AEROELASTIC PREDICTION AND VALIDATION METHODS FOR USV1

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ABSTRACT

This paper is concerned with the preliminary aeroelastic analyses of the Unmanned Space Vehicle 1 (USV1), during the Dropped Transonic Flight Test (DTFT) mission. The USV1 is a multi-mission, re-usable vehicle under development at CIRA, the Italian Aerospace Research Centre. The first USV1 mission is aimed at experimenting the transonic flight of a re-entry vehicle.

This work is focused on the execution of the appropriate aeroelastic analyses, the definition of the acquisition points both for Ground Vibration Tests (GVT) and for flight tests. Finally a sensitivity study of flutter instability to elevon stiffness has been conducted in order to estimate possible modifications.
The theoretical model was developed beginning from dynamic (structure and mass) and aerodynamic models. Dynamic model will be validated through GVT results.
The analysis was conducted using an in house software, validated for subsonic flow regimes. The theoretical results showed no aeroelastic instabilities in the flight envelope.
Beginning from numerical results USV1 vehicle was instrumented with suitable accelerometers, positioned on wings, fuselage and fins. This instrumentation will acquire acceleration time history during DTFT mission.
The next step will be the validation of numerical model with DTFT data.

1. INTRODUCTION

Italian Aerospace Research Centre is conducting a national research program named USV (Unmanned Space Vehicle). The main objective is designing and manufacturing unmanned Flying Test Beds, conceived as multi-mission flying laboratories, in order to test innovative materials, verify structural and aerodynamic behaviour, advanced guidance, navigation and control (GN&C) functionalities and critical operational aspects typical of future Reusable Launch Vehicles. The development of such a vehicle requires, in particular, the availability of a number of specific key technologies.

In this framework, a series of missions of increasing complexity has been planned, the first of which is the Dropped Transonic Flight Test (DTFT), as presented in [1]. The latter is mainly aimed at testing the aerodynamics and flight behaviour in transonic flight regime, in conditions likely to be experienced by a winged launcher stage during its atmospheric re-entry trajectory.
As outlined in [2] and [3] the field of aeroelasticity continues to play a critical role in the design of modern aerospace vehicles.
In particular several important problems are still not completely solved. One of these is the transonic regime. The analyses presented in this paper are the first steps required for more refined analyses, based both on test results and on models able to predict vehicle behaviour during more critical flight regimes.

1.1. An Overview on USV1 Vehicle and DTFT Mission

The design of the DTFT mission is based on using a two-stage system that is composed by an expendable first stage, a carrier based on a stratospheric balloon, and the winged re-entry flight test bed (FTB_1 vehicle) as the second stage. The nominal mission profile of DTFT is schematically depicted in Figure 1 and can be summarized as follows.

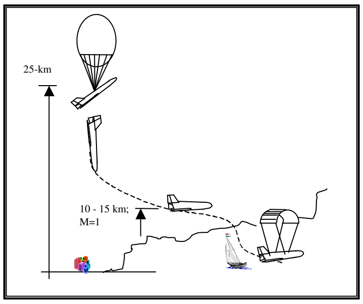

Fig. 1. DTFT mission scheme

The basic operations consist of three main phases:

1. the ascent phase, from lift-off to the release (around 20 km altitude), during which the carrier system brings FTB_1 to the release altitude by means of the stratospheric balloon;
2. the flight phase, from vehicle release to parachute opening, where FTB_1 leaves the carrier and flies accelerating to achieve the required velocity to perform the experiments. In this phase FTB_1 passes through the transonic regime (Mach number around 1.1), between 10 and 15 km, in stabilized attitude while performing an autonomous aero-controlled flight.
3. the deceleration phase, from parachute opening to splashdown, in which FTB_1 opens the parachute and ends its mission by sea splashdown and recovery.

Fig. 2 shows USV FTB_1 mission profile.

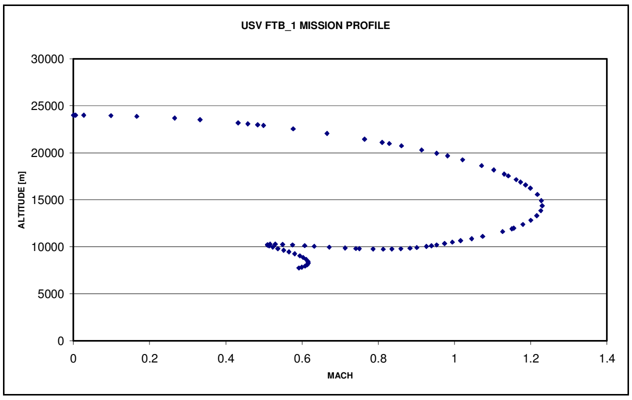

Fig. 2: USV FTB_1 mission profile

From a structural point of view the USV1 has an aluminum alloy multi spars delta wing with low aspect ratio and high swept-back angle as shown in the following scheme.

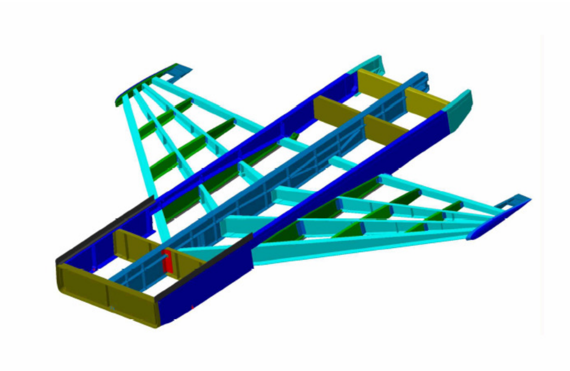

Fig. 3: USV wing structure

2. PERFORMED ACTIVITIES

Beginning from the dynamic and aerodynamic models, flutter analyses have been conducted, followed by a sensitivity study of flutter instability to elevon control circuit stiffness, carried through dynamic substructuring.

2.1. Dynamic and Aerodynamic models

The dynamic model used for flutter analyses has been obtained by a 13000 nodes Finite Elements model (MSC NASTRAN solver). As regards elevons control circuit stiffness, the value coming from qualification tests has been used:

$$K_{\vartheta} = 2.762*10^{4} \text{ N m / rad}$$

A picture of the FE model is shown below:

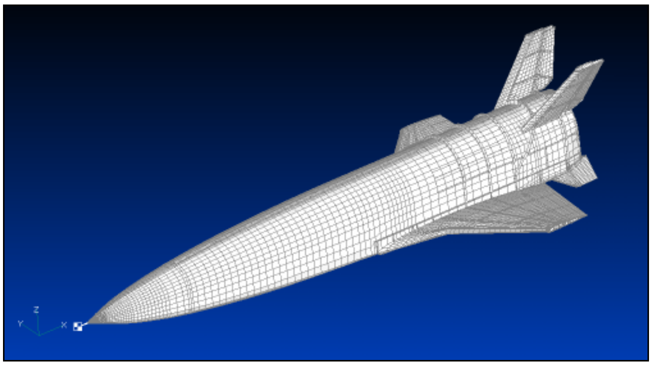

Fig. 4: USV FE model

The following table shows the first 13 natural frequencies:

MODE n.	FREQUENCY (Hz)	CHARACTERIZATION
1	0	Rigid fore and aft
2	0	Rigid lateral
3	0	Rigid plunging
4	0	Rigid roll
5	0	Rigid pitch
6	0	Rigid yaw
7	26.49	1st fuselage symmetrical
8	35.72	1st fuselage anti-symmetrical
9	38.62	1st wing anti-symmetrical flexural
10	39.30	1st wing symmetrical flexural
11	42.62	1st elevon symmetrical harmonic
12	44.26	1st elevon anti-symmetrical harmonic
13	46.70	1st fin symmetrical flexural

Tab. 1: First 13 numerical modes of FTB_1

The aerodynamic model has been obtained using a Doublet Lattice scheme.
The transfer of mode shapes on the aerodynamic model has been obtained by spline-based interpolation matrices $\underline{\underline{S}}$.
The grid points used for structural and aerodynamic matching will be used for accelerometric acquisition during Ground Vibration Tests.

2.2. Flutter analysis

The analysis has been performed using the first 13 elastic modes. The Aerodynamic Influence Coefficients have been evaluated at Mach=0.85 and the flutter analysis has been performed at an altitude of 10000 m. The chosen values of Mach and altitude characterize the main flight regime of FTB_1. Fig. 5 shows the obtained v-g diagram:

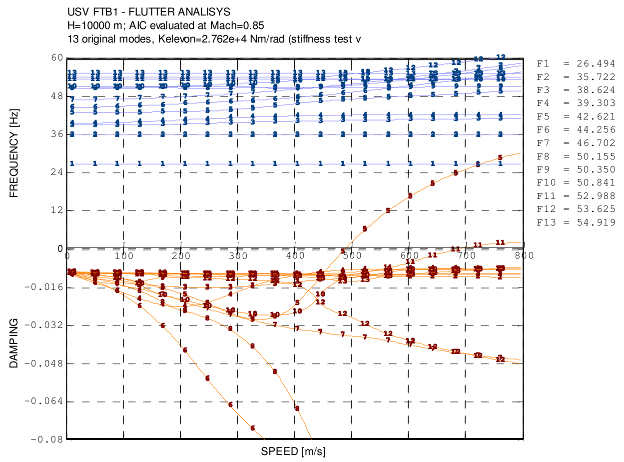

Fig. 5: v-g diagram for USV

that shows a flutter speed equal to:

$$V_F = 488.797 \text{ m/s}$$

It was found that the minimal modal association of the above mentioned flutter solution is realized by symmetric modes with high uderbalanced participation of elevons.

2.3. Flutter sensitivity to elevon stiffness

In this section a flutter sensitivity study to elevon stiffness is presented. Dynamic substructuring has been used to model elevon.

The sub-structures generation is useful in order to reduce the impact - on already performed analysis - due to the several changes that may occur during the design of an aircraft, as explained in [4].

Control circuit stiffness is an example of parameter subjected to continuous changing. The changing in control circuit stiffness usually imposes a new flutter analysis to be performed according to the following main steps:

1. Modifications on structural model
2. Modes evaluation
3. Modes interpolation on aerodynamic lattice
4. Aerodynamic generalized forces evaluation
5. Flutter analysis

The first four steps require a relevant time consuming; all the five steps may be repeated several times until the freezing of the control circuit parameters.

By using a sub-structure definition approach, the first four steps can be performed only one time and just the fifth step (the less time consuming) has to be repeated for each changing to control circuit parameters.

Let us impose an unitary deflection to the control surface and let us suppose that dynamic modal model is without elevon participation. Regarding the deformation due to an imposed unitary control surface rotation around its hinge axis as a modal shape, it can be obtained the so called extra-mode.

The field of the displacements orthogonal to the control surface can be expressed as a combination of the displacements related to the modes ($\underline{\underline{\Phi}}_p$) and to the extra-mode ($\underline{d}_{ex}$):

(1) $$\underline{w}_{mobile}(r,t) = \underline{\underline{\Phi(r)}}_p\, \underline{q}(t) + \underline{d}_{ex}(r)\delta(t)$$

For an unitary control surface rotation, the extra-mode displacements are coincident with the distances of the control surfaces masses from the hinge axis:

$$\underline{d}(r) = [x_i]$$

Being $\underline{\underline{M}}_{mobile}$ the control surface mass matrix, by substituting eq. (1) into the control surface kinetic energy expression:

$$\Delta T_{mobile} = 1/2\, \underline{\dot{w}}^t_{mobile}(r,t)\, \underline{\underline{M}}_{mobile}\, \underline{\dot{w}}_{mobile}(r,t)$$

it can be obtained the control surface generalized mass matrix:

(2) $$\underline{\underline{\Delta M}}_{Gen} = \begin{bmatrix} \underline{\underline{\Phi}}_p^T \underline{\underline{M}}_{mobile} \underline{\underline{\Phi}}_p & \underline{\underline{\Phi}}_p^T \underline{\underline{M}}_{mobile} \underline{d}_{ex} \\ \underline{d}_{ex}^T \underline{\underline{M}}_{mobile} \underline{\underline{\Phi}}_p & \underline{d}_{ex}^T \underline{\underline{M}}_{mobile} \underline{d}_{ex} \end{bmatrix} = \begin{bmatrix} \underline{\underline{\Phi}}_p^T \underline{\underline{M}}_{mobile} \underline{\underline{\Phi}}_p & \underline{m}_{p,ex} \\ \underline{m}^T_{p,ex} & I \end{bmatrix}$$

Taking into account all the masses included in the aircraft inertial model, the global generalized mass matrix can be written as follows:

(3) $$\underline{\underline{M}}_{Gen} = \begin{bmatrix} \underline{\underline{M}}_{p,p} & \underline{m}_{p,ex} \\ \underline{m}^T_{p,ex} & I \end{bmatrix}.$$

In eq. (3) $\underline{\underline{M}}_{p,p}$ is the principal generalized mass matrix, generally diagonal[1], I is the control surface moment of inertia respect to hinge axis, $\underline{m}_{p,ex}$ are the crossed generalized masses due to the coupling between the principal modes and the extra-mode.

In the same manner the control circuit stiffness of the mobile surface gives an additional contribution to the potential energy of the system:

(4) $$2U = \underline{q}^T \underline{\underline{K}}_{ex}\, \underline{q}$$

[1] This is an evident consequence of principal modes orthogonality
.

Without modal damping, the aeroelastic stability equation can be written as follows:

(5)

$$\left[s^2\begin{pmatrix} \underline{M}_{p,p} & m_{p,ex} \\ m^T_{p,ex} & I\end{pmatrix} + \begin{pmatrix}\underline{K}_{p,p} & 0\\ 0 & K_{ex}\end{pmatrix} - \frac{1}{2}\rho V^2 \begin{pmatrix}\underline{Q}_{p,p} & Q_{p,ex}\\ Q_{ex,p} & Q_{ex,ex}\end{pmatrix}\right]\begin{pmatrix}q\\ \delta\end{pmatrix} = \begin{pmatrix}0\\0\end{pmatrix}$$

To carry on the sensitivity study it is necessary to have normal modes without elevon participation. The aforementioned modes have been obtained by introducing a generalized stiff matrix in the modal model. The generalized stiffness matrix is obtained by introducing elevon rotation in terms of inboard and outboard displacements into Potential Energy expression and assuming a very high value of stiffness.

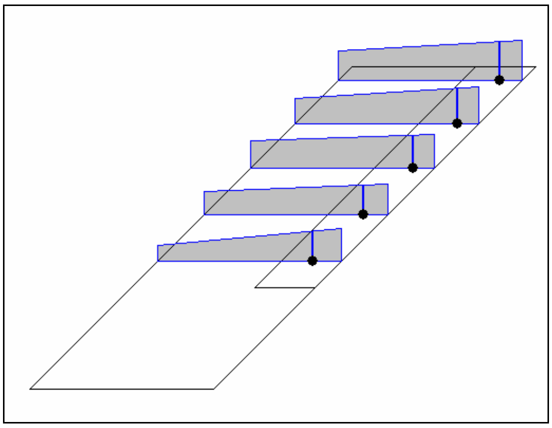

Fig. 6: Principal mode (control surface fixed)

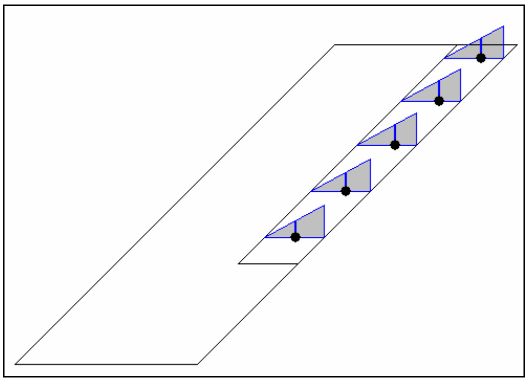

Fig. 7: Control surface rotation mode (Extra Mode)

Eq. (5) represents a formulation of the aeroelastic stability equation that is a simple function of the following parameters:

- Control circuit stiffness
- Dynamic pressure

By solving eq. (5) respect to the speed for several values of the control circuit stiffness, a sensitivity diagram can be obtained in order to find the best value of the control circuit stiffness coherently with the absence of instability.

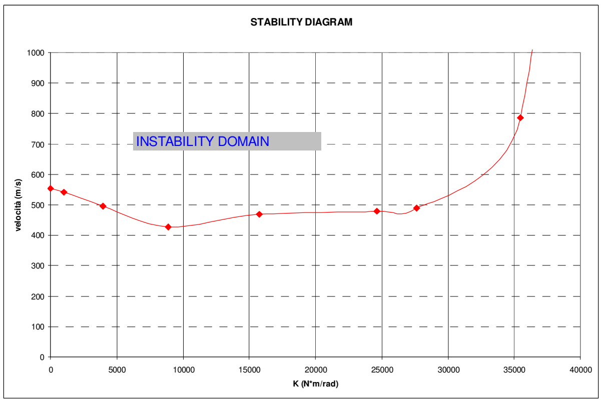

Fig. 8: Flight speed vs elevon control circuit stiffness

The stiffness values obtained are coherent with the modal model used for flutter analysis.
Being evaluated the principal modal characteristics and the generalized aerodynamic forces, the great advantage of eq. (5) consists in the fact that it can be applied to several values of control circuit stiffness without requiring a new evaluation of the modal characteristics and generalized aerodynamic forces thus leading to a relevant time saving.

3. CONCLUSIONS

The performed flutter analysis shows no instability during the examined flight envelope.
The performed sensitivity study gives a pattern of elevon control circuit stiffness values useful for contingent modifications. Moreover the use of dynamic substructuring makes possible to realize relevant time saving in case of the aforementioned modifications.
The next steps will be the integration of Ground Vibration Tests results in the model used (in terms of natural frequencies, modes and elevon stiffness) and the execution of more accurate flutter analyses aimed to characterize FTB_1 behaviour in the transonic regime.
Finally accelerometric acquisition during flight will allow to validate the complete aeroelastic model of DTFT mission.
All this studies will be starting point to the development of numerical models for future missions of USV.

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