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A STUDY OF THE ACCURACY OF GROUND VIBRATION TEST DATA USING A REPLICA OF THE GARTEUR SM-AG19 TESTBED STRUCTURE

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Abstract

Ground Vibration Tests have been performed on a replica of the Group for Aeronautical Research and Technology in Europe (GARTEUR) testbed structure SM-AG19. The aim of the Ground Vibration Tests was to study the impact on modal data stemming from the test data, from the boundary conditions used to mimic a free-free condition. For the tests an air-spring support system was designed with the aim to give a behaviour that is in resemblance with the behaviour of real aircraft test conditions.

To eliminate a potential, unwanted, impact on the test results generated by the wing to fuselage interface as it was designed for the original structure (SM-AG19), a deviation from the original interface has been made on the structure for this particular study.

1 Introduction

In the aerospace industry, finite element (FE) models are traditionally used to represent the global structural dynamics of an aircraft. The models are for example used for aeroelastic analyses of the aircraft and to predict the responses (loads and accelerations) due to dynamic excitations. Hence, it is vital that the models represent the essential dynamics of the real structure. Due to certification requirements and flight test permits, aeroelastic stability must be verified based on validated test data such as those stemming from a Ground Vibration Test (GVT). For this purpose, either modal data stemming from the GVT directly and/or from an FE-model being successfully correlated to GVT data can be used. In either of these cases above, the damping values are almost always taken from the GVT alone and can therefore not be validated.

The modal data estimated from an Experimental Modal Analysis (EMA) of GVT data are always affected by the test procedure and its omnipresent imperfections. One possible source of biased modal data is the suspension used [3]. Especially, experimentally obtained damping values are well known to have relatively high uncertainties. It is also well known that dynamic models' response predictions are highly dependent on the damping values used. In addition, damping is a notoriously difficult parameter to estimate correctly. It is also well known that in EMA, the estimated damping of a structure is prone to effects on damping from the suspension. An example of the difficulties in obtaining free-free boundary conditions and its effects on natural frequencies and damping estimates has been reported [2].

At SAAB Aeronautics, as in the aerospace industry in general, air-spring support systems are generally used to establish as close as possible a free-free condition during a GVT of an aircraft. The aircraft can usually only be supported by the air-springs at predefined positions which cannot easily be changed. On the GARTEUR SM-AG19 testbed structure [1] however, the support positions can easily be changed and the effect can be studied.

2 Ground Vibration Test

The GVTs of the SM-AG19 replica were conducted at the Linnaeus University (LNU) in Växjö, Sweden, as a collaboration between the department of mechanical engineering at LNU and the structural dynamics department at SAAB Aeronautics.

2.1 Testbed Structure

The structure used in this study is a replica of the testbed used in a round robin work performed in the 90's by the Structure and Materials Action Group of GARTEUR, SM-AG19. The replica structure is shown in Fig. 1. Examples of the design criteria for the original structure were; to be suited for instrumentation similar to an aircraft and to have closely spaced modes in order to make the problem even more challenging [1]. The original model also had a viscoelastic material located on the upper surface of the wing in order to accomplish sufficient damping [1]. The structure used in this study, was not equipped with such a viscoelastic material.

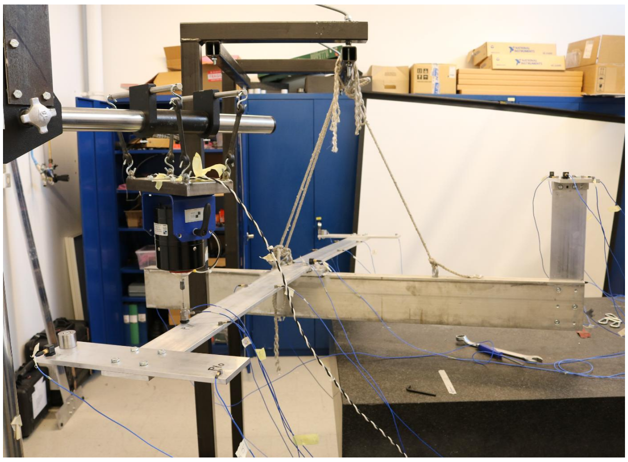

Fig 1. The replica of the GARTEUR SM-AG19 testbed structure at Linnaeus University. Here, the structure is in its reference support condition.

In order to ensure a repeatable behaviour in the wing to fuselage attachment for all support configurations, the wing was welded to the fuselage instead of only bolted as for the original structure. By doing this one abandons the original structure somewhat since the behavior of the wing/fuselage interface will be slightly different. However it was considered necessary in order to avoid unwanted variations in the GVT results due to the interface itself when changing the support condition.

The total mass of the structure used in this study is 41.7kg, with a wing span of 2.0m and a fuselage length of 1.5m.

2.2 GVT equipment and setup

The test object was excited using a modal shop 2025E shaker via a stinger rod and PCB TLD288D01 impedance head. The accelerances were measured using PCB T356A16 triaxial and 352A56 single axis sensors. LMS Scadas Mobile units were used for the data acquisition.

A small scale air-spring support system was manufactured for the testbed structure. The aim of that system was to give a similar dynamic behaviour for the testbed structure as its large scale counterpart does for real aircraft, e.g. rigid body mode frequencies lower than about one third of the first elastic eigenmode. For the testbed structure this implies rigid body frequencies lower than about 2Hz. The small scale air-spring support system consists of three air-bellows which are all connected to one large pressure vessel, into which air is supplied through a pressure regulator. The pressure vessel consists of two barrels, see fig. 2. The air-springs supporting the structure are shown in fig. 3.

Fig 2. The two-barrel pressure vessel for the air-spring support system.

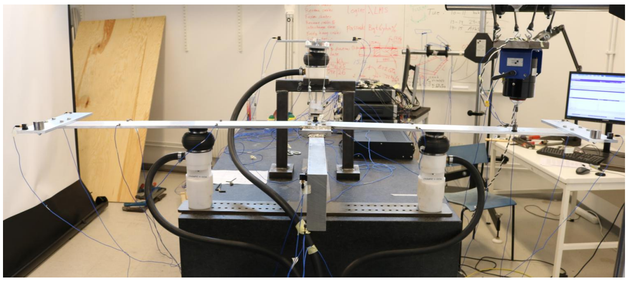

Fig 3. The air-spring system supporting the structure.

The air-spring support system was designed to facilitate accurate and fast positioning of each individual air-spring, by having predefined positions on a support frame structure.

Sensors were placed according to Fig. 4 and Fig. 5. All three Degrees-Of-Freedom (DOFs) were measured at position 1, 3, 9, 16, 21, 23 and 27 with triaxial accelerometers. At position 10-14, 16-20 and 22 on the wings and position 24-26 and 28 on the horizontal tail, only the –Z DOFs (the normal direction perpendicular to the wing area) were measured. On the fuselage, at positions 2, 4-8, 29 and 30, measurements were made in the –Y DOFs (the sideway direction) only.

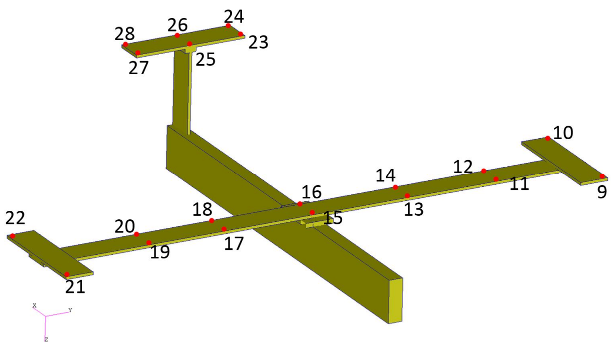

Fig 4. The sensor placements and position numbers on the wing and horizontal tail.

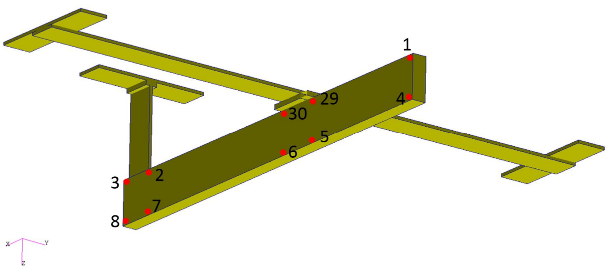

Fig 5. The sensor placements and position numbers on the fuselage.

The structure was excited by a single electromagnetic shaker, which excited the structure in the +Z DOF at position 11, see Fig. 4. The shaker was attached to the structure through a stinger rod and an impedance head, measuring both the force applied and the corresponding acceleration for the same DOF, which enabled the achievement of a high quality direct point Frequency Response Function (FRF).

As a reference for the measurements involving the air-springs, the structure was tested when supported by cords, connected at the wing/fuselage interface and to the rear part of the fuselage of the structure, see Fig. 1.

When involving the air-springs, both the positions and the internal pressure level of the system were varied. The air-springs supporting the structure under the wing, were positioned in three ways: a) as close to the fuselage as possible i.e. at a distance equal to 6.25% wing span, b) at 27.5% wing span and c) at 42.5% wing span, all at 50% chord. The position of the air-spring supporting the rear fuselage was kept constant throughout the GVTs. With the air-springs positioned at 42.5% wing span, their internal pressure level was reduced in two steps. Unfortunately the pressure indicator of the regulator was not sensitive enough for the exact pressure level to be monitored. The sensor and actuator setup was done once and thereafter preserved during all measurements.

All measurements presented in this paper are based on stepped sine measurements with an excitation force level equal to 0.5N, and an acceptable force amplitude deviation of 1dB. As a baseline, a frequency range of 5-65Hz was selected with a frequency step size of 0.05Hz.

3.3 GVT results

All the experimental modal analysis has been performed using LMS Test.Lab© utilizing PolyMAX©, which is a least-squares complex frequency-domain estimator method. Eigenmodes were selected based on located stable poles in the stabilization diagram and the Complex Mode Indicator Function (CMIF).

Throughout the study, the Modal Assurance Criterion (MAC) [4] was calculated in order to compare modal matrices stemming from the test data. The MAC number between mode *i* and mode *j* is defined as:

$$MAC_{ij} = \frac{\left|\{\phi_i\}^T\{\phi_j\}\right|^2}{\left(\{\phi_i\}^T\{\phi_i\}\right)\left(\{\phi_j\}^T\{\phi_j\}\right)} \quad (1)$$

Rigid body natural frequencies were estimated for support condition with the air-springs positioned at 42.5% wing span and with a nominal pressure level. The highest rigid body natural frequency for movements within the XZ-plane was estimated to 0.9Hz.

3.3.1 Reference configuration

When examining the stabilization diagrams for the reference configuration, the number of eigenmodes present in the frequency range 30-40Hz is not obvious. However when examining the FRFs in more detail using a Nyquist diagram, see Fig. 6, one can more clearly note the presence of three modes within the frequency range; the first two eigenmodes are closely spaced.

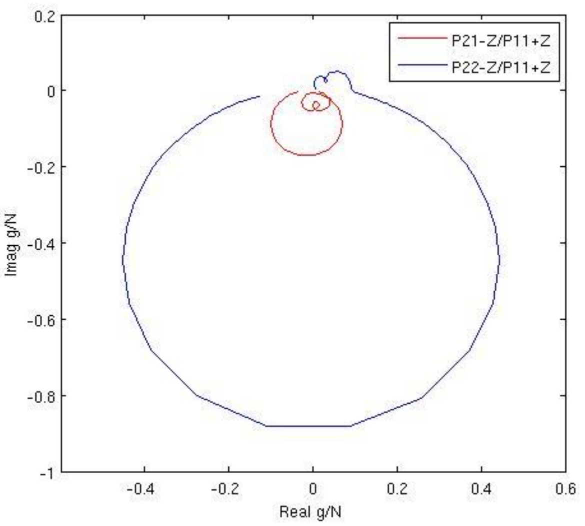

Fig 6. The Nyquist diagram of synthesized FRFs (g/N) P21:-Z/P11:+Z (red), P22:-Z/P11:+Z (blue), frequency range 32-39Hz.

The modal analysis performed for the reference configurations resulted in eight eigenmodes within the frequency range 5-65Hz, see Table 1. and Fig. 7.

Table 1. Results for reference configuration.

Mode number	Frequency [Hz]	Damping %
1	5.36	0.63
2	16.46	0.50
3	33.29	0.61
4	34.14	1.01
5	37.22	0.61
6	50.12	0.33
7	54.04	0.13
8	56.91	0.11

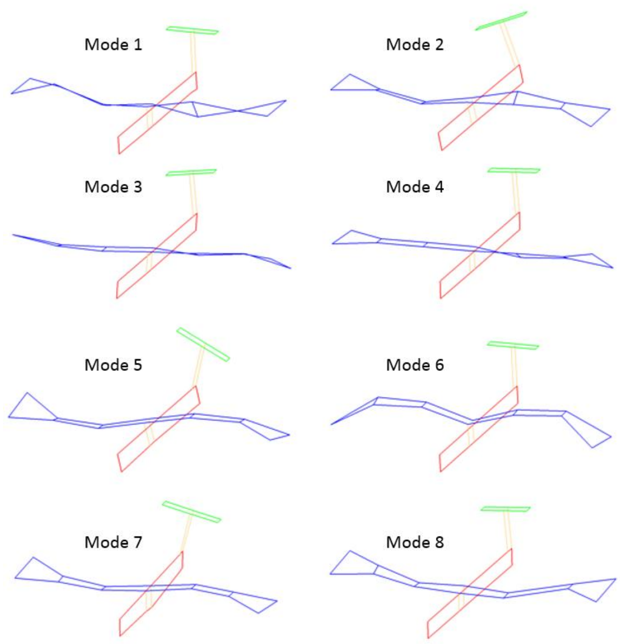

Fig 7. Eigenmode 1-8 for the reference configuration.

$$\begin{bmatrix} 1.00 & 0.22 & 0.56 & 0.33 & 0.30 & 0.65 & 0.18 & 0.08 \\ 0.22 & 1.00 & 0.37 & 0.24 & 0.80 & 0.23 & 0.40 & 0.06 \\ 0.56 & 0.37 & 1.00 & 0.63 & 0.44 & 0.47 & 0.26 & 0.10 \\ 0.33 & 0.24 & 0.63 & 1.00 & 0.23 & 0.29 & 0.11 & 0.05 \\ 0.30 & 0.80 & 0.44 & 0.23 & 1.00 & 0.42 & 0.52 & 0.10 \\ 0.65 & 0.23 & 0.47 & 0.29 & 0.42 & 1.00 & 0.18 & 0.05 \\ 0.18 & 0.40 & 0.26 & 0.11 & 0.52 & 0.18 & 1.00 & 0.42 \\ 0.08 & 0.06 & 0.10 & 0.05 & 0.10 & 0.05 & 0.42 & 1.00 \end{bmatrix}$$

Fig 8. The AUTOMAC-matrix for the reference configuration.

Table 2. Results for different air-spring support positions, a = 6.25%, b = 27.5% and c = 42.5% wing span.

Mode no. #	Freq a [Hz]	Damp a %	Freq b [Hz]	Damp b %	Freq c [Hz]	Damp c %
1	6.32	0.60	6.18	0.47	6.16	0.48
2	16.50	0.77	16.62	0.79	16.64	0.81
3	33.19	0.45	33.18	0.32	33.18	0.42
4	34.08	0.62	34.36	0.83	34.13	0.64
5	37.24	0.13	37.71	0.71	38.09	1.04
6	50.21	0.25	50.31	0.28	50.37	0.34
7	54.05	0.12	54.16	0.14	54.13	0.14
8	56.90	0.12	57.07	0.13	57.07	0.10

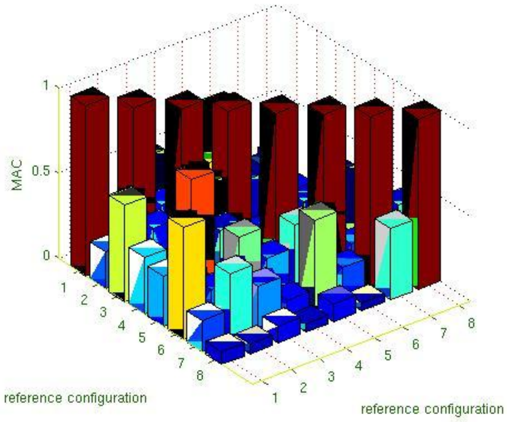

Fig 9. The AUTOMAC for the reference configuration.

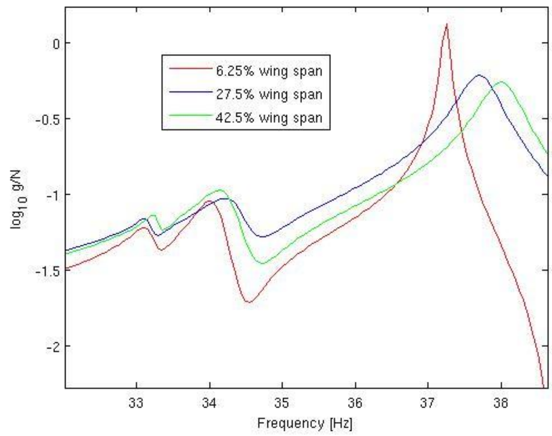

Fig 10. Synthesized direct point FRFs with air-springs supporting the wing at different wing span position.

3.3.2 Air-spring support system position

As for the reference configuration, eight eigenmodes were estimated for each position of the air-springs. EMA estimates of the eigenfrequencies and their associated damping values are presented in Table 2. Synthesized direct point FRFs for a frequency range of 32-39Hz are presented in Fig. 10. MAC matrices for the reference configuration versus each of the air-spring position are presented in Figs. 11-13 together with an eigenmode comparison plot of eigenmode number three in Figs. 14-16. Eigenmode number three is chosen to be illustrated due to the low MAC numbers associated with it.

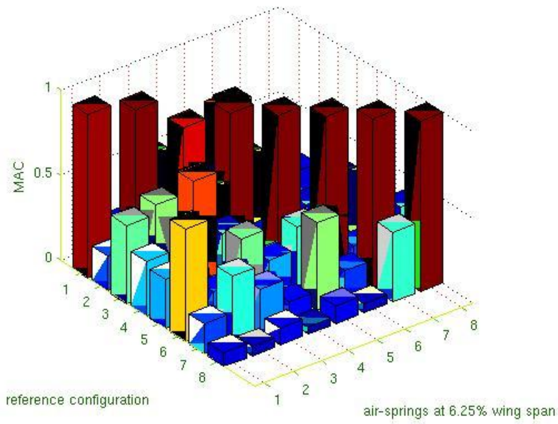

Fig 11. The MAC-matrix for the reference configuration versus air-spring support at 6.25% wing span.

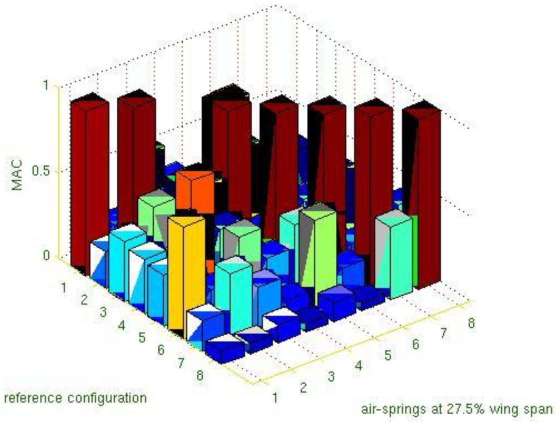

Fig 12. The MAC-matrix for the reference configuration versus the air-spring support at 27.5% wing span.

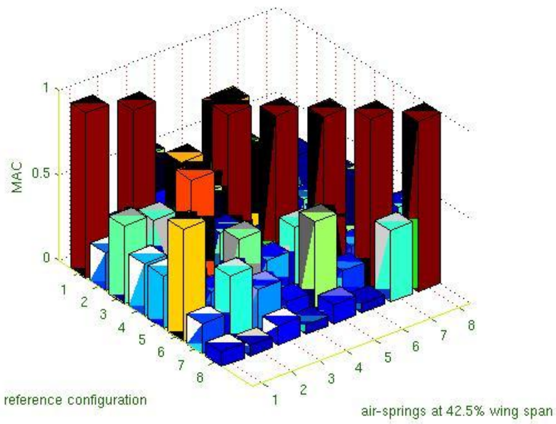

Fig 13. The MAC-matrix for the reference configuration versus the air-spring support at 42.5% wing span.

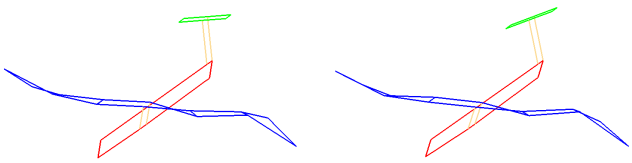

Fig 14. Eigenmode number 3, the reference configurations (left) and the air-springs at 6.25% wing span (right). MAC=0.90.

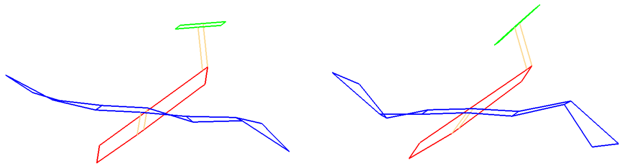

Fig 15. Eigenmode number 3, the reference configurations (left) and the air-springs at 27.5% wing span (right). MAC=0.55.

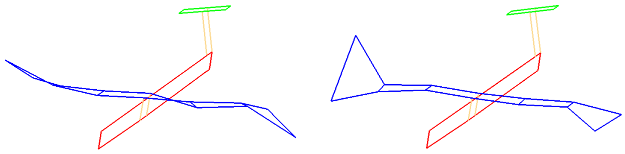

Fig 16. Eigenmode number 3, the reference configurations (left)and the air-springs at 42.5% wing span (right). MAC=0.70.

3.3.3 Air-spring support system pressure

With the air-springs supporting the structure at 42.5% wing span, the air-spring support internal pressure was reduced in two steps. The 42.5% wing span position was chosen since the largest impact was expected for this position. Since the pressure regulator monitor was not accurate enough, the precise pressure level could not be monitored. The pressure level was therefor reduced to levels based on geometrical aspects of the air-springs as depicted in Fig. 17.

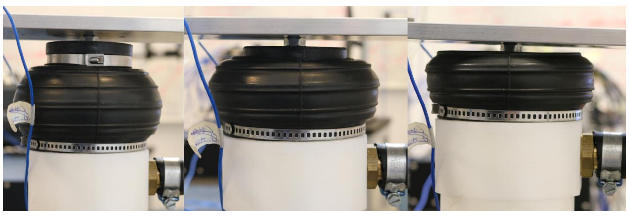

Fig 17. Air-springs at the nominal (left), reduced (center) and low (right) pressure level.

In an early stage of the study, the most significant impact of reducing the air-spring pressure level from the nominal one was shown to be for frequencies above 30Hz. Therefor the frequency range for these measurements was zoomed into 30-55Hz instead of 5-65Hz.

EMA estimates of the eigenfrequencies and their associated damping values are presented in Table 3. Synthesized direct point FRFs for a frequency range of 36-54Hz are presented in Fig. 18. The MAC matrices and illustrated eigenmodes including all comparable estimates for the reference configuration versus each air-spring pressure level condition are presented in Figs. 19-22.

Table 3. Results for different air-spring pressure levels.

Mode no. #	Freq nom [Hz]	Damp nom %	Freq red [Hz]	Damp red %	Freq low [Hz]	Damp low %
1	6.16	0.48				
2	16.64	0.81				
3	33.18	0.42	33.35	0.36	33.33	0.42
4	34.13	0.64	33.85	0.87	33.57	0.98
5	38.09	1.04	39.88	1.67	43.32	2.58
6	50.37	0.34	50.78	0.52	51.48	0.73
7	54.13	0.14	54.15	0.13	54.28	0.20
8	57.07	0.10				

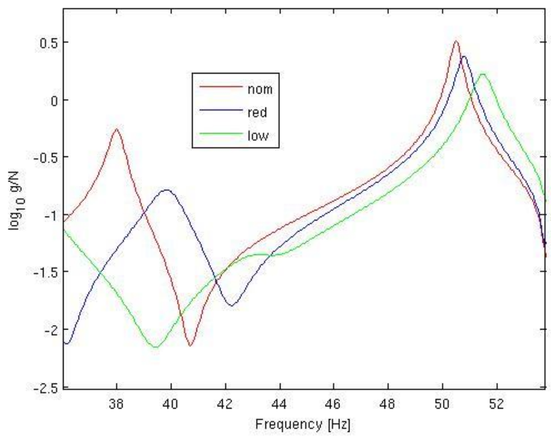

Fig 18. The synthesized direct point FRFs with air-springs supporting the wing at 42.5% wing span position with different pressure levels.

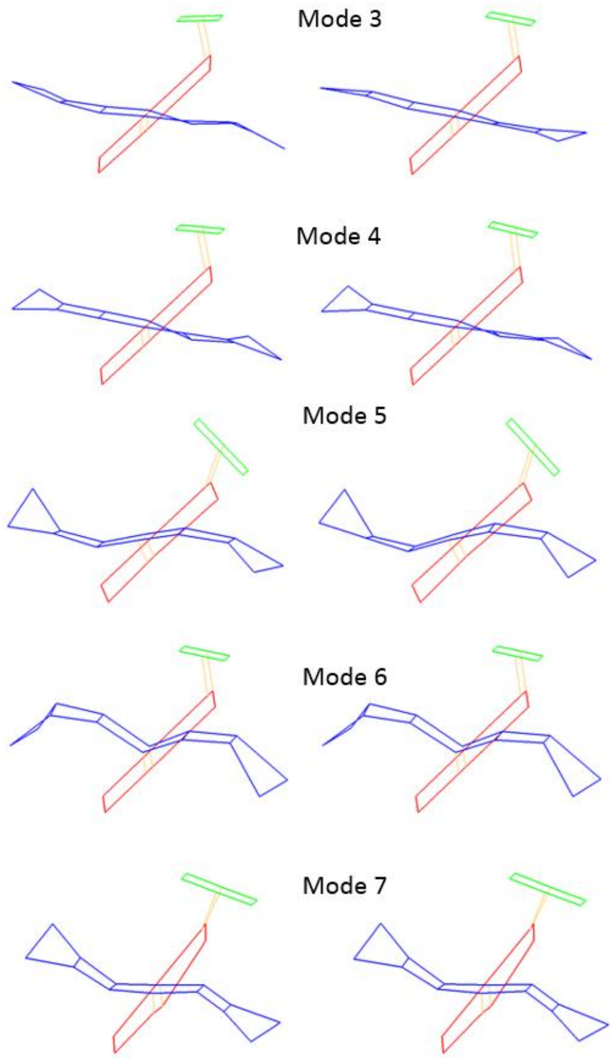

Fig 19. Eigenmodes 3-7 for the reference configuration (left) and with the air-springs positioned at 42.5% wing span at reduced pressure level (right).

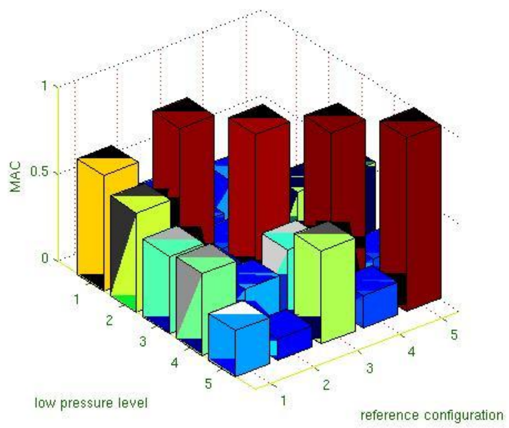

Fig 20. The MAC-matrix for the reference configuration versus the air-spring system at 42.5% wing span and at the reduced pressure level.

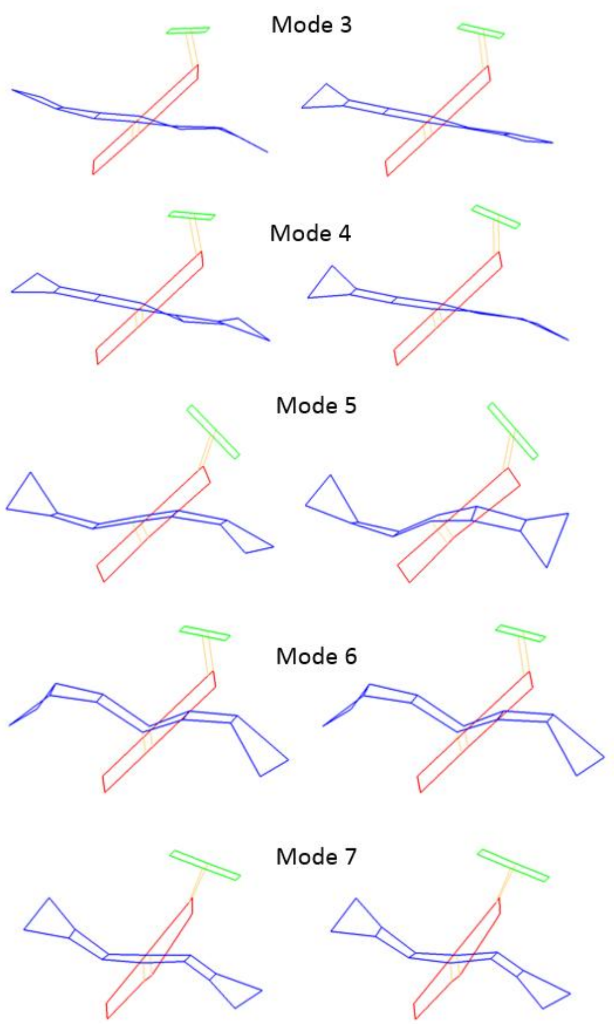

Fig 21. Eigenmodes 3-7 for the reference configuration (left) and with the air-springs positioned at 42.5% wing span at low pressure level (right).

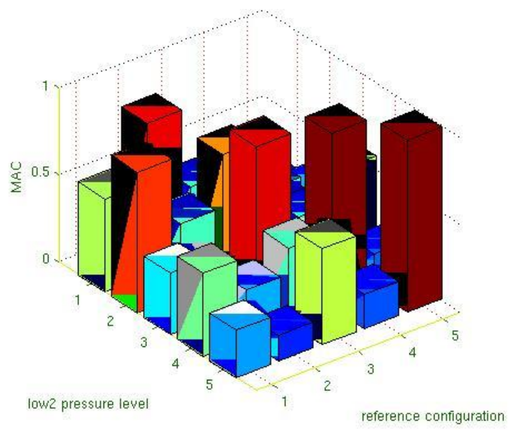

Fig 22. The MAC-matrix for the reference configuration versus the air-spring system at 42.5% wing span with low pressure level.

4 Conclusion

EMA estimates for the reference configuration do not compare as accurately as desired with the original structure as presented in [1]. Some overall characteristics and the closely spaced eigenmodes within the frequency range of 30-40Hz are somewhat comparable in terms of estimated eigenfrequencies but some eigenmodes can be judged, simply from a visual inspection not to compare well. Two sources of the deviation from the original structure are associated with the welded wing/fuselage interface and the fact that the additional viscous damping is not included. These are believed not to be the only sources causing the deviations. However, for the study presented in this paper, the slightly different behaviour is of less importance.

In principle, the designed air-spring support system worked well. The highest rigid body motion in the XZ-plane has a natural frequency of about 0.9Hz, which is well below one third of the lowest estimated elastic eigenfrequency. Hence, the setup is believed to be fairly comparable with an ordinary full scale GVT setup.

Changing the positions of the air-springs supporting the wing had a large impact on eigenmodes number three and five. For eigenmode number three, the eigenvector changes significantly with a MAC number as low as 0.55 for the air-springs positioned at 27.5% wing span compared to the reference configuration. Its eigenfrequency and associated damping value are however not strongly affected. For eigenmode number five the opposite apply, the eigenvector is not affected and it has a MAC number of 1.00 compared to the reference configuration, for all investigated air-spring positions. However, the eigenfrequencies and their associated damping values change drastically. Especially that is true for the damping value of eigenmode No. five that shows an increase from 0.13% to 1.04%. It should be noticed that the change in positions of the air-springs is also excessively large compared to the possibilities to move the suspension positions in a real full scale GVT which in general are none.

A change in the pressure of the air-springs affected eigenmodes number three and five principally in the same way as a change in its positons. Here, the changes are however more severe, especially for eigenmode number five for which an increase in eigenfrequency and the associated damping value of about 5Hz and 1.5% (units) respectively are found. The change in frequencies and MAC numbers for eigenmodes number three and four show that the two eigenmodes are becoming even more closely spaced when reducing the pressure of the air-springs. For the "low" air-spring pressure level the difference in frequency between the two eigenmodes is only about 0.15Hz. If the pressure level would have been reduced even more, the two eigenmodes would most likely have changed order. This is well known as the mode switching phenomenon.

The study shows that the support used for the SM-AG19 replica structure which is supposed to be somewhat similar to a real aircraft structure support, strongly affects the estimated modal parameters. The effect on closely spaced eigenmodes is such that it may introduce unwanted difficulties when performing an FE-model correlation based on GVT data, especially if the used support has resulted in the changing of the order of eigenmodes.

5 Future work

By welding the wing to the fuselage instead of bolting it, the original structure was abandoned. Depending on the objectives of future studies, a structure more similar to the original in this sense should be developed, possibly also including the extra viscous damping which is applied to the wing of the original structure. To be able to compare data with previous studies based on comparable structures, this is considered as a requirement. To continue the work related to the air-spring support system, a more sensitive regulator should be included, by which pressure levels can be monitored more accurately. This will facilitate a better control of the structure support conditions. The air-springs should also be included in an FE-model for comparison and further investigations of the drastic changes shown for some eigenmodes due to its characteristics.

6 Acknowledgement

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