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# FLUTTER ANALYSIS OF A WING-LIKE STRUCTURE WITH PAYLOADS UTILIZING FINITE ELEMENT AND GROUND VIBRATION TEST MODES

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## ABSTRACT

*Flutter prediction is a very important task in the design or modification of an aircraft wing. The main aim of this paper is to compare flutter analysis results of a wing-like structure that has three stations with integrated payloads. The modal information of the wing is first acquired by finite element analysis and then ground vibration test of the structure separately. Modal results obtained by the finite element analysis and ground vibration test are then used in frequency domain flutter solution and comparisons are made between the flutter speeds obtained in the low-subsonic flow regime. While GVT-based flutter analysis yields higher flutter onset speeds with different assumed structural damping, FEM-based one stays in conservative side by turning out lower flutter speeds.*

## INTRODUCTION

“Aeroelasticity” is the term used to denote the field of study concerned with the interaction between the deformation of an elastic structure in an airstream and the resulting aerodynamic force [Hodges and Pierce, 2011]. In detail, the science of aeroelasticity is divided into two main branches: static aeroelasticity and dynamic aeroelasticity. While static aeroelasticity examines the trim characteristic of the aircraft under both aerodynamic and inertial loadings, dynamic aeroelasticity investigates the dynamic behavior of lifting surfaces (i.e. wing-like structures). The most catastrophic aeroelastic phenomenon, flutter, occurs when the structure extracts energy from air stream [Nikbay, Acar, 2012]. Therefore determination of flutter boundary become an important requirement that has to be taken into consideration in course of preliminary and detailed design phase of an aircraft. In addition, this necessity has to be satisfied after structural modifications performed on an in-service aircraft. In aeronautical industry, structural modifications are generally implemented on fighters and special mission aircrafts for the purpose of integration of the rocket or electronic warfare systems. Certification processes of all those newly added systems are explained in MIL-HDBK-1763 “Aircraft/Stores Compatibility Systems Engineering Data Requirements and Test Procedures”. This handbook also addresses Ground Vibration Test (GVT), flutter analyses and tests of modified aircraft for compliance purposes [Dalmış, 2014].

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Flutter analysis can be performed in time domain or frequency domain. Frequency domain flutter analyses require modal results of the structure and these results can be obtained by numerical methods (i.e. FEM based natural frequency analysis) or ground vibration test (GVT) of the structure. In spite of the fact that these two methods are applied on the same structure, due to some modeling errors, FE results can yield a bit different natural frequencies and corresponding mode shapes than the GVT results. The correlation between two can be checked according to MAC (Modal Assurance Criteria). From aeroelastic point of view, it is very important to determine how these distinctions affect the flutter results i.e. flutter speed and frequency.

The objective of this study is to compare flutter analysis results of a wing-like structure based on different modal input i.e. FEM modal analysis results and GVT results. Effects of those on flutter analysis are investigated and interpreted. FEM-based natural frequency analysis and GVT are done by MSC Nastran© 2013.0 and LMS Test.Lab© 15.0 respectively. Flutter analysis are performed by ZONA ZAERO© 9.2 relying on g-method [Chen, 2000].

## THEORY

### Aeroelasticity

Aeroelastic response of aircraft originate from interactions of aerodynamic forces, inertial forces and elastic forces. In the elastic regime, aerodynamic forces are also dependent on the structural deformation alongside the flow parameters. Accordingly, the general equation of motion of the structure can be written as,

$$M\ddot{x}(t) + Kx(t) = F(t, x(t)) \tag{1}$$

where,

“M” is the mass matrix

“K” is the stiffness matrix

“x(t)” is the structural deformation

“F(t, x(t))” is external force matrix

External force matrix is composed of two main parts; aerodynamic forces due to structural deformation $F_a$(t, x(t)) and other forces $F_o$(t, x(t)),

$$F(t, x(t)) = F_a(t, x(t)) + F_o(t, x(t)) \tag{2}$$

Moreover, other forces can be split into three main parts; atmospheric turbulence forces $F_t$(t), store separation and trim forces $F_0$(t) and aerodynamic forces due to pilot or control system command $F_c$(t, x(t)),

$$F_o(t, x(t)) = F_t(t) + F_0(t, x(t)) + F_c(t, x(t)) \tag{3}$$

Because of the feedback aerodynamic force originating as a result of the structural deformation, dynamic system can be self-excited in nature. This feedback system can be shown as in Figure 1.

$$M\ddot{x}(t) + Kx(t) - F_a\big(t, x(t)\big) = F_o(t, x(t)) \tag{4}$$

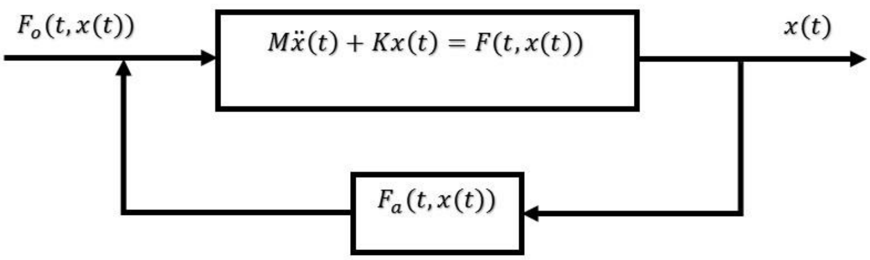


Figure 1 Aeroelastic Functional Diagram (Closed Loop)

As it is known, any closed loop system could encounter some stability problems. In the aeroelastic case, this instability is called flutter [ZONA Inc.].

**Correlation Analysis**

Frequency domain flutter analysis is very dependent on externally provided modal results. To be able to comprehend effects of FEM-based modal results and GVT results on flutter solutions clearly, those two are to be correlated by correlation analysis.

In the correlation analysis, the differences between the finite element model and test model are obtained. It is completed in 2 stages, namely geometric correlation and dynamic correlation. Data acquisition points in GVT are paired with related nodes in the finite element model in the geometric correlation phase. In the dynamic correlation, GVT and finite element model natural frequency and mod shape results are compared with each other. Mode shape correlation degree is determined according to Modal Assurance Criterion (MAC) function. MAC function is calculated as follows:

$$\boldsymbol{MAC_{rs}} = \frac{\left|\{\boldsymbol{\varphi}\}_r^T\{\boldsymbol{\varphi}\}_s\right|^2}{\left|\{\boldsymbol{\varphi}\}_r^T\{\boldsymbol{\varphi}\}_r\right|\left|\{\boldsymbol{\varphi}\}_s^T\{\boldsymbol{\varphi}\}_s\right|} \quad (5)$$

where,

$\{\boldsymbol{\varphi}\}_r$: numerical modal vector

$\{\boldsymbol{\varphi}\}_r^T$: transpose of $\{\boldsymbol{\varphi}\}_r$

$\{\boldsymbol{\varphi}\}_s$: test modal vector

$\{\boldsymbol{\varphi}\}_s^T$: transpose of $\{\boldsymbol{\varphi}\}_s$

MAC=1 represents the perfect correlation whereas MAC=0 means no correlation. For the practical purposes, for example for satellite projects, for main bending mode, MAC value is stated to be higher than 0.9 and frequency deviation is stated to be smaller than 3%. For other structural modes, MAC value should be higher than 0.8 and frequency deviation should be smaller than 10% between the finite element and GVT results [Ersoy, Atasoy, Genç, 2016].

## METHOD

In order to observe the effects of the modal data, which are separately obtained from FEM based solver and GVT of the geometry, on the flutter solutions, a reference structure is to be determined. There are several parameters influencing the flutter characteristics of the wing: sweep angle, taper ratio, inertia axis etc. [Molyneux, 1954]. Also by taking into consideration of natural frequencies of the wing-like structure, these parameters are tuned to be able to achieve flutter speed at the low subsonic regime. Wing-like structure is shown on Figure 2:

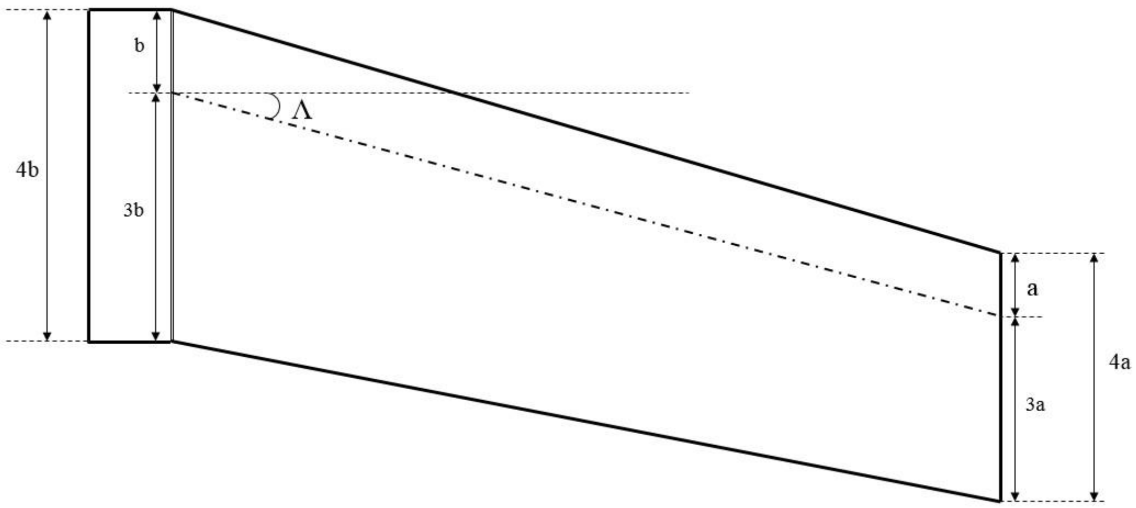


Figure 2 Wing-like Structure

Wing-like structure has also three stations on which payloads are integrated by the help of pylons (see Figure 3). Also, manufactured wing-like model is indicated in Figure 4.

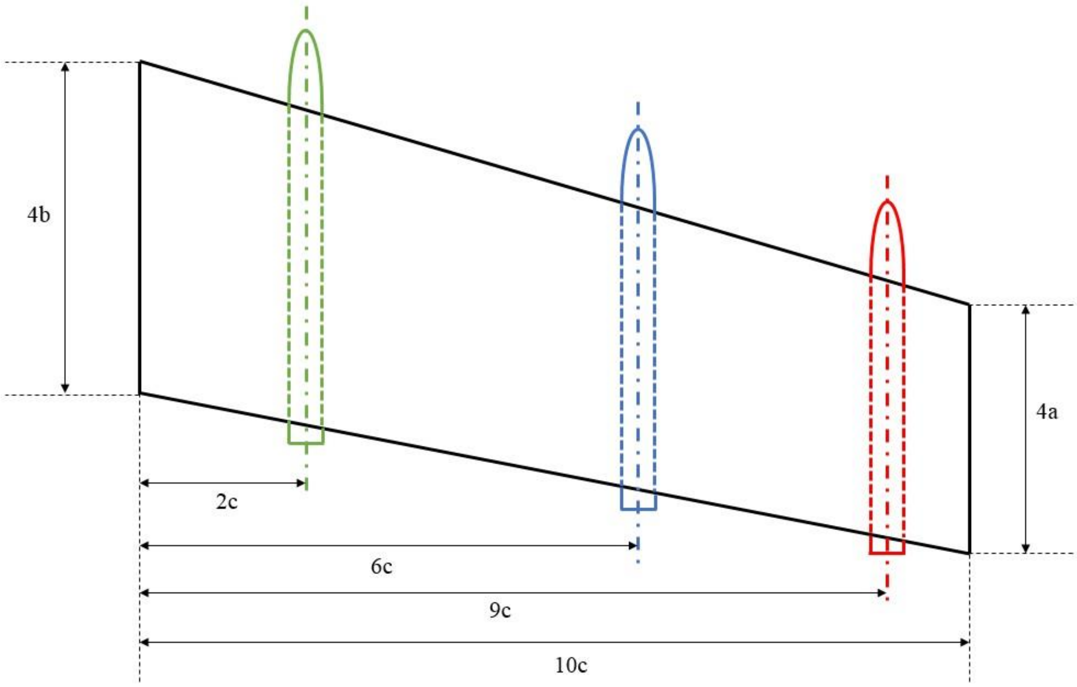


Figure 3 Payload Locations

Figure 4 Manufactured Wing-like Structure

In order to perform frequency domain flutter analyses, modal information of the structure are to be obtained. In this study, these are acquired by means of FEM based normal modes analysis performed by MSC Nastran© 2013 and GVT of the structure by LMS Test.Lab© 15.0. Finite element model of the wing, GVT flow and test setup are given in Figure 5, Figure 6 and Figure 7 respectively.

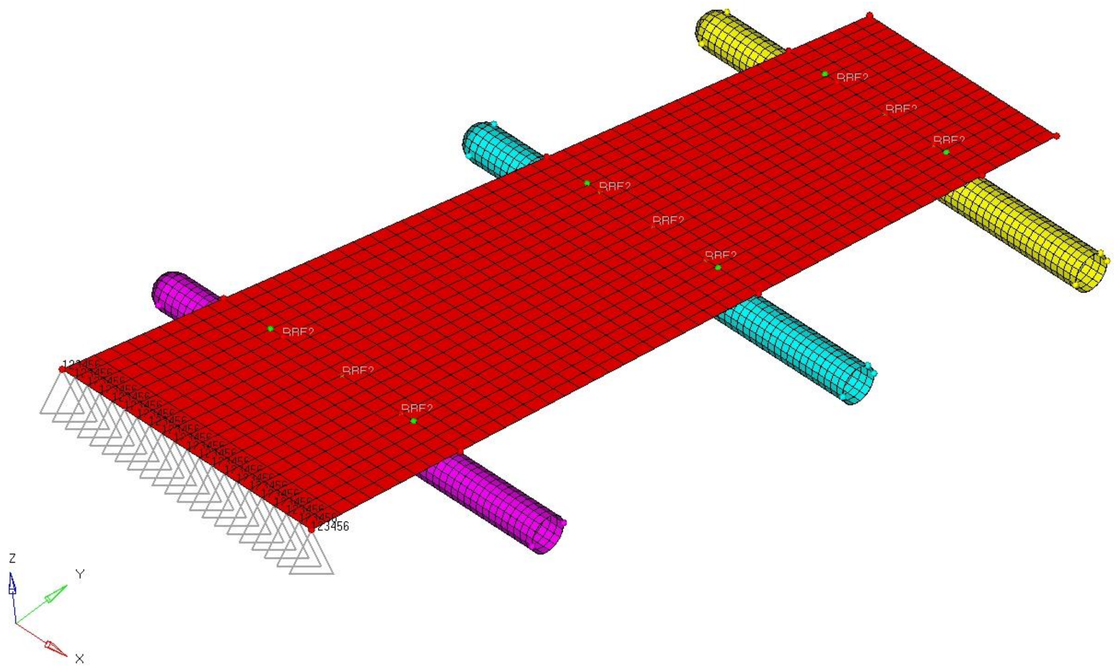


Figure 5 Finite Element Model of the Wing-like Structure

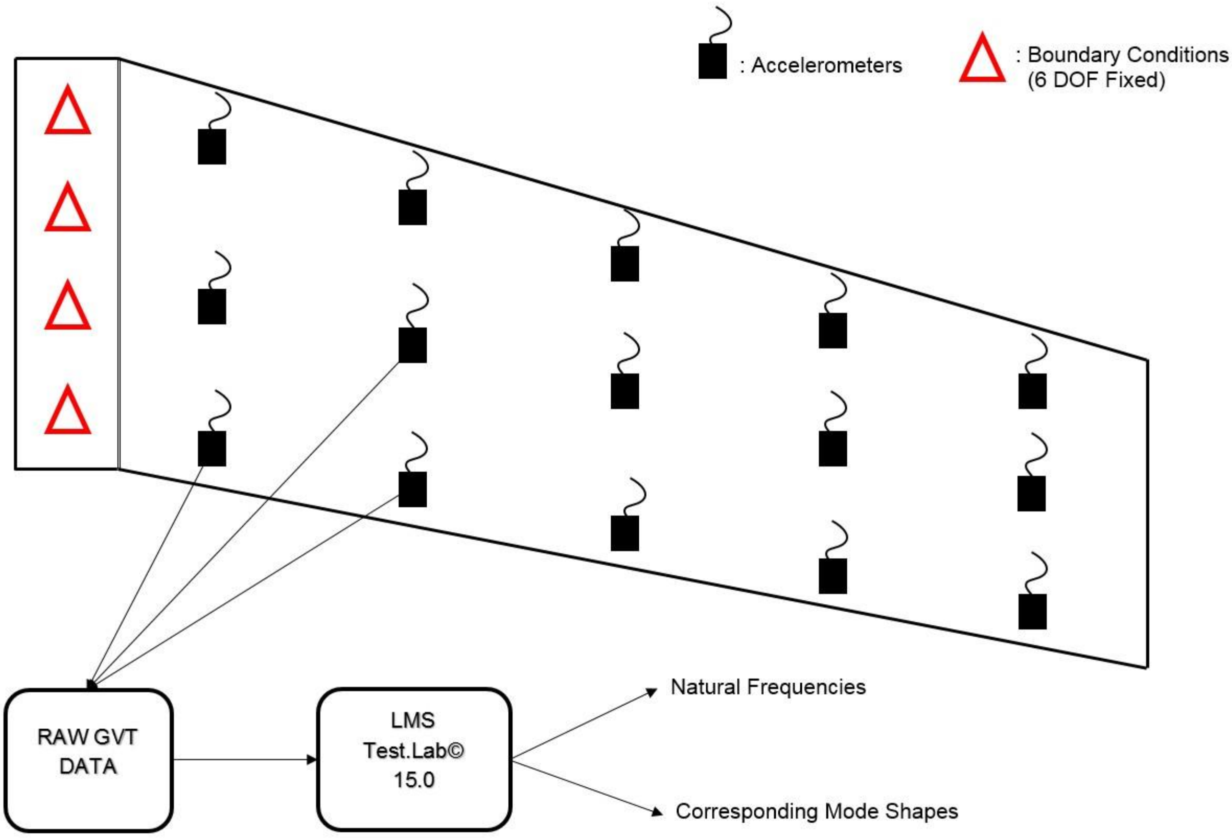


Figure 6 Ground Vibration Test Flow of the Wing-like Structure

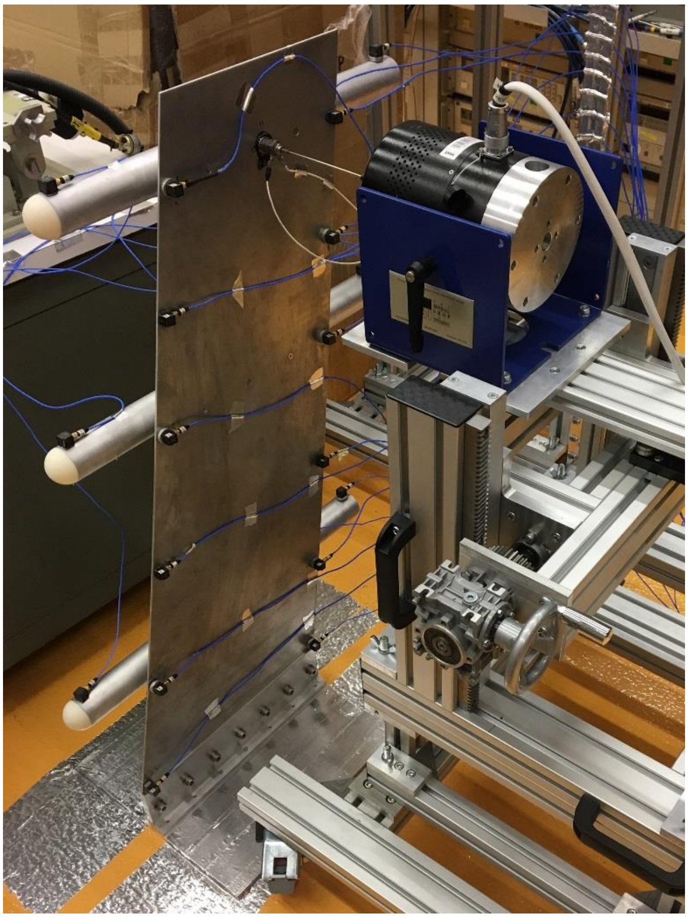

Figure 7 Ground Vibration Test Setup

Modal results obtained by the modal analysis and GVT of the wing-like structure are provided as input to frequency domain flutter solver ZONA ZAERO© 9.2 for flutter analysis. ZAERO solves linear potential equation by using aerodynamic panel model on which structural solutions are mapped to estimate flutter onset speed and frequency in the specified flight envelope. In spite of the fact that the wing-like structure is not attached to any fuselage-like structure, ZAERO requires fuselage aerodynamic panel model which represents the ground. For this purpose aerodynamic meshes are generated on the fuselage in a way to take ground effect on flutter onset into consideration, as seen by green panels in Figure 8.

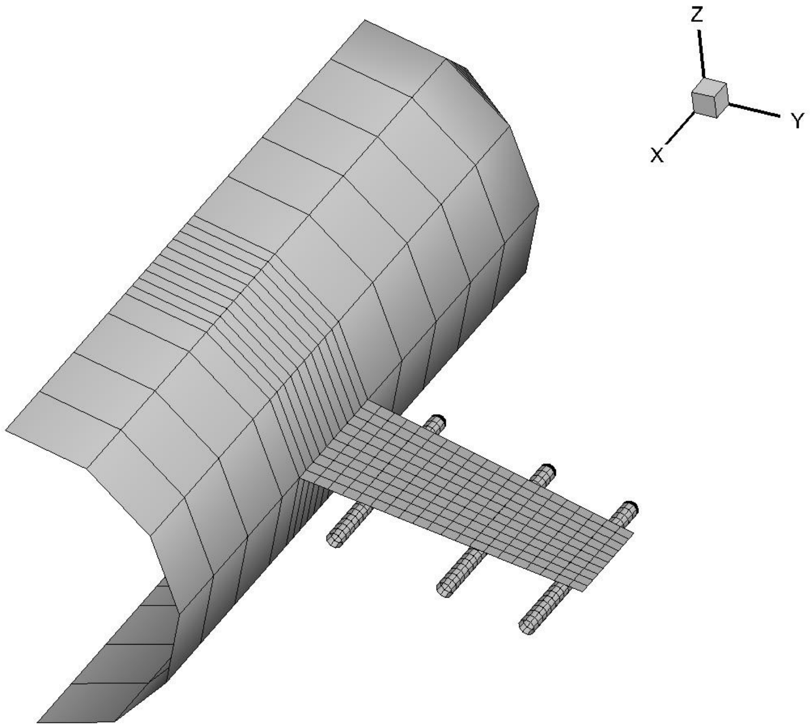


Figure 8 Aerodynamic Panel Model

## RESULTS AND DISCUSSIONS

### FEM Based Normal Mode Analysis Results

Especially for plate-like wing models, bending and torsional modes of the structure plays determining role on flutter characteristic. Therefore only bending and torsional modes (first and second modes respectively) of the wing-like structure are extracted from normal modes analysis. Results are shown in Figure 9 and Figure 10.

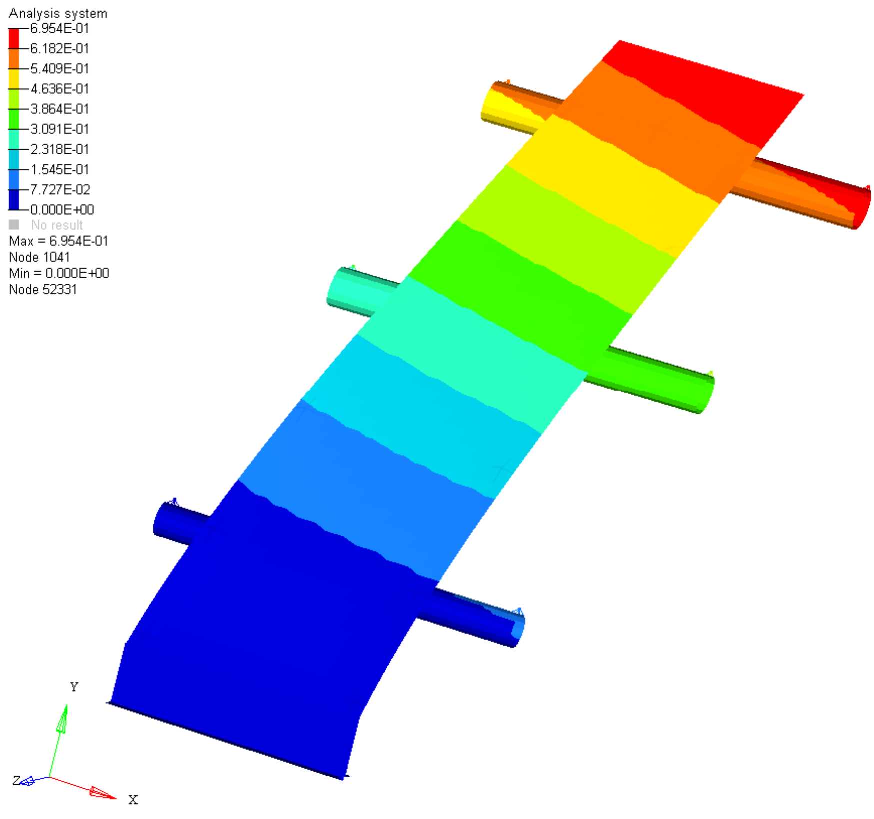


Figure 9 FEM Results, Bending Mode Shape of Wing Model (1.35 Hz)

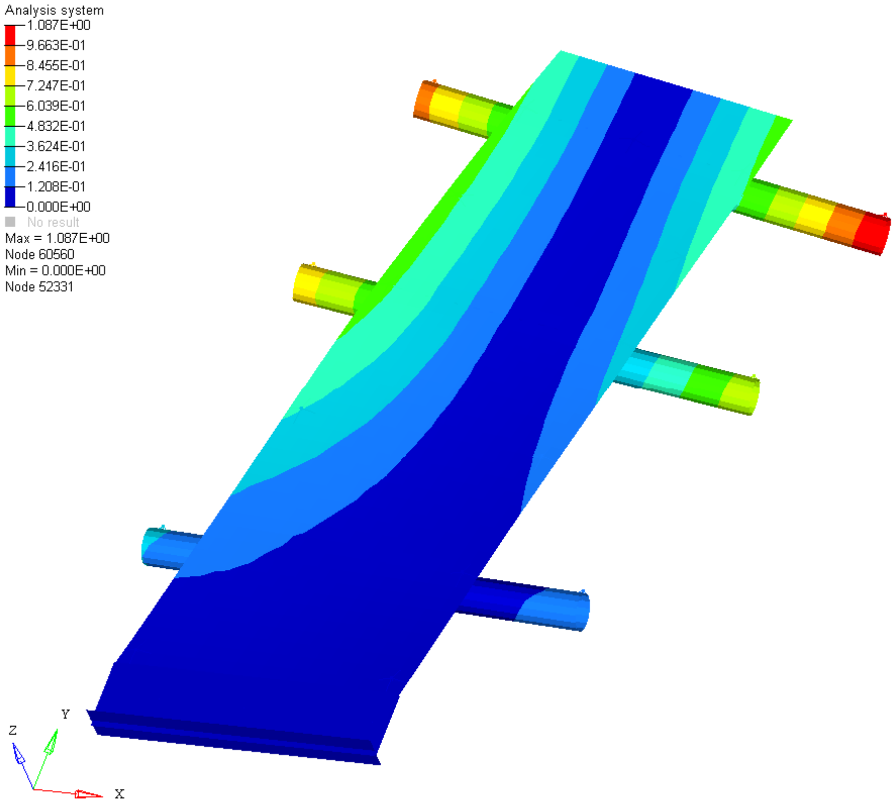


Figure 10 FEM Results, Torsional Mode Shape of Wing Model (6.38 Hz)

**Ground Vibration Test Results**

Similar to FEM, only bending and torsional modes are obtained from GVT. Results are given in Figure 11 and Figure 12.

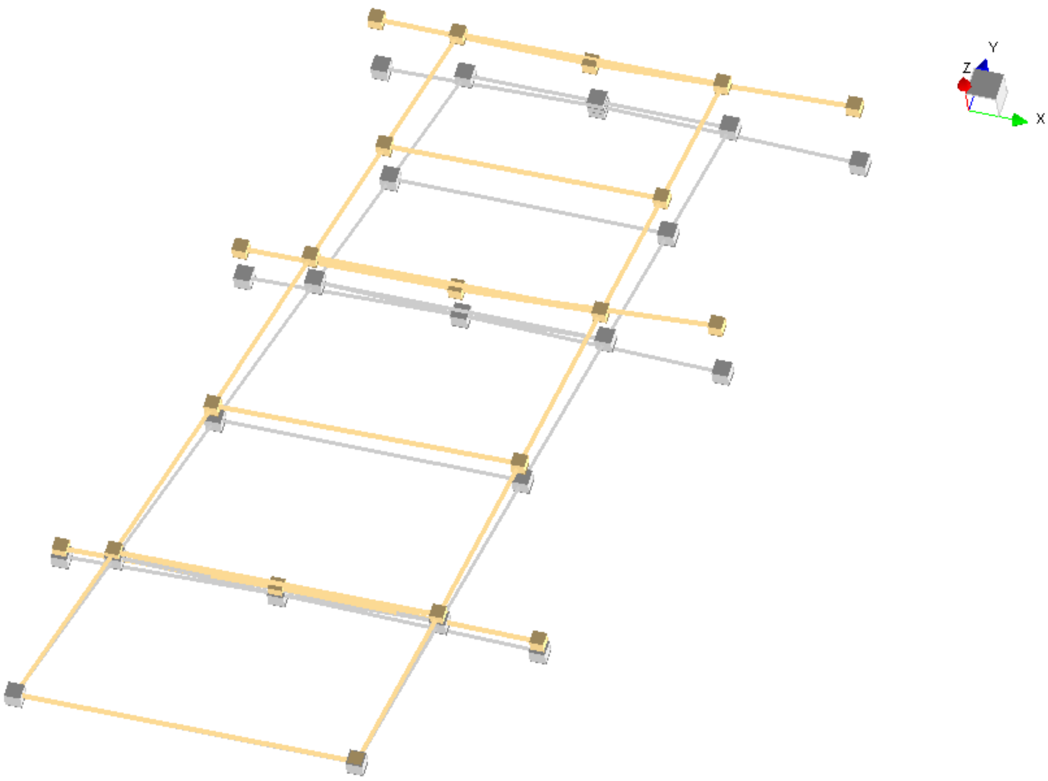


Figure 11 GVT Results, Bending Mode Shape of Wing Model (1.46 Hz)

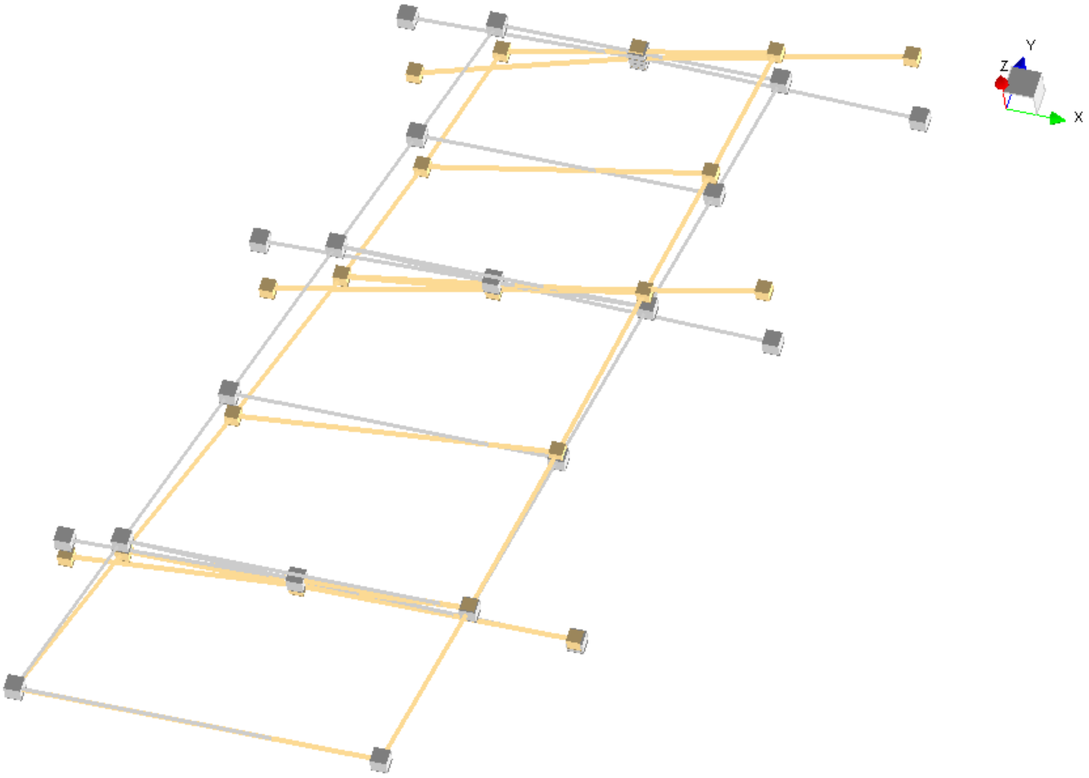


Figure 12 GVT Results, Torsional Mode Shape of Wing Model (7.15 Hz)

Modal results comparison are indicated in Table 1:

Table 1 Comparison of Modal Results

| | **Finite Element Analysis** | **Ground Vibration Test** |
|---|---|---|
| **Bending Mode Frequency [Hz]** | 1.35 | 1.46 |
| **Torsional Mode Frequency [Hz]** | 6.38 | 7.15 |

**Correlation Analysis**

Modal results obtained by modal analysis and GVT are compared with each other by calculating the metric Modal Assurance Criteria (MAC) in LMS Virtual.Lab© 13.1. MAC values belonging to first and second modes are calculated as 0.92 and 0.98 respectively. Values bigger than 0.9 manifest that GVT and FE modal results are highly correlated. 3D plot of the MAC is given in Figure 13.

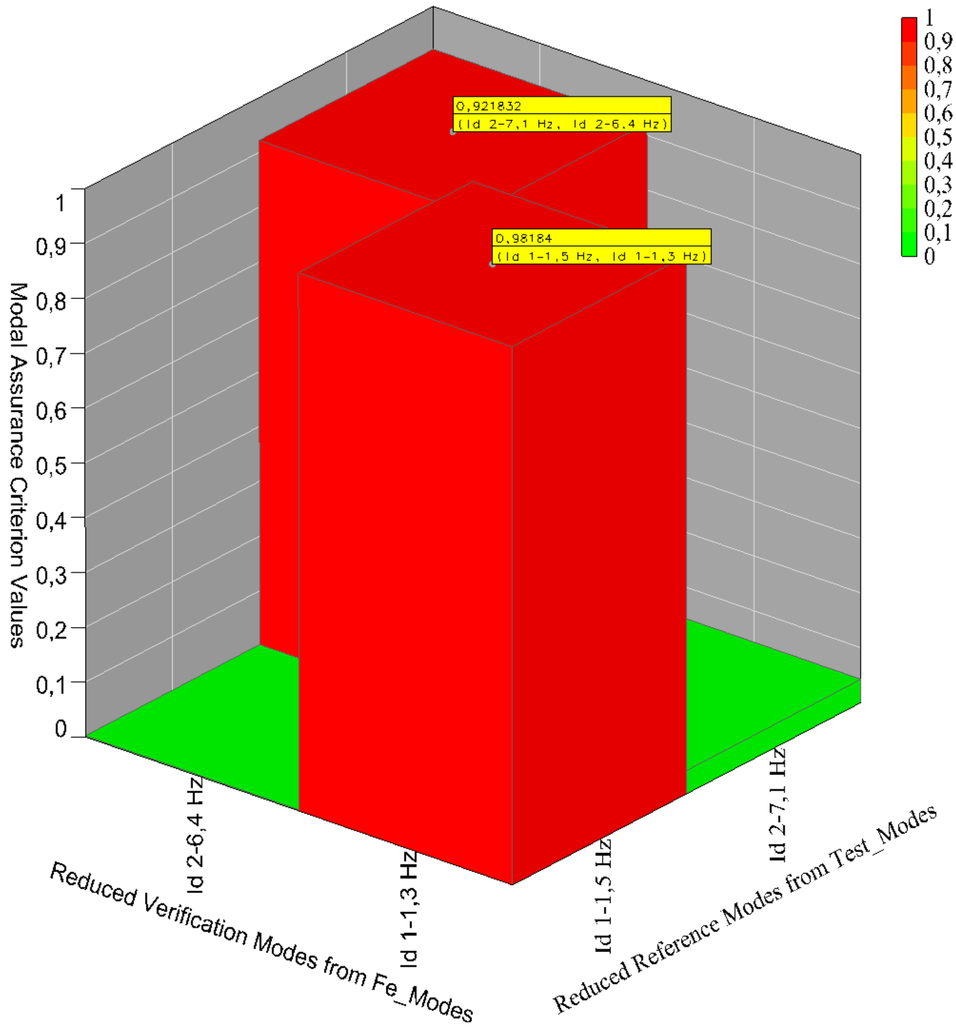


Figure 13 3D MAC Plot of FE Modes and GVT Modes

**Flutter Analysis Results**

To be able to observe and comment on the possible effects of the GVT and FE modal outputs on the flutter results of the wing-like structure, two separate analyses are conducted in ZONA ZAERO© 9.2.

**FEM Based Flutter Analysis Results**

Analysis results are given as follows according to different structural damping (Table 2). All graphical results (Figure 14 and Figure 15), however, are given for 0.0 % structural damping to be conservative.

Table 2 FEM Based Flutter Analysis Results

| **Structural Damping** | 0.00 % | 1.00 % | 2.00 % | 3.00 % |
|---|---|---|---|---|
| **Flutter Speed [m/s]** | 45.5 | 46.6 | 47.4 | 48.0 |
| **Flutter Frequency [Hz]** | 4.6 | 4.5 | 4.4 | 4.3 |

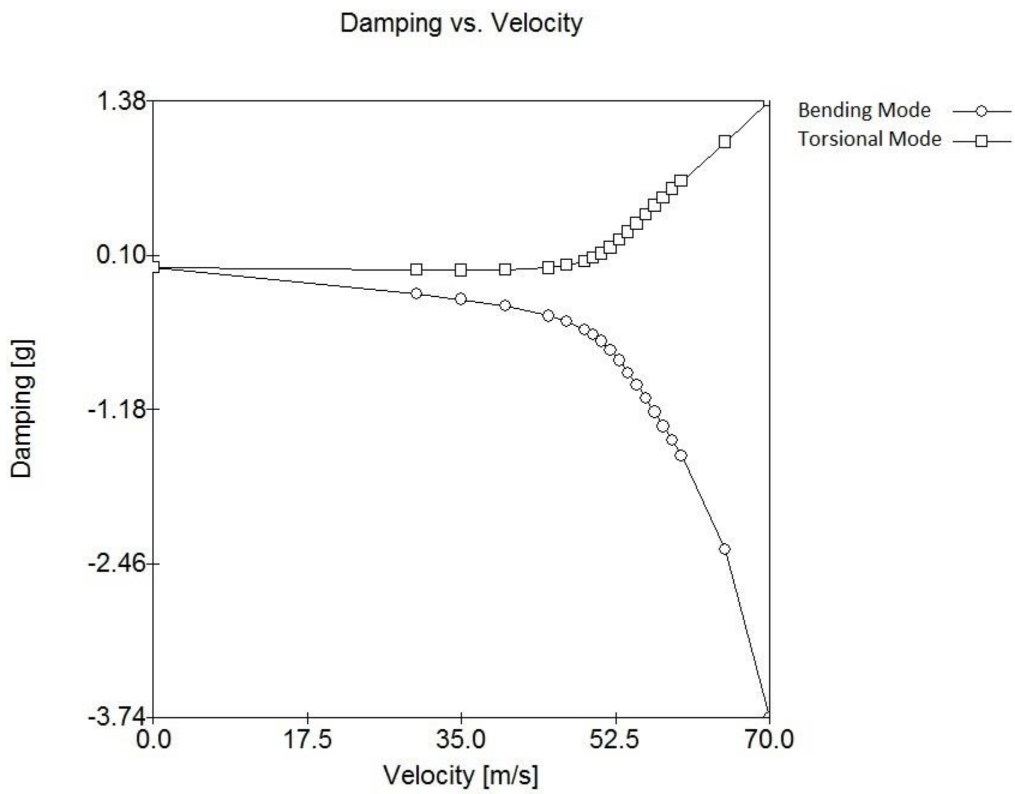


Figure 14 FEM Based Flutter Analysis - Damping vs. Velocity Graph (0.0 % Structural Damping)

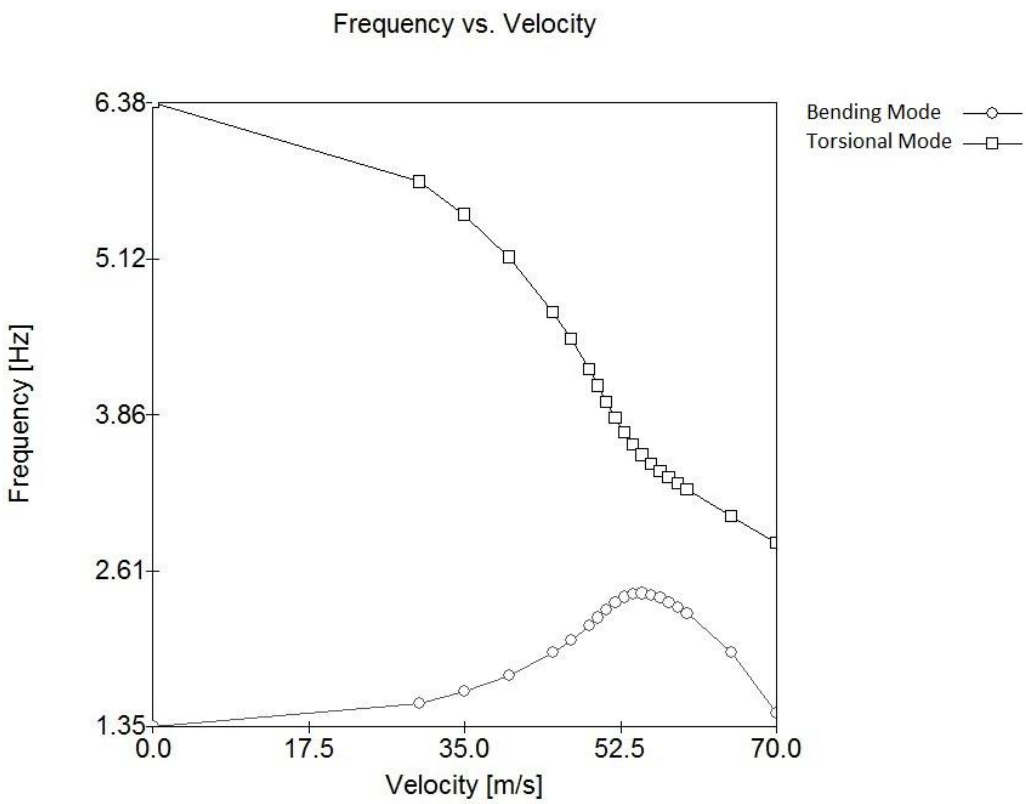


Figure 15 FEM Based Flutter Analysis - Frequency vs. Velocity Graph (0.0 % Structural Damping)

### GVT Based Flutter Analysis Results

Test results are given as follows according to different structural damping (Table 3). All graphical results (Figure 16 and Figure 17), however, are given for 0.0 % structural damping to be conservative.

Table 3 GVT Based Flutter Analysis Results

| **Structural Damping** | 0.00 % | 1.00 % | 2.00 % | 3.00 % |
|---|---|---|---|---|
| **Flutter Speed [m/s]** | 62.8 | 71.4 | 76.3 | 80.0 |
| **Flutter Frequency [Hz]** | 6.6 | 6.4 | 6.2 | 6.1 |

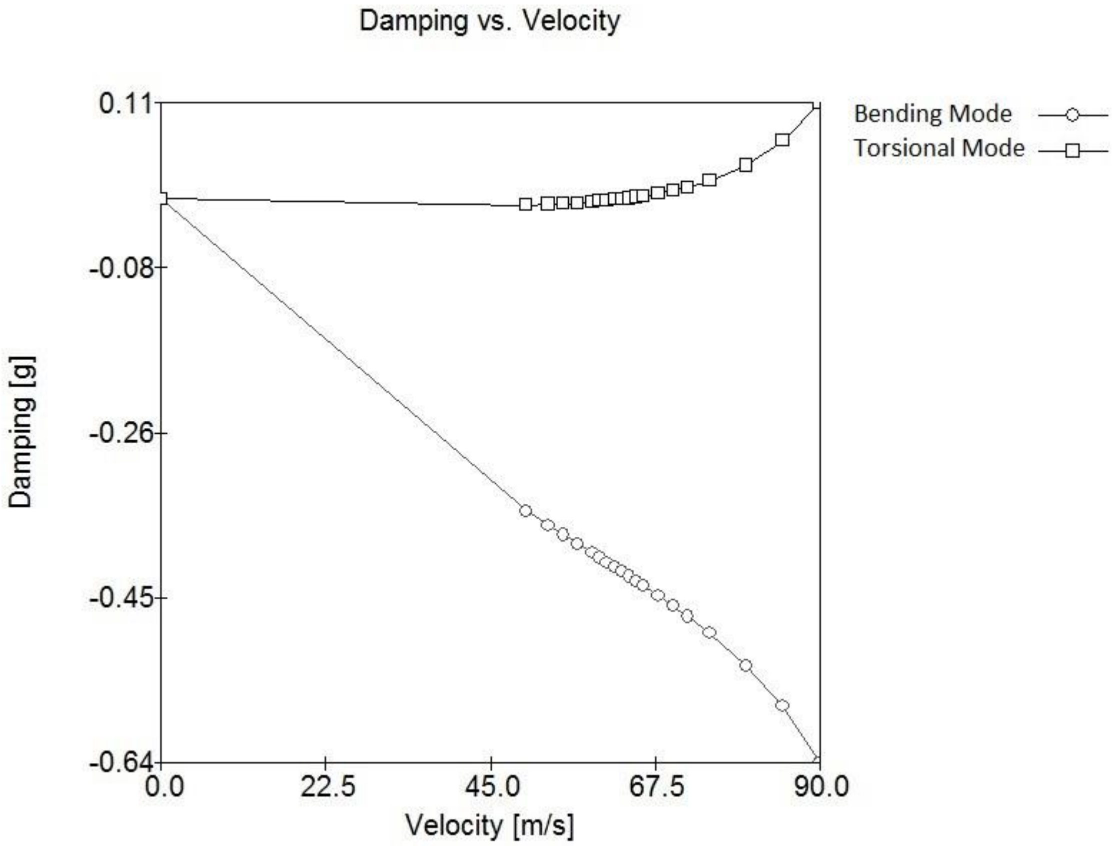


Figure 16 GVT Based Flutter Analysis Results - Damping vs. Velocity Graph (0.0 % Structural Damping)

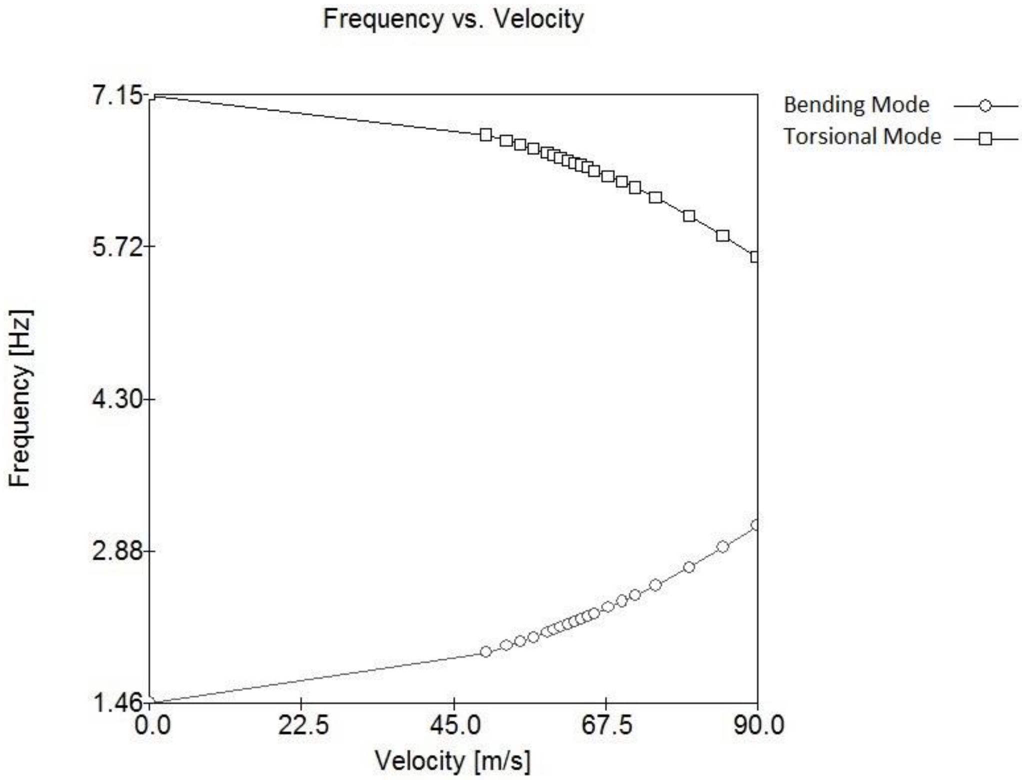


Figure 17 GVT Based Flutter Analysis Results - Frequency vs. Velocity Graph (0.0 % Structural Damping)

## CONCLUSIONS

Within the context of this paper flutter characteristic of a wing-like structure having three stations on which payloads are integrated is investigated. Modal information of the wing are extracted with both FE based solver MSC Nastran© 13.0 and Ground Vibration Test of the structure (LMS Test.Lab© 15). All these modal results are firstly correlated according to Modal Assurance Criteria (MAC) in LMS Virtual.Lab 13.1. Then they are provided as input to frequency based aeroelastic solver ZONA ZAERO© 9.2 in order to acquire flutter onset speed and frequency of the wing at low subsonic speed.

When both flutter results are investigated, GVT based analysis yields higher flutter onset speed and frequency compared to FEM based analysis. Furthermore it is easily observed that they are more sensitive to structural damping. That is, as structural damping increases by 1.0 % flutter speed increases by approximately 13.7 %. This difference is at the level of 2.4 % for FEM based analysis. All of these deviations may be originated from distinction between torsional mode frequencies, which are main modes triggering the flutter for both analyses (see Figure 14 and Figure 16), obtained from modal analysis and GVT. As the torsional mode frequency increases, related damping curve intercepts the zero line on higher velocity values. Furthermore, number of degree of freedom of the FE model is much more compared to GVT model due to the limitation of accelerometer usage. This may result in incorrect representation of elastic manner of the wing-like structure with GVT outputs and implicitly higher flutter onset speeds.

### Future Work

To be able to determine main driving reasons underlying these differences, modal updating of aforementioned finite element model according to GVT results is planned to be the future work. Then by utilizing modal results of the updated FE model, flutter analyses will be re-performed. Finally all of them will be planned to be correlated with wind tunnel tests at low-subsonic regime.

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