MODAL TESTING OF VERTICAL TAIL OF F/A-18 HORNET

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Abstract: The goal of the study was to identify experimentally dynamic vibration characteristics of the aft fuselage and especially the Vertical Tail (VT) of a fighter aircraft. The object of the study was F/A-18 Hornet of the Finnish Air Force. Vibration properties, i.e., natural frequencies, modal damping factors and mode shapes were determined experimentally by impact testing. Special focus was on the modes around about 15 Hz and 45 Hz. Based on earlier analysis of the measured (in-flight) acceleration and strain data, it has been found that the VT experiences high vibration levels around these frequencies due to flow-induced excitations.

The plane was standing on the landing gears during the measurements. The left and right Vertical Tails were excited by an instrumented impact hammer having a soft plastic tip. Both VTs were excited separately and responses from both VTs and other locations were measured during all tests. Frequency Response Functions (FRFs) were calculated between measured input excitation force and acceleration responses. To identify closely spaced double modes, separate measurements were conducted where both VTs were excited simultaneously randomly at random locations of the VT surface by two impact hammers having soft plastic tips. Time histories of acceleration responses were recorded for Operational Modal Analysis (OMA). Natural frequencies, modal damping factors and mode shapes were identified using both conventional experimental modal analysis and Operational Modal Analysis methods.

Lowest elastic natural modes of the VT of the F/A-18 Hornet were identified experimentally successfully. It was found that due to symmetry of the structure, main VT modes are divided into symmetric and antimetric modes having close natural frequencies. Random impact excitation technique for Operational Modal Analysis was demonstrated to be applicable for identification of very closely spaced modes.

Keywords: Modal testing, modal analysis, vibration, fatigue, Vertical Tail

INTRODUCTION

The goal of this study was to identify experimentally dynamic vibration characteristics of the Vertical Tail (VT) of a high-performance fighter aircraft. The object of the study was the F/A-18 Hornet (HN-416) of the Finnish Air Force (FINAF). Special focus was on the modes around about 15 Hz and 45 Hz. Vibration properties, i.e., natural frequencies, modal damping factors and mode shapes were determined experimentally by impact testing. The identified data was used to validate the FE model of the VT and its support structure in order to evaluate model expansion capabilities for single accelerometer data [2].

High performance fighter aircraft, like the F/A-18 Hornet, is extremely manoeuvrable thus capable of flying at high angles-of-attack, too. In those flight regimes the high-energy vortices from by the inner wing leading edge extensions (LEX) generate additional lift but as a drawback, induce severe cyclic loading to the downstream structure by exciting the resonance frequencies of the empennage (Figure 1). The broad band dynamic loads, i.e. buffet loads, together with the static manoeuvring loads, contribute to the fatigue of the Vertical Tails (VT) of the aircraft. The Vertical Tail first bending mode has a significant impact on the fatigue life of the lower aft root region, especially the fuselage to the VT attachment frames. The Vertical Tail first torsion mode predominantly affects the life of the upper region of the structure [1].

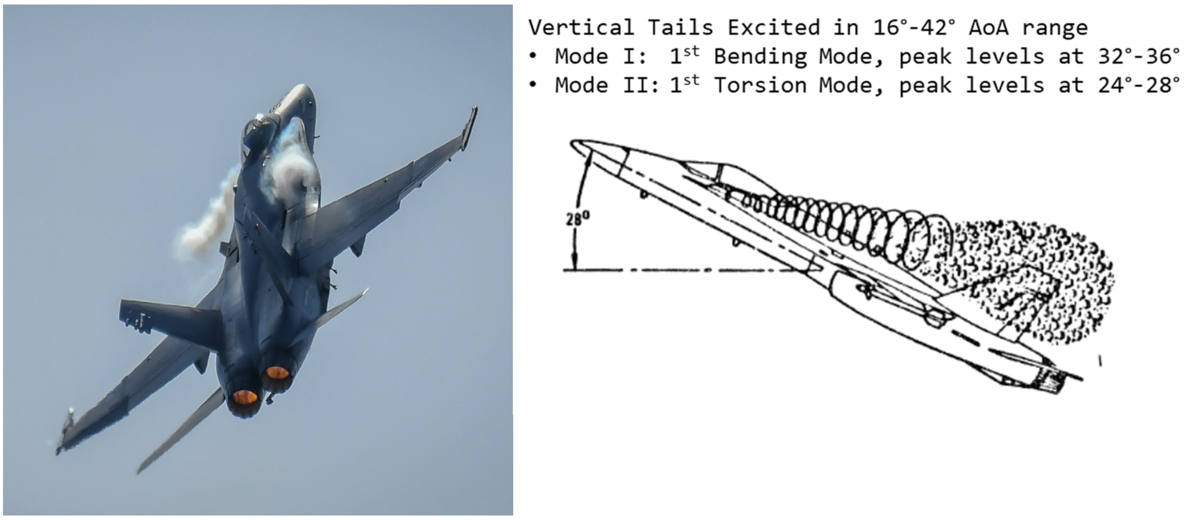

Figure 1. High-energy vortices generated by the inner wing leading edge extensions (LEX) resulting regions of low pressure that condenses the water vapor of the air (left figure: courtesy of the FINAF) and induce severe cyclic loading to the downstream structure, like Vertical Tails, by exciting the resonance frequencies of the empennage (right figure, edited from Ref. [1]).

The Vertical Tail structure comprises a multispar main structural box extending from the 22.5 % spar to the 77.5 % spar and from the lower closing rib to the upper closing rib. The face sheets are multi-directional carbon fiber-reinforced polymer (CFRP) composite laminates. The VT structure is connected to the aft fuselage by six attachment frames, so called stubs, forming a highly redundant structure (Figure 2). The attachment stubs have an I-beam cross-sectional geometry.

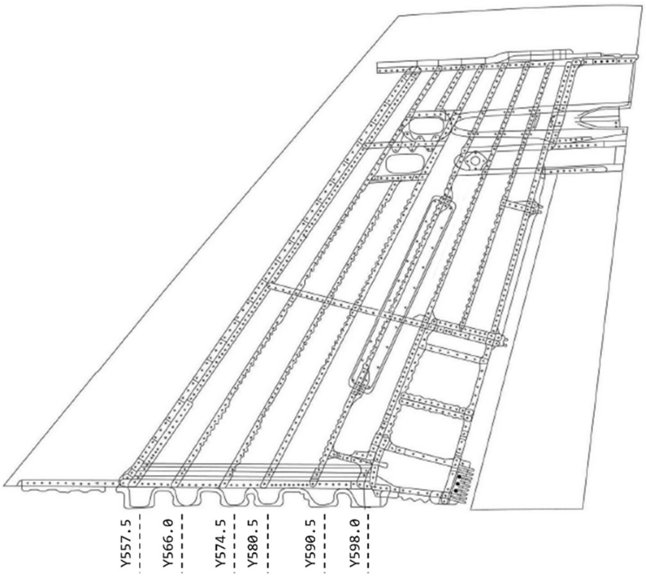

Figure 2. The Vertical Tail structure. The locations of the six attachment frames (stubs) are presented.

MEASUREMENT ARRANGEMENTS

The plane was standing on the landing gears during the measurements. Outer wings were unfolded, all control surfaces were in a neutral position except ailerons, and some of them were also locked by locking pins. The aircraft was refueled before the tests, and the canopy was open during the tests. The rudders could not be locked easily using any internal structural or hydraulic locking system during the tests. For this reason, the RH rudder tended to drift slowly outwards during the tests and therefore the RH rudder was locked by a softened wedge, see Figure 3.

The VT (LH and RH side separately) was excited by an instrumented impact hammer having a soft plastic tip (type PCB 086D20). Responses were measured by 18 triaxial IEPE-type accelerometers (Kistler K8766A050BH). Signal acquisition hardware used was Siemens Scadas mobile SCM209 (88 ch). Analyses were carried out using Simcenter TestLab 2019 software.

To identify also global mode shape characteristic of the aircraft, measurement points were located also to other parts of the aircraft. However, special focus was on the modes around about 15 Hz and 45 Hz and therefore all modes of the aircraft were not identified. Totally 50 acceleration response points were measured, all locations in three directions, see Figure 4. Both VTs were excited separately and responses from both VTs and other locations were measured during all tests. Due to limited number of accelerometers, measurements were repeated three times and locations of the accelerometers (except two reference points) were changed between the tests to cover all locations. Part of the measurement locations on the LH VT are shown in Figure 5.

Figure 3. A general view of measurement arrangements. The RH rudder was locked by a soft wedge as shown in the photo.

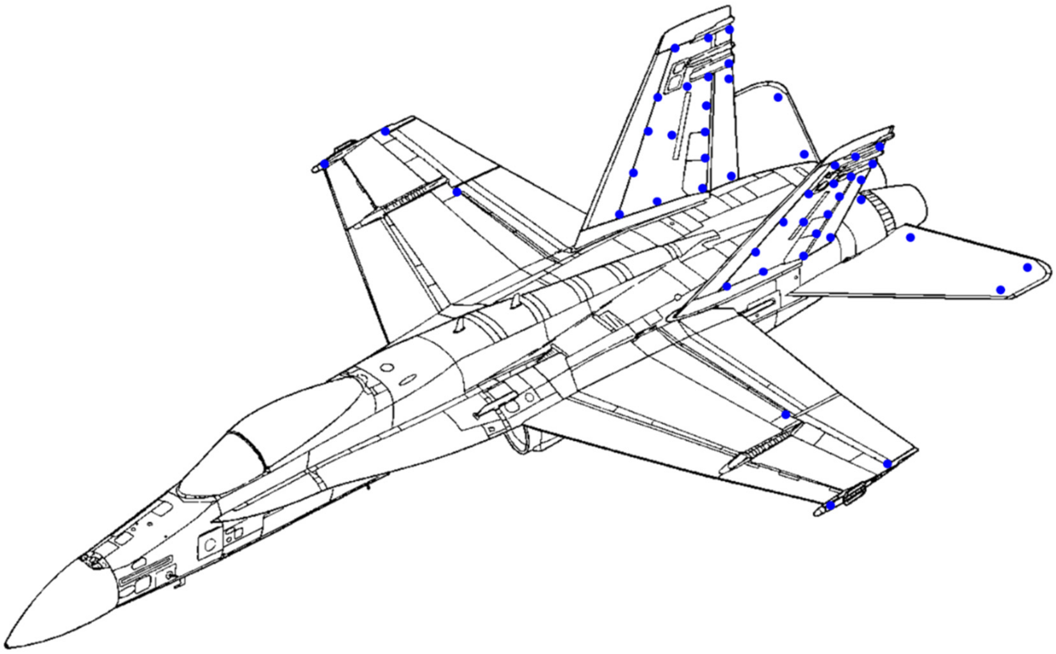

Figure 4. The measurement points in the experimental modal analysis. A total of 50 measurement points were used.

Figure 5. Some of the measurement locations on the LH VT (left) and excitation location of impact testing for LH VT (Tip Rib/Spar joint) (right).

METHODS

The VT (LH and RH side) was excited by instrumented impact hammer having soft plastic tip. Traditional impact testing and random impact excitation for Operational Modal Analysis (OMA) was used to identify the modal parameters.

Impact testing

Averaged Frequency Response Functions (FRFs) were calculated between the measured input excitation force and acceleration responses (H1 estimate), see Figure 6. Poly-reference least squares complex frequency domain estimation method (PolyMAX) was used for modal parameter estimation [3]. In addition, maximum likelihood modal model-based (MLMM) estimator was used to improve the initial PolyMAX modal parameter estimates, i.e. for improving modal model fit to the measured FRFs [4].

Random impact excitation for Operational Modal Analysis (OMA)

To identify closely spaced double modes, separate measurements were conducted where both VTs were excited simultaneously randomly at random locations of the VT surface by two impact hammers having soft plastic tip. Basic assumption in OMA is that the unknown broadband excitation force is randomly distributed both in time and space and therefore this type of multiple input excitation situation was simulated by random impact excitations. To identify closely spaced modes or even repeated modes, the loading must be multiple input so that multiple input multiple output OMA technique can be used. However, the excitation points were restricted to the VT box structure (rib/spar locations) only in this case, so that the sandwich structures were untouched. Length of 4-min time histories of acceleration responses were recorded for Operational Modal Analysis. Excitation force was not measured for these analyses.

Natural frequencies, modal damping factors and operational reference factors were identified using PolyMAX method [5]. Least-Squares Frequency-Domain method was used to identify the mode shapes.

RESULTS

Identified modes are presented in Table 1. Due to symmetry of the structure, each main VT modes (modes at about 15 Hz and 45 Hz) are divided into two modes having close natural frequencies: symmetric and antimetric modes, see Figure 8 - Figure 11. Other mode shapes are shown in Figures Figure 12 - Figure 19. All presented modes are extracted from traditional FRF-based impact testing except modes no 9 and 10 at about 45 Hz, which are determined through Operational Modal Analysis due to very closely spaced modes.

Identified modal parameters for the rudder rotation modes have uncertainties to some extent because the rudders were not properly locked and there existed looseness during the tests.

To quantify orthogonality or independency of identified mode shapes, AutoMAC criterion was applied, see Figure 7. Modal Assurance Criterion (MAC) is a measure of the degree of similarity or correlation of two modal vectors. The elements of the MAC matrix (j,k) for the modal vectors $\boldsymbol{\phi}_j$ and $\boldsymbol{\phi}_k$ are defined as (Eqn. 1):

$$\boldsymbol{MAC_{jk}} = \frac{\left(\boldsymbol{\phi}_j{}^T\boldsymbol{\phi}_k\right)^2}{(\boldsymbol{\phi}_j{}^T\boldsymbol{\phi}_j)(\boldsymbol{\phi}_k{}^T\boldsymbol{\phi}_k)} \tag{1}$$

MAC takes values between 0 and 1; values closer to 0 indicate that those vectors are orthogonal, while the closer to 1 indicates high correlation. It is evident that measurement mesh is not enough extensive to identify properly the lowest global mode shapes of the aircraft (modes at 8.96 Hz and 9.65 Hz, Figure 12 and Figure 13) resulting spatial aliasing, and therefore the MAC values are high between these modes.

However, the main focus in this study was on the VT modes and the diagonals are quite low between these modes.

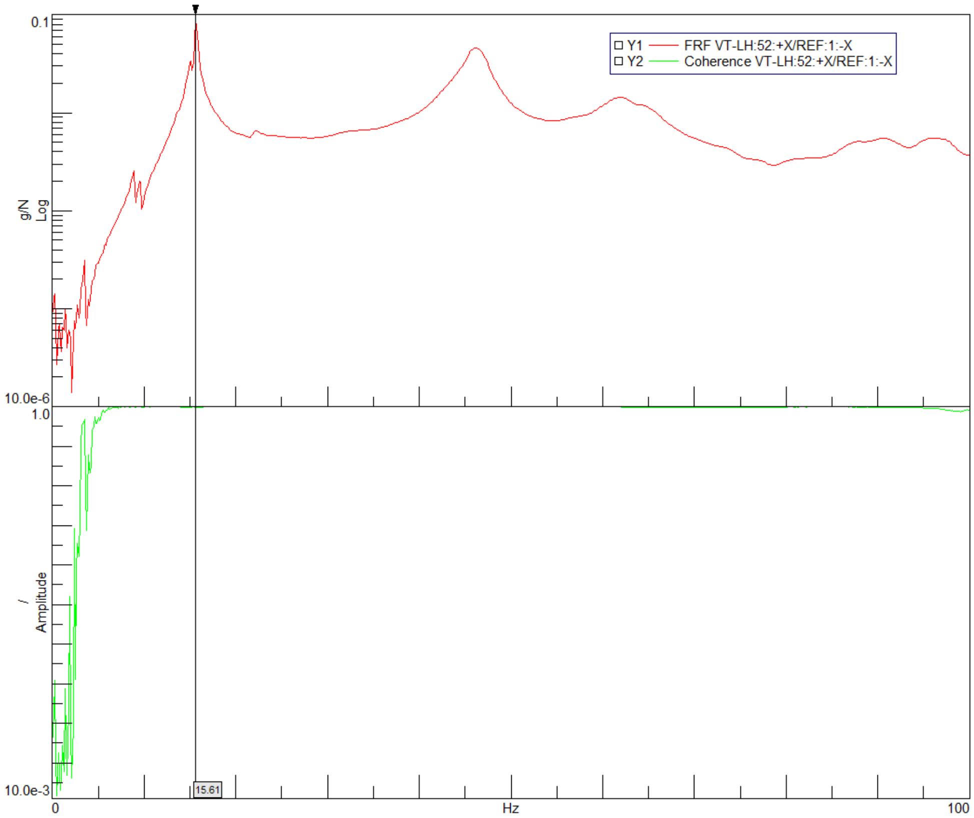

Figure 6. An example of measured Frequency Response Functions (FRF) and corresponding coherence. The excitation location is at the tip of the LH VT (trailing edge) and response location is at the tip of the LH VT (leading edge).

Table 1. The experimentally identified modes.

Mode no	Freq [Hz]	Damp [%]	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

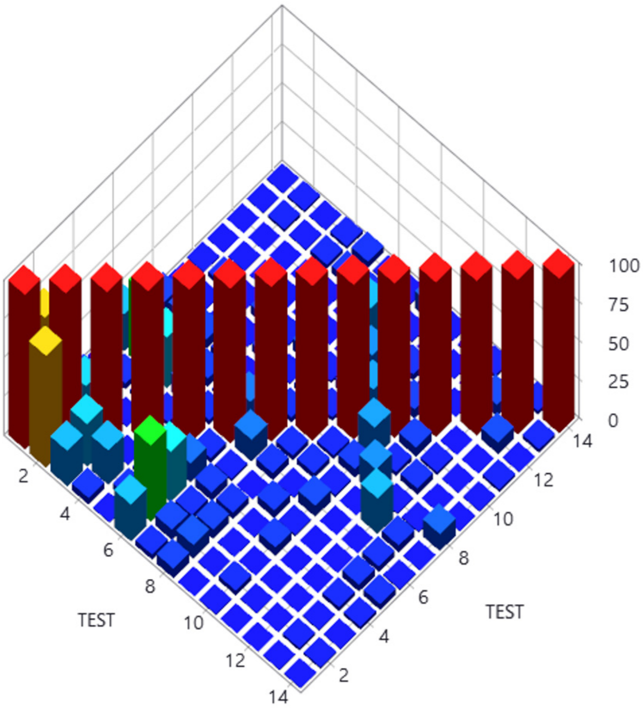

Figure 7. The AutoMAC matrix of the identified mode shapes.

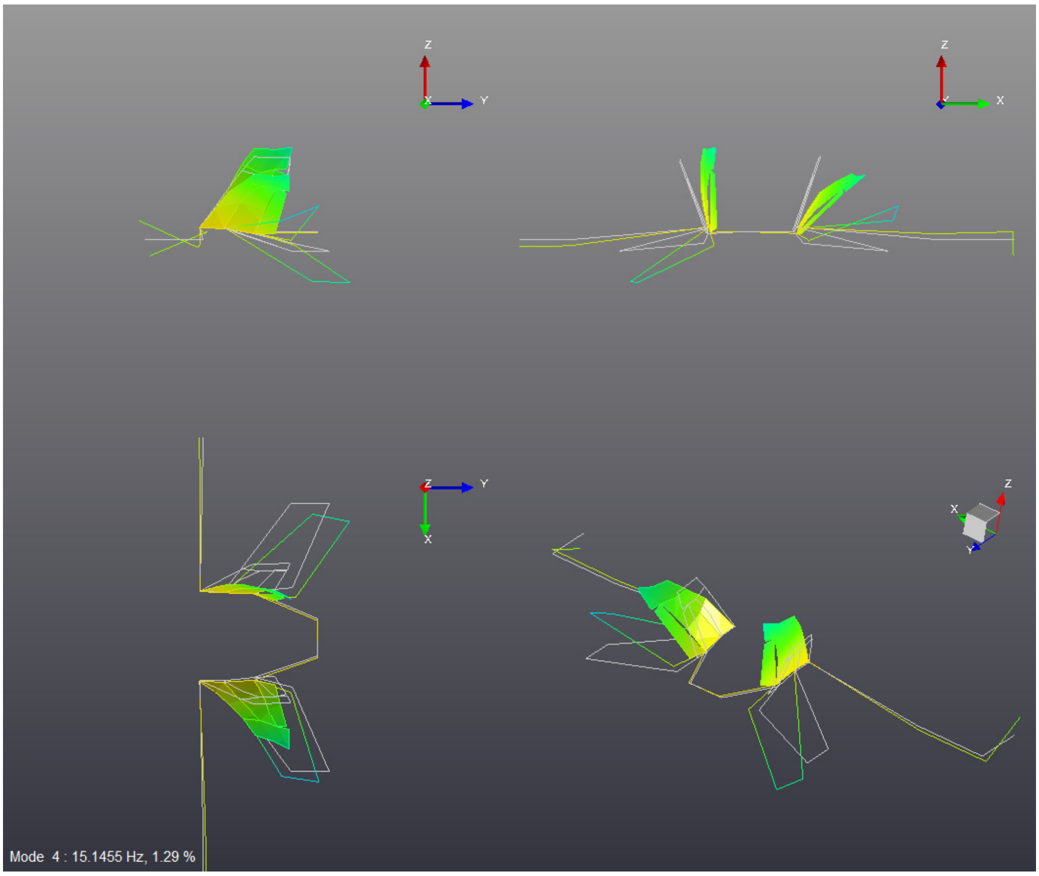

Figure 8. The identified mode shape at 15.15 Hz (antimetric).

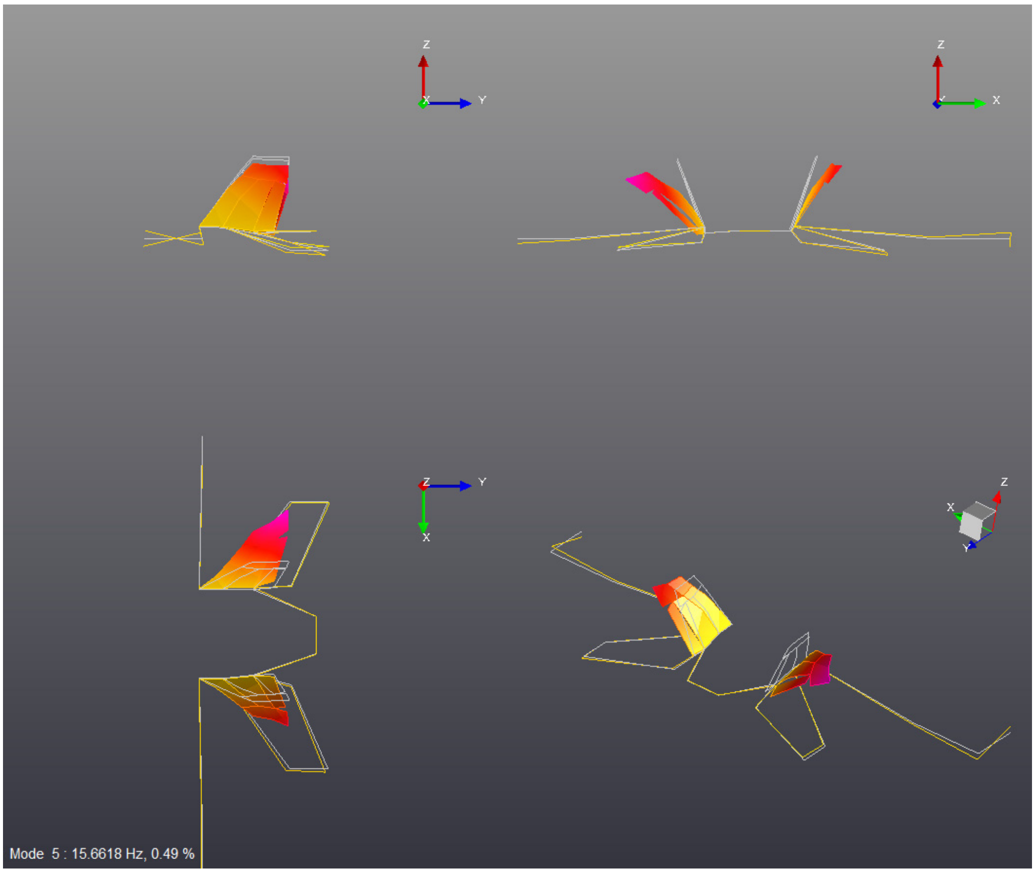

Figure 9. The mode shape at 15.66 Hz (symmetric).

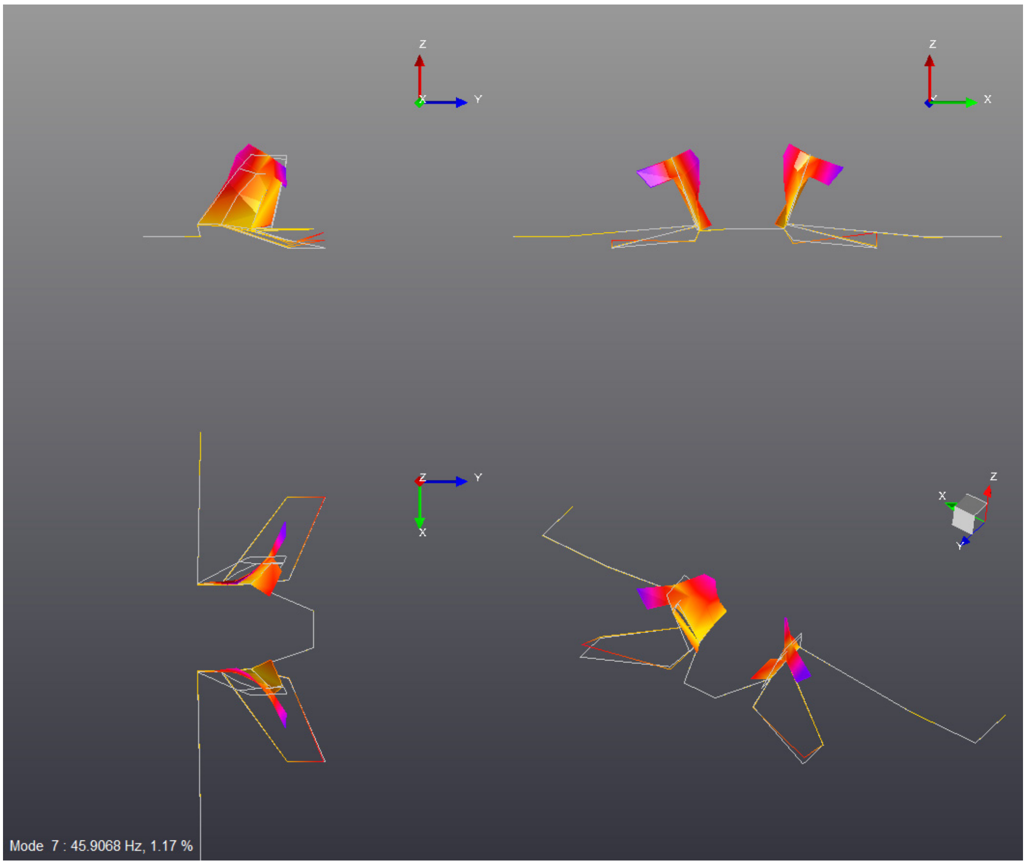

Figure 10. The identified mode shape at 45.91 Hz (symmetric).

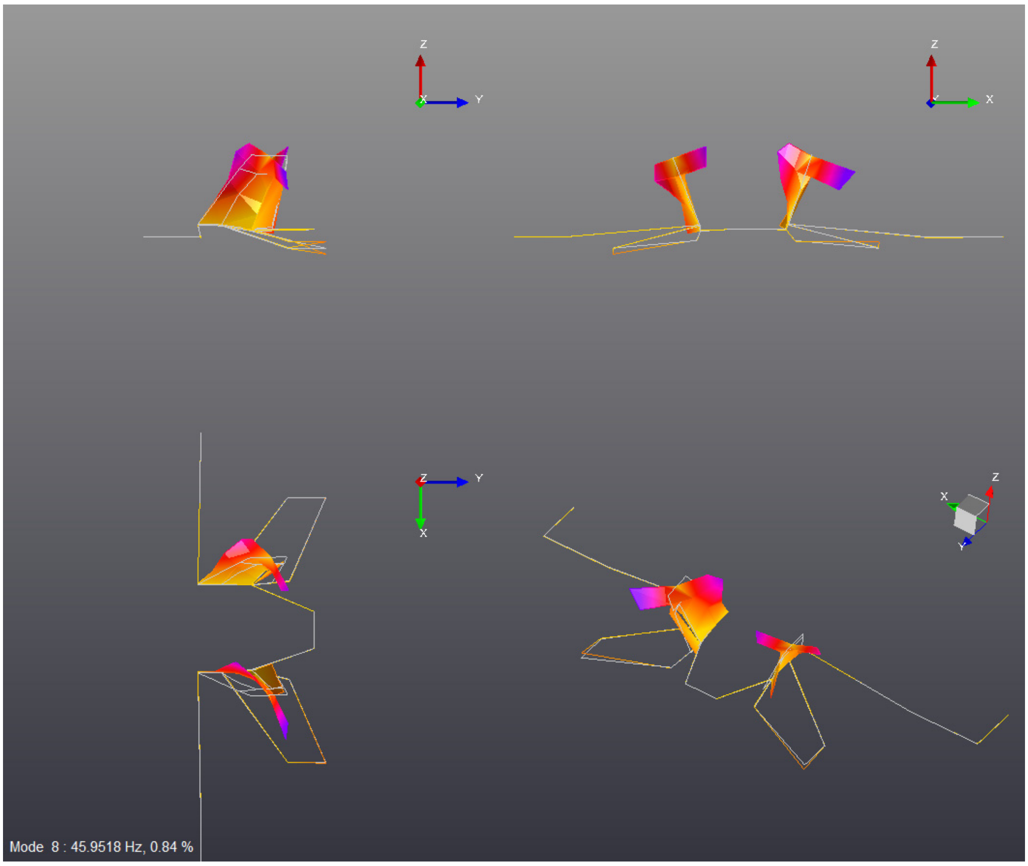

Figure 11. The mode shape at 45.95 Hz (antimetric).

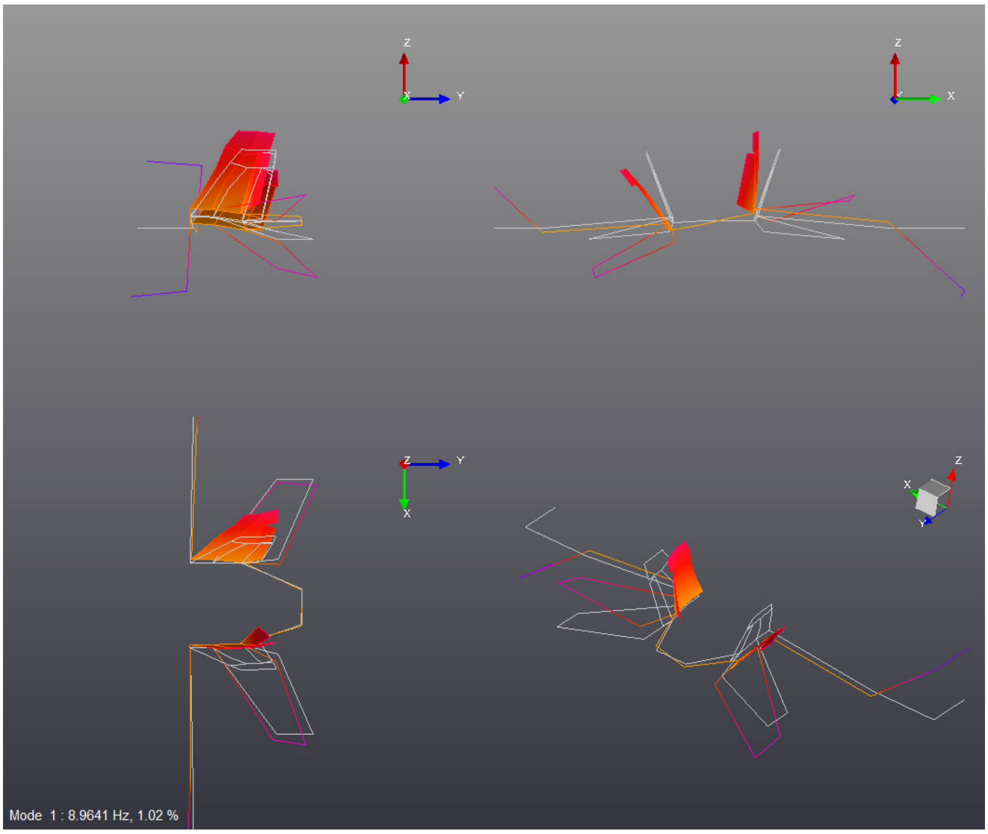

Figure 12. The mode shape at 8.9 Hz. A global torsional behaviour of the aft of the fuselage can be seen.

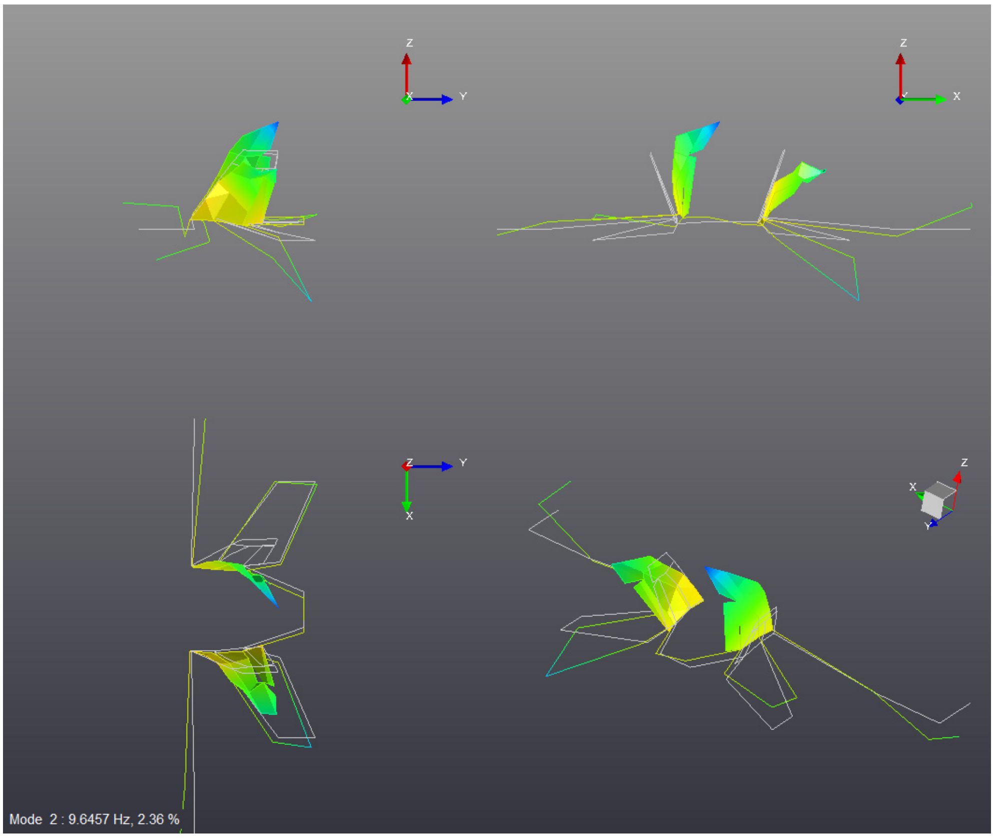

Figure 13. The mode shape at 9.6 Hz.

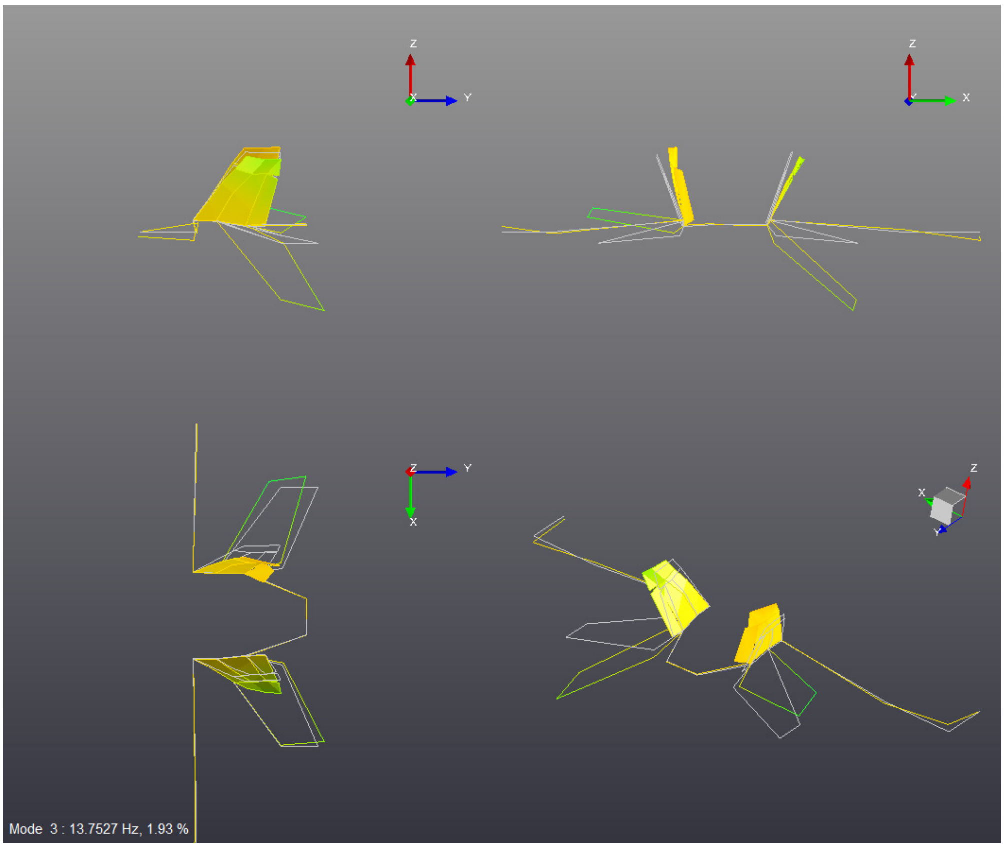

Figure 14. The mode shape at 13.7 Hz.

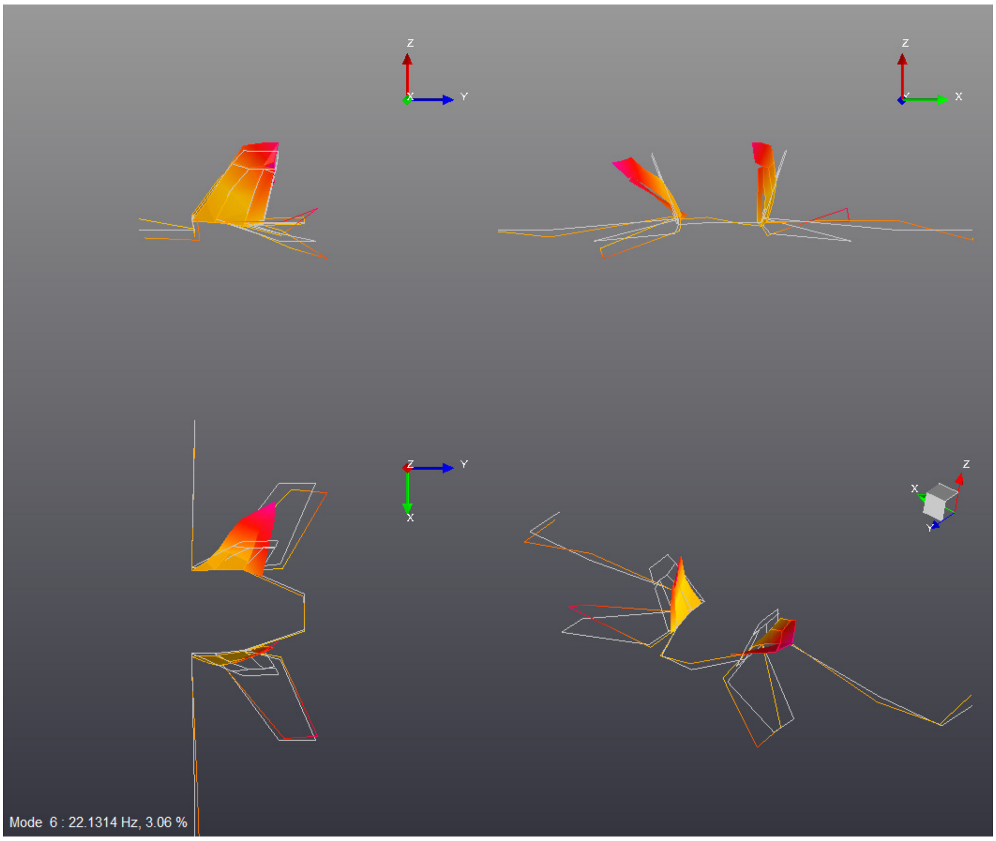

Figure 15. The mode shape at 22.1 Hz.

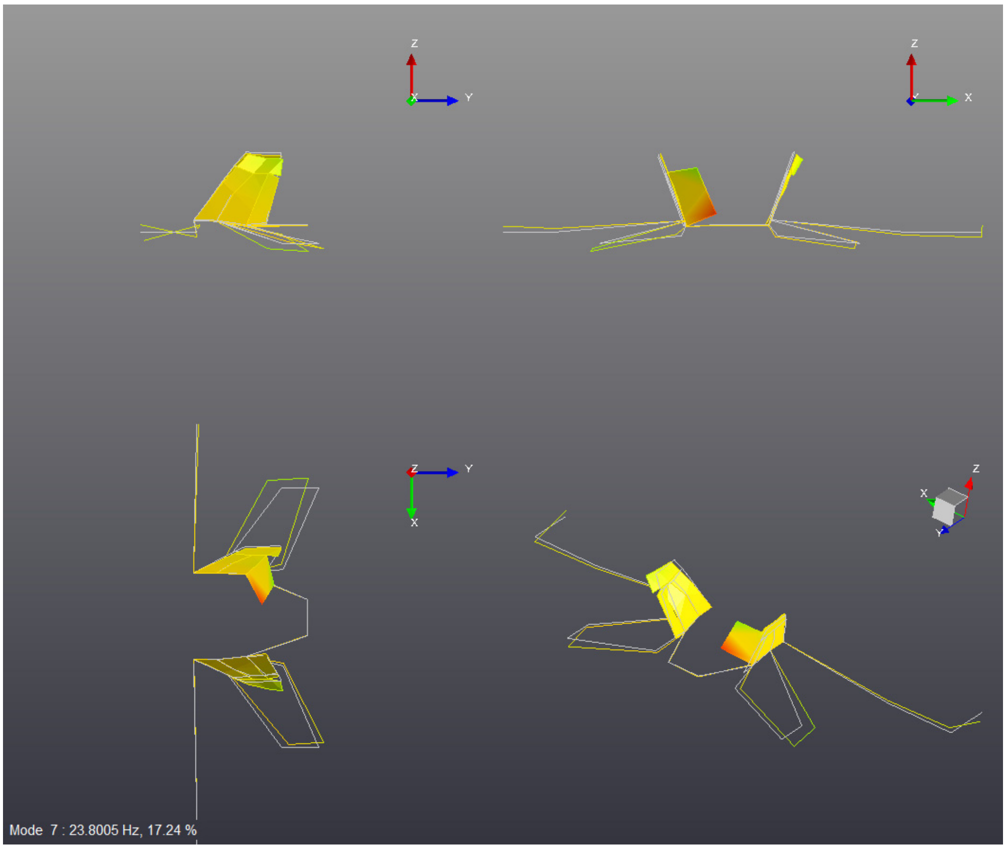

Figure 16. The mode shape at 23.8 Hz.

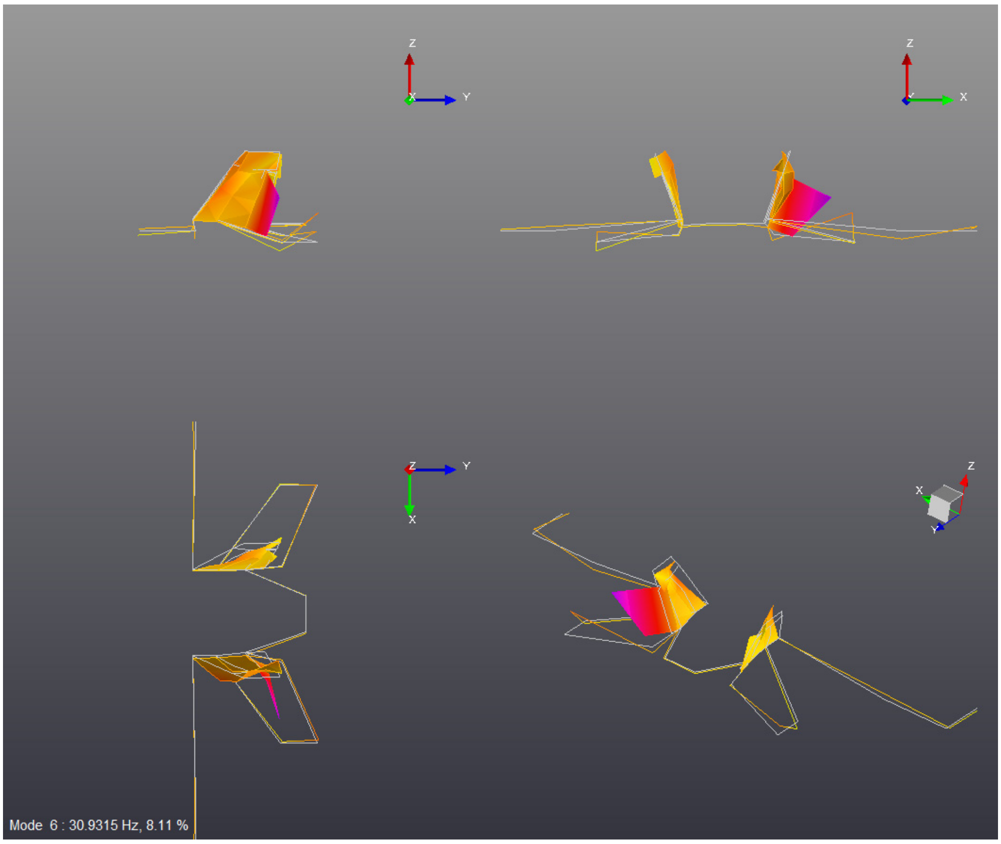

Figure 17. The mode shape at 30.9 Hz.

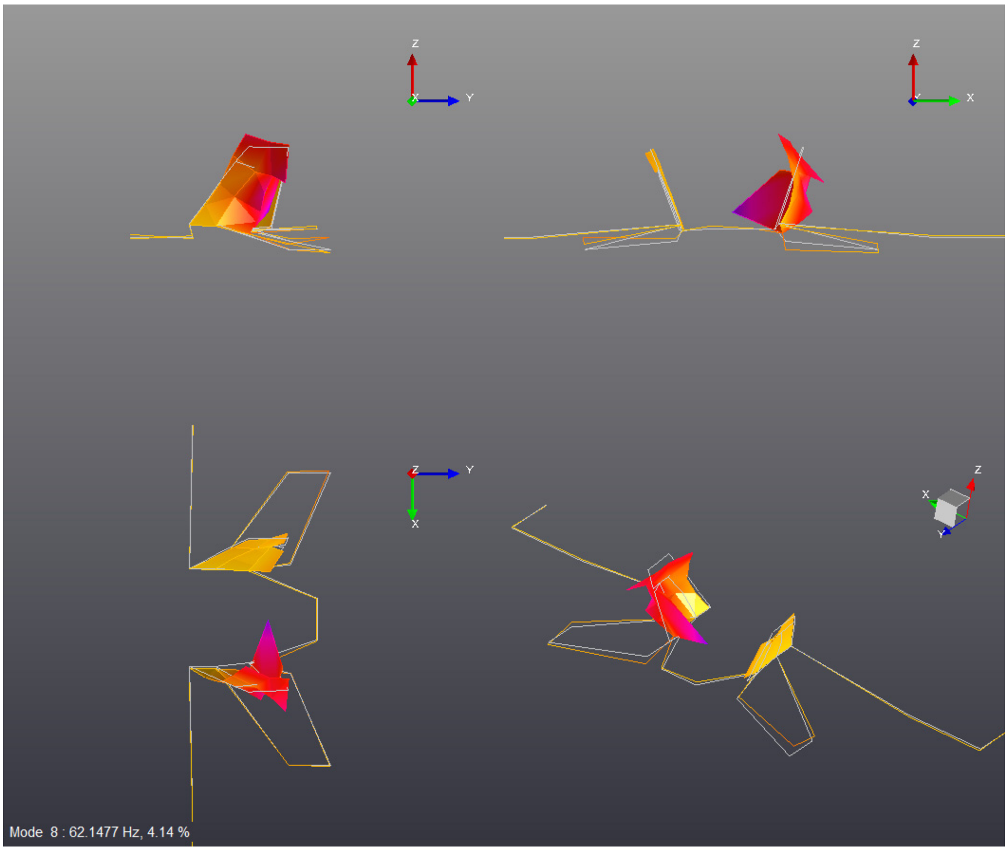

Figure 18. The mode shape at 62.1 Hz.

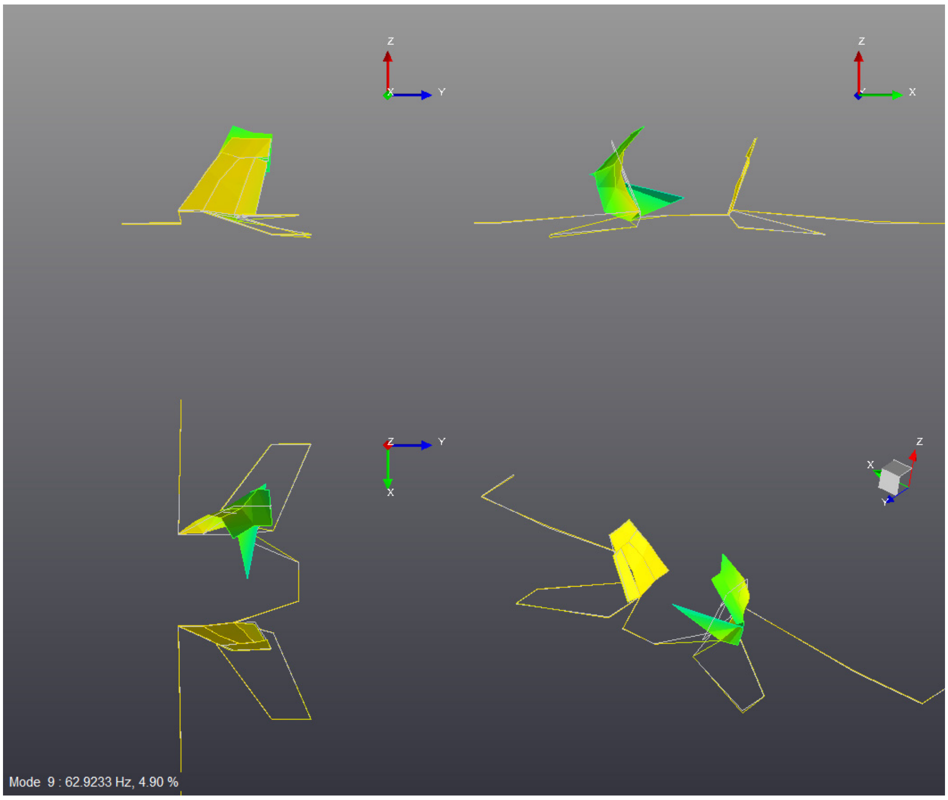

Figure 19, The mode shape at 62.9 Hz.

CONCLUSIONS

Lowest elastic natural modes of the VT of the FINAF F/A-18 Hornet were identified experimentally successfully. It was found that the main VT modes of interest (modes at about 15 Hz and 45 Hz) are divided into two modes having close natural frequencies. Random impact excitation technique for Operational Modal Analysis was demonstrated to be applicable for identification of very closely spaced modes.

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