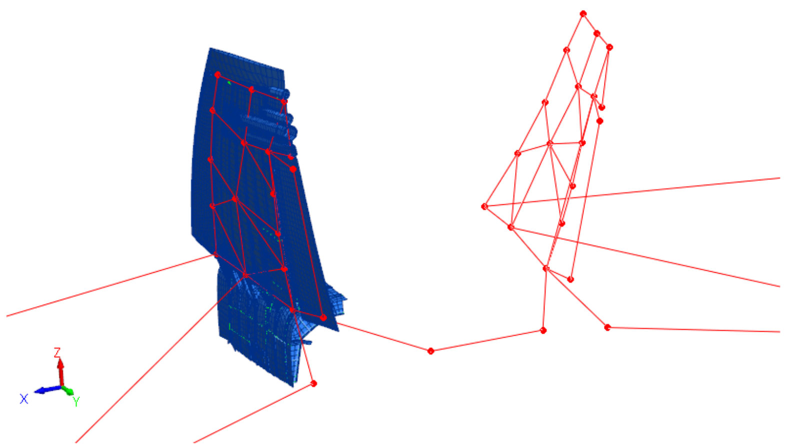


#	FEA mode#	Hz	EMA mode#	Hz	Freq. Diff. (%)	MAC (%)	Description
1	*1*	*14.93*	*1*	*8.96*	*-*	*73.4*	*Global torsional*
2	*1*	*14.93*	*2*	*9.65*	*-*	*83.4*	*Global torsional+roll*
3	*1*	*14.93*	*3*	*13.75*	*-*	*92.6*	*HT bending, out of phase*
4	1	14.93	4	15.15	-1.4	98.6	First VT+HT bending, antimetric, VTs in phase
5	**1**	**14.93**	**5**	**15.66**	**-4.7**	**99.2**	**First VT bending, symmetric, VTs out of phase**
6	*1*	*14.93*	*6*	*22.13*	*-*	*73.9*	*Tail twisting*
7	*1*	*14.93*	*7*	*23.80*	*-*	*67.4*	*RH Rudder rotation*
8	2	31.46	8	30.93	1.7	77.1	LH Rudder rotation
9	**3**	**45.15**	**9**	**45.91**	**-1.7**	**96.0**	**VT torsion, symmetric**
10	3	45.15	10	45.95	-1.8	93.0	VT torsion, antimetric
11	4	55.93	11	62.15	-10.0	88.1	LH VT 2. bending
12	6	77.78	14	86.24	-9.8	62.9	LH Rudder torsion

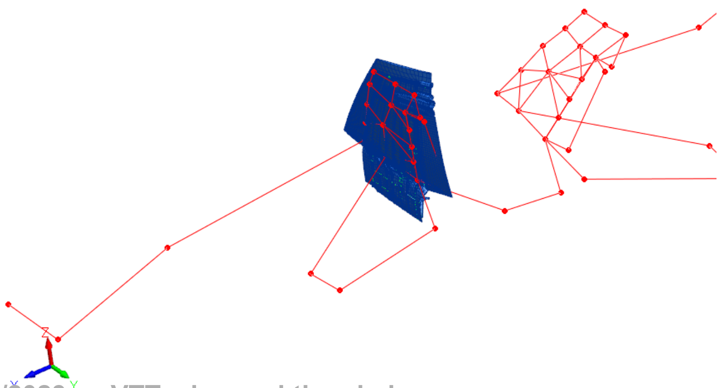
Rows marked in *red* are artificial; compared mode shapes are not the same in these cases and they do not correspond each other

FE-model validation

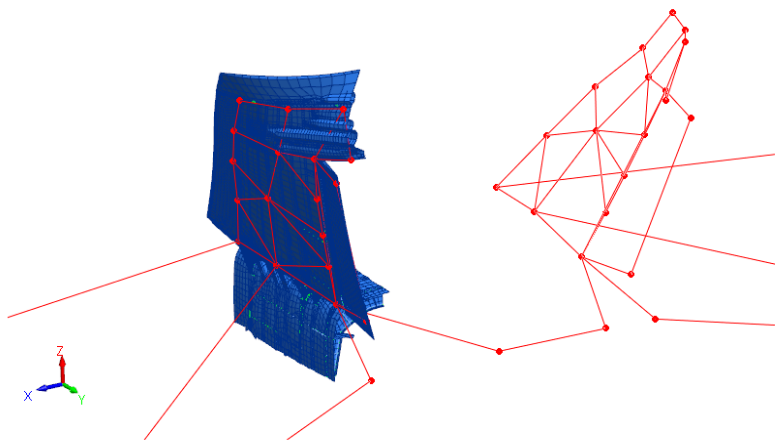
- Good correlation (FE vs EMA) for the dominant 1st symmetric bending and torsional modes of the VT
  - Strain reconstruction should work satisfactory for corresponding frequency bands
- Local FE-model cannot simulate lowest modes (e.g., global torsional mode at 8.9 Hz)
- ⇒ Best which one could try to do is to estimate these modes by the first calculated bending mode of the VT and use this FE-mode in modal expansion process for the frequency range of these lowest modes
  - This estimation introduces error for this frequency band due to rigid body movement
  - Error introduced can be roughly predicted by the MAC value



EMA 15.7Hz vs FEA 14.9Hz (MAC 99.2%)



EMA 8.9Hz vs FEA 14.9Hz (MAC 73.4%)



EMA 45.9Hz vs FEA 45.1Hz (MAC 96.0%)

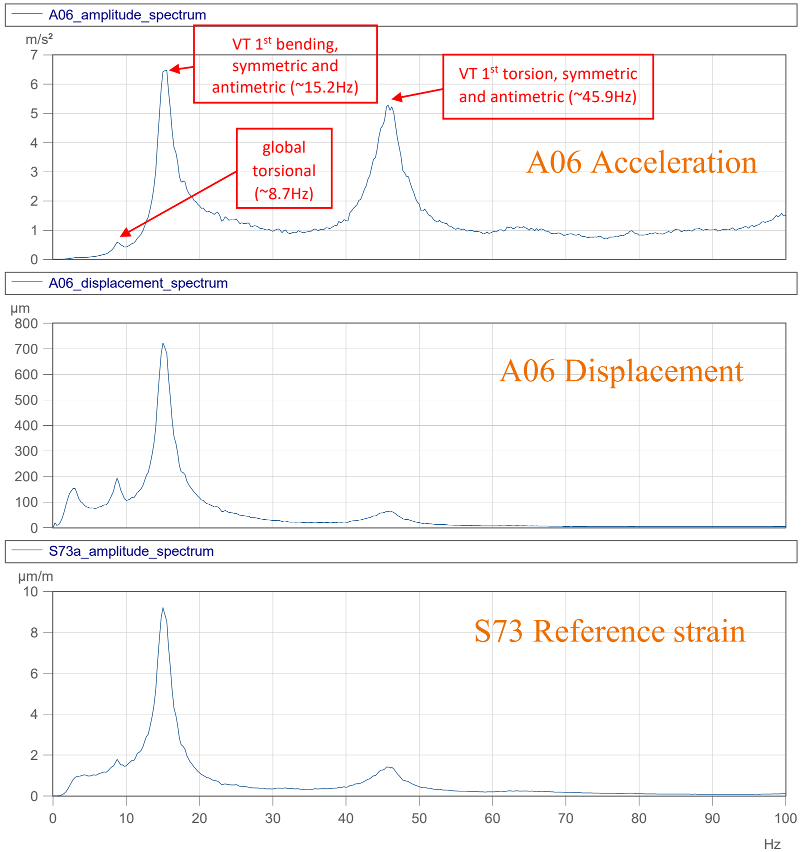
Virtual sensing case study; example flight data

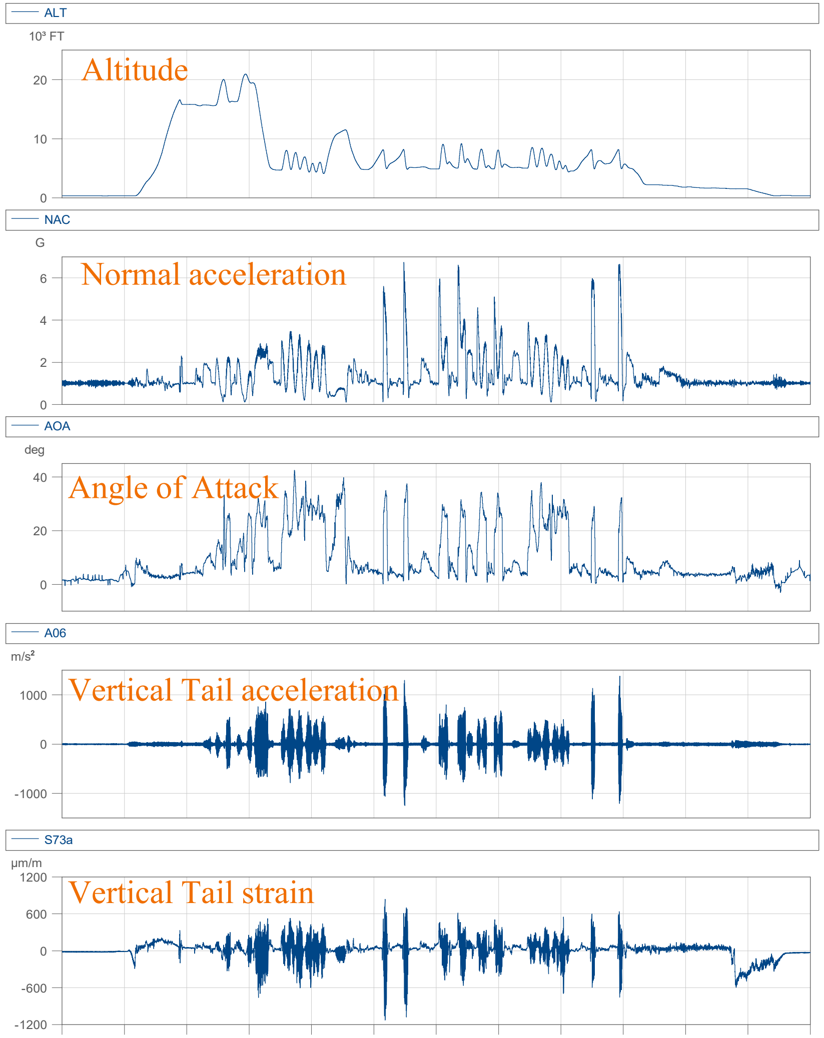
- Includes a decent amount of maneuvering
  - Maximum accelerations in the region of ±140 G in the aft tip of the VT
- Dominant resonance peaks at 15.2Hz and at 45.9Hz, corresponding to the 1st bending and 1st torsional modes of the VT
- Resonance peaks at 8.75Hz corresponds the global torsional mode

⇒ Bandwidths of interest for the virtual sensing:

- 10-20 Hz (1st bending)
- 40-50 Hz (1st torsional)
- 5-10 Hz; (Strain-displacement factor of the first calculated bending mode was used also for this bandwidth)

- Acceleration and strain Autospectra averaged over the example flight

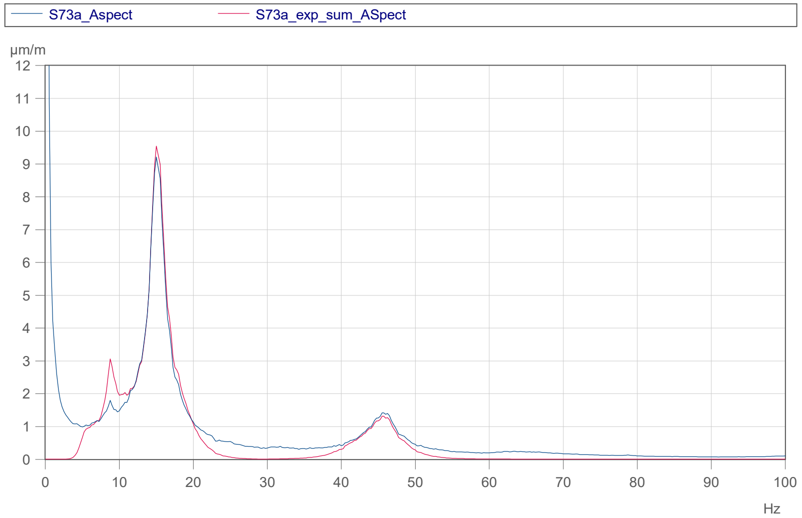




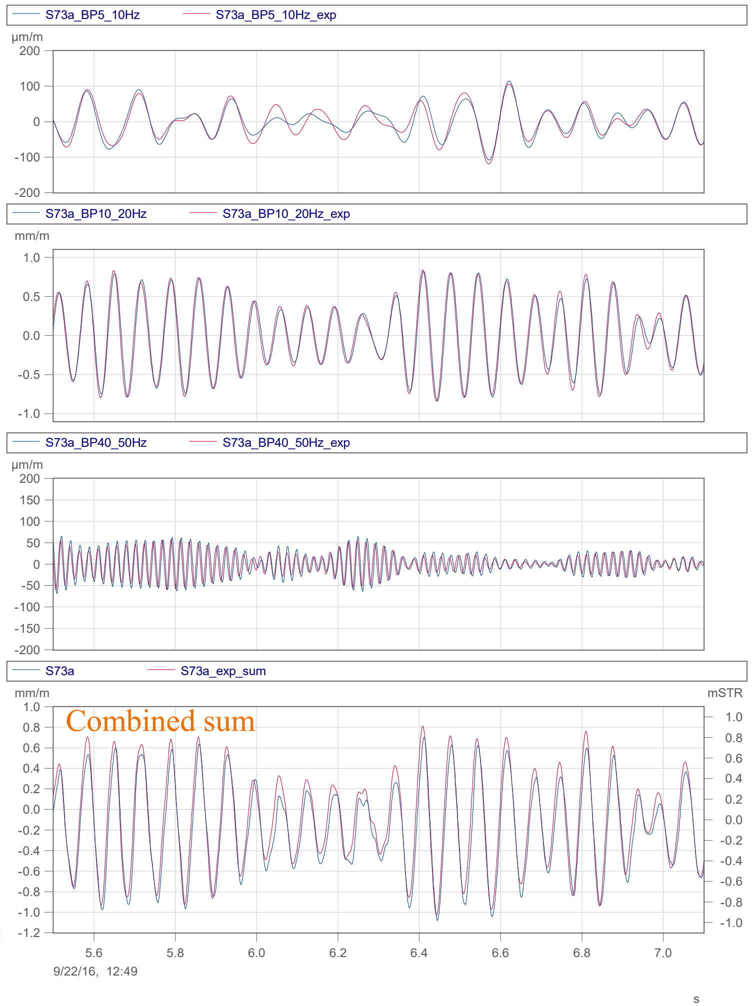
Virtual strain reconstruction

Reconstructed virtual strain vs measured reference strain:

- Satisfactory overall correlation of virtual strains for the bandwidth of 10-20Hz and 40-50Hz
- For 5-10Hz bandwidth, the estimation error caused by inaccurate FE-mode shape used can be detected
  - Global torsional mode induces rigid body movement for the VT, which the component FE-model cannot simulate

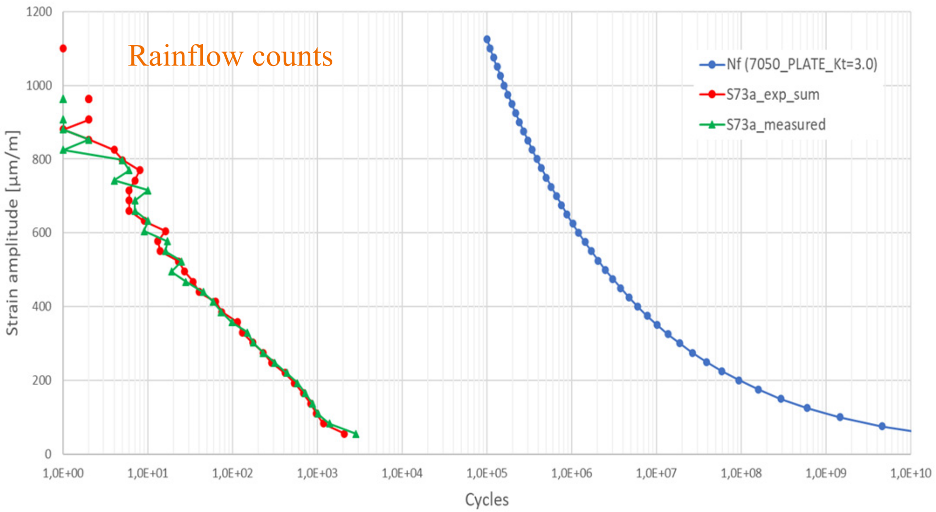


Reconstructed virtual strain (S73a_exp) vs measured reference strain (S73a) in different bandwidths



Rainflow counting ⇒ cumulative fatigue damage with representative S/N curve:

- Fatigue damage difference between the reconstructed virtual strain and the measured strain was ~9%



Conclusions

- Satisfactory overall correlation of virtual strains with the measured ones for the bandwidths of dominant modes of the VT (10-20 Hz and 40-50 Hz) were achieved
  - 1st VT bending mode is the major contributor for the fatigue life of the Vertical Tail root region
  - Main sources of the error for 10-20 Hz and 40-50 Hz frequency bands are probably:
    - Lower correlation of the antimetric modes (low MAC)
    - Non-linearities due to high operational loading conditions may change the modes -> lower mode correlation
  - For 5-10 Hz bandwidth, the estimation error caused by inaccurate component FE-mode shape used was larger
    - Overall contribution of this mode for total response was still limited

- Considering inaccuracies due to limitations of the component FE-model, the overall accuracy of this virtual sensing method can be considered satisfactory in this case
  - Limitations of the component model should be checked case by case, e.g., by MAC correlation analysis for each dominant mode
  - Impact of ignored maneuver-induced quasi-static loadings was limited for VT structure as expected

- The results demonstrated applicability of local component FE-model and only a single acceleration measurement for virtual sensing in cases where dominant modes are well separated
  - In more complicated cases where dominant modes are not well separated, additional sensors are generally needed and modal contributions of different modes during operation can be estimated, e.g., by least squares method [1]

[1] Nieminen V., Sopanen J, Optimal sensor placement of triaxial accelerometers for modal expansion, Mechanical Systems and Signal Processing, Vol 184, 109581, Feb 2023 https://doi.org/10.1016/j.ymssp.2022.109581

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