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AEROELASTIC DESIGN OF VERSATILE THERMAL INSULATION (VTI) PANELS

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Abstract

The problem considered in the present work deals with Versatile Thermal Insulation (VTI) panel, embedded in the Cryogenic Upper Stage Technologies (CUST2) frame, that is a part of the FLPP (Future Launchers Preparatory Programme) sponsored by ESA. VTI is attached to the outside of the Upper Composite LH2 tank cylinder in order to reduce heat fluxes during the long coasting phases. During its mission VTI-panel is exposed to a large number of load that have to be taken into account in the design procedure. The aeroelastic behaviour of Versatile Thermal Insulation (VTI) is investigated in the present work. In the first part is presented a review of the available results from literature related to similar problems. Some preliminary analyses, only in the supersonic regime, have been performed with a dedicated finite element model. The models used for coupling orthotropic layered structural model with Piston Theory aerodynamic models allows the calculations of flutter conditions in case of curved panels supported in a discrete number of points. Advanced Computational Aeroelasticity (CA) analyses were perdormed by using various dedicate commercial software (CFX, ZAERO, EDGE) in order to investigate the aeroelastic behaviour in the transonic regime. A Wind Tunnel (WT) test campaign was carried out in order to assess the computational tool in the analysis of the problem. The results show that the aeroealsticity play an important role in the design of the VTI panel.

Keywords:Thermal insulations,Panel stability, Panel flutter, Launchers

1 Introduction

The VTI panels are attached at the upper stage of launcher for some dozens of seconds and then released by means of pyrotechnical separation nuts. The competitiveness of VTI solution with respect to existing and used upper stage structures must be checked carefully in order to make a proper decision for its use in future launcher.

Among the various loadings acting on the panels a particular attention is in this activities devoted to fluid structure interaction coupling sensitive loads, therefore an effort has been addressed focusing in the aero-elastic analyses and in particular in panel-flutter phenomena.

During the last fifty years many works on panel flutter have been proposed. Many efforts have been made during the sixties in order to develop a first approach to the problem. Some reviews have been presented in [1],[2],[3]. In these works some elementary approaches have been proposed based on the classical plate theory and on supersonic linear aerodynamic models like the piston theory [4]. The results concern simple geometry and simple boundary conditions (simply supported or clamped) along with analytical solutions available at that time.

Further improvements of the works just mentioned have been presented in the following years in order to extend the analyses to different geometries. In [5] are given some results taking in to account the curvature; skew panels have been analyzed in [6] that considered also the yawed angle of the flow. A comprehensive analysis of composite panels have been presented by Dixon [7] which introduced the effects of the orthotropy.

In the recent years some new developments have been proposed in order to overcome the problem related to the piston theory which ensure a good accuracy only for Mach number greater then 1.5 . In [8] is used a 3D viscid aerodynamic model coupled with a nonlinear structural model to study the transonic behavior of the panel flutter, taking in to account also the effects of the boundary layer. In [9] the effects of the boundary layer have been studied comparing the results from CFD analysis with those from a shear flow model proposed in [10].

Despite the number of work that has been presented on panel flutter, problems as the transonic analysis, boundary layer effects and ’non standard’ boundary conditions have not been developed in all their features although these are critical in the design process.

The aim of the activity performed in this project is whether to clarify aeroelastic loads should be considered in VTI design. If the effects of the aeroelastic loads are not negligible it is important to investigate whether they are critical or not.

2 Design approach

The mission profile of the VTI panel makes this structure subject to many different loads. The aim of the present activity is to answer to the question:

1. Are the aeroelastic loads negligible in the VTI panel design?
2. If not, are we able to predict if these loads are critical?

The activities devoted to answer these questions have been split in 3 different *Levels*. The firsts 2 *Levels* were devoted to answer the first question by means of literature review and some preliminary analyses in the supersonic regime. The third *Level* had to answer the second question. A more accurate computational approach has been used and some WT tests have been performed to assess the computational tool. In Figure 1 is depicted the work-flow of the design process.

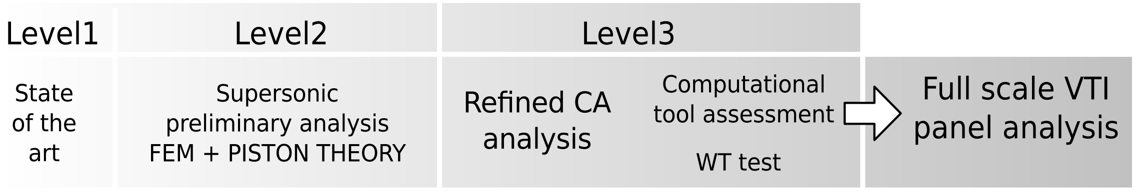


Figure 1: VTI Panel aeroelastic design workflow

The approach used in the three level is reported in the following section.

2.1 Phase 1: State of the art

The first activity performed in the present work is a large review of the remarkable results found in literature related to panel flutter. Many parameter have been considered in order to investigate their effects on flutter boundaries.

The literature overview has been focused on:

- Identification of the aeroelastic phenomena at different Mach number
- Effect of the panel configuration (load, BC) on the aeroelastic instabilities
- Available computational approach

Different aeroelastic instabilities can appear in different regimes. In the subsonic regimes the panels show static divergence. In the transonic regime the singular mode flutter can appear as shown by [11], in this Mach range the nonlinearity of the flow and the viscosity dominate the aeroelastic phenomena. In the supersonic range usually the classical coupled mode flutter appears.

In Table 1 the effects of some panel parameters on the aeroelastic instabilities are reported. In the first column the parameters investigated are given, the increasing of these parameters could have strong effects on the behaviour of the flutter flow parameter (q_f), on the flutter frequency (f_f) and on the LCO amplitude (h_f/t). The up arrow means increasing while the down arrow means decrease, the empty space means that no information was found in literature. As an example, the increase of the curvature radius, R, increases the flutter frequency, f_f, while it decreases the critical dynamic pressure, q_f.

Param.	q_f	f_f	h_f/t	References
a/b	↑	↑	↓	[1]
R	↓	↑		[5];[1]
$\frac{E_{11}}{E_{22}}$	↑	↑	↓	[12]; [7];[13]
Δp	↑			[1]
ΔT	↓		↑	[14];[15]
P_{cr}	↓		↑	[6];[1]
δ	↑	↑	↓	[8];[9]; [10]

Table 1: Panel flutter parameter influence

The literature review suggests the following considerations:

- The choice of the aerodynamic model is crucial in order to describe properly the whole physical phenomena;
- The transonic range is the most critical range in which aeroelastic phenomena may occur;
- The effects of the boundary layer are not negligible and they have a strong influence on the flutter boundary, as consequence a refined aerodynamic model is requested, specially in the transonic and low supersonic regimes.

2.2 Phase 2: Supersonic Preliminary analysis

In phase two some preliminary analyses in the supersonic range have been performed by using a Finite Element (FE) approach. The structural model and the aerodynamic model are briefly introduced in this section.

The structural model introduced in this work is based on the Carrera Unified Formulation (CUF).

In the Carrera Unified Formulation frameworks the displacements field is assumed to be the product of the cross section-deformation (approximate by a function expansion, F_τ) and the axial (y-direction) displacement, this assumption is summarized in the formulation:

$$\mathbf{s}\,(x, y, z; t) = F_\tau(x, z)\mathbf{s}_\tau(y, t), \quad \tau = 1, 2, ..., J \tag{1}$$

where J stands for the number of terms of the expansion. The structural model is considered linear both for geometry and for materials behaviour.

As first approach in the VTI-panel aeroelastic analysis a linear quasi-static flow model has been chosen, in particular in the present work is used the model introduced by [16] and [4] called *piston theory*. The piston theory assumes the flow on a panel to be similar to an one-dimensional flow in channel (in a piston). Generally speaking the pressure acting on the panel may be expressed in the form reported in eq.2.

$$\Delta p(y, t) = \frac{2q}{\sqrt{M^2 - 1}}\left\{\frac{\partial w}{\partial y} + \frac{M - 2}{M - 1}\frac{1}{V}\frac{\partial w}{\partial t}\right\} \tag{2}$$

The complete derivation of this formulation can be found in the work by [17],[16]. The aeroelastic model can be expressed, in the frequency domain, using the formulation:

$$([\boldsymbol{K}] + [\boldsymbol{K}_a]) + ([\boldsymbol{D}_a])\, i\omega - ([\boldsymbol{M}])\, \omega^2 = 0 \tag{3}$$

The roots of this quadratic eigenvalues problem were used to investigate the aeroelastic instabilities.

2.3 Phase 3: Advanced Computational Aeroelasticity (CA) and Wind Tunnel (WT) test

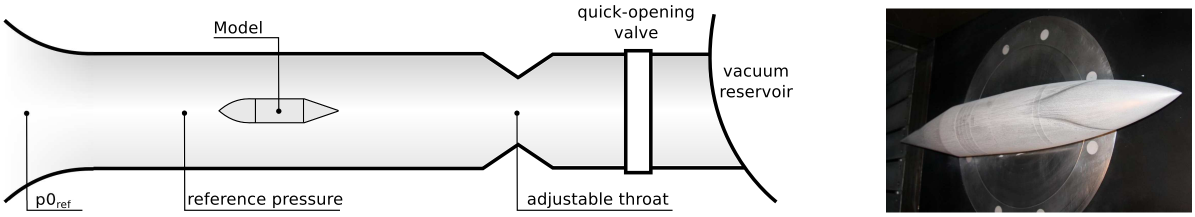
An advanced computational analysis activity has been planned in order to investigate the flutter boundary of the full scale model.

In order to increase the confidence in the computational tool reliability two different approach have been adopted to provide a results cross-check.

The approach by LKE consider a full coupled FSI approach. The structural solution is provided by the commercial FE code ANSYS®, the flow solution is provided by the CFD code CFX®. This solution is computed in the time domain.

The approach used by VZLU is based on the ZAERO® commercial code. This code has been developed only for aeroelastic analysis. As depicted in Figure **??** the code use input from different programs: The information from NASTRAN and EDGE are used by ZAERO to evaluate the aerodynamics coefficients collected in the aerodynamic matrices. The solution is computed in the frequency domain by means of the $g - method$ [18].

The assessmento of the computational model have been performed using some Wind Tunnel experiments.



(a) Wind Tunnel configuration (b) 1/2 RM in the WT.

Figure 2: Wind Tunnel configuration and model setup.

The wind tunnel configuration is shown in Figure 2.

The WT test was performed considering four models: 1/2 Cylinder Rigid Model (RM), 1/2 Cylinder Active model (AM), 1/8 Cylinder Rigid Model (RM), 1/8 Cylinder Aeroelastic model (AERM). Two Rigid Models (RM) were build: the first with a 1/2 cylinder geometry (1/2 RM), the second with a 1/8 cylinder geometry (1/8 RM). The models was used to evaluate the quality of the flow over the panel and the noise level of the WT facility.

The 1/2 AM was focused on the FSI approach assessment.

The 1/8 AERM model was devoted to the flutter analysis assessment considering a reliable configuration (4 pinched corner).

3 Results

3.1 Panel geometry

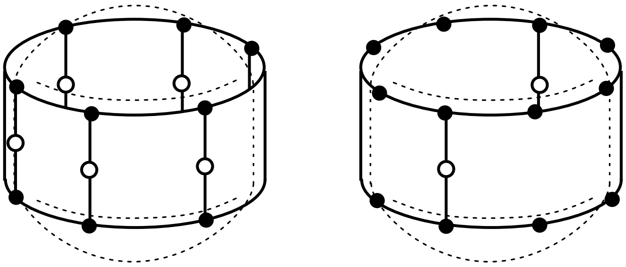
The VTI panels are a part of a larger structure which acts as thermal protection of an internal tank. The characteristic dimensions of the structure are collected in Table 2.

Panel lenght	a	[m]	2.52
Panel width	b	[m]	2.71
Curvature radius	R	[m]	2.79
Thickness	t	[m]	0.02132

Table 2: Physical dimensions of the VTI panel.

The configuration considered in phase one and two considered the structure divided into six panels. A Panel was pinched in 4 points, close to the corner, and it is connected (in the longitudinal direction) to the adjacent panels with correspondence to half length of the panel $a/2$.

In phase three the design was improved and the configurations moved from six to two panels. Each panel has five pinched points on the leading and trailing edge. In Figure 3 both configurations are depicted.



(a) Six Panels Configuration

(b) Two Panels Configuration

Figure 3: Different panel configurations. (●) Pinched Points; (◯) Connection between panels.

The VTI panels are made of a sandwich material. The lightweight core is covered by two skins built by four layers of composite material each.

3.2 Level 2: Preliminary analysis results

In the phase 2 a preliminary aeroelastic analysis has been carried out by considering only the supersonic range. and to describe the effects of the geometric parameter and boundary condition. In Figure 4 different models are depicted. On $x - axis$ the flight time since launch is reported. The solid line represents stability, the dashed line means instability.

The evolution of the natural frequencies along the whole supersonic range have been considered for each model considered. The instabilities have been detected looking for positive value of damping factor.

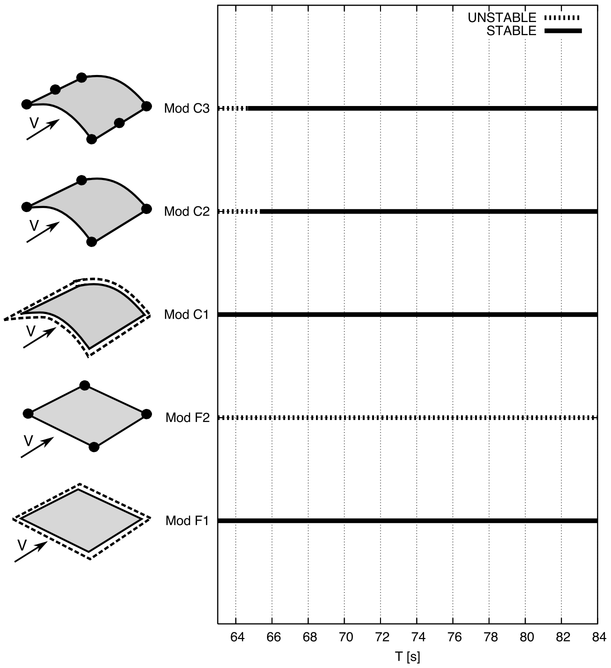


Figure 4: Stability range summary.(– – – –) Simply supported; (●) Piched.

In Figure 5 the results for the model C2 (curved panel with four pinched corner) are reported. In the first part of the mission profile the second and the third modes are coupled in an aeroelastic instability. This condition lasts up to the second 65.5 when the unstable branch of the damping factor from positive (unstable - ○) turns in negative (stable - ●). The coalescence of the frequencies lasts up to second 67.8 when they splint into to different modes.

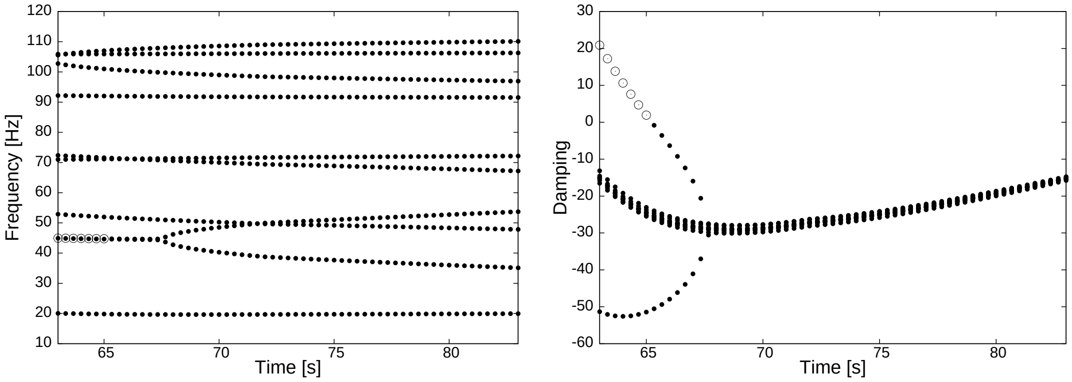


Figure 5: Time evolution of the natural frequencies and damping factor. Model C2. (●) Stable;(○) Unstable.

In Figure 4 the results of all the cases considered are summarized.

The results show that the two model simply supported, Mod.F1 an Mod.C1, are stable along the whole supersonic range (solid line). The Mod.F2 if always instable (dashed line), but, if the curvature is considered , Mod.C2, it becomes stable in the second part of the supersonic range. In the Mod.C3 two additional constrains have been introduced in order to investigate the effects of connection between the panels. The VTI-panel configuration is the one closer to Mod.C2 because the Mod.C3 is non enough conservative (the connections can not be considered as rigid constraints)

The results show that the model is critical in the first part of the supersonic regimes, so, the panel configuration seems non suitable for the mission profile.

3.3 Level 3: WT/CA results correlation

This part of the activity is devoted to the assessment of the computational tool. Because there was not available experimental results that deal with the VTI-panel problem it was mandatory to make some WT test in order to investigate the phenomena related to the VTI panel configuration.

The Rigid Models (RM) had the aim to investigate the flow field around the geometry that has to be used in the 1/2 AM and 1/8 AERM.

In Table 3 the maximum values of the percentage pressure difference between WT test and CFD have been reported for each model and at each Mach number.

While the percentage pressure difference at M=0.776 and M=1.729 is lower than 10%, at Mach equal to 1.529 there is a difference equal to 20% for both the

M	1/2 RM	1/8 RM
0.776	-1.36%	-1.46%
1.529	-19.29%	-20.08%
1.729	-8.76%	-6.88%

Table 3: Maximum pressure difference (%) between WT test results and CFD model.

models. This difference is due to an interaction between the WT facility and the model, a shock wave caused by the leading edge of the model has been reflected by the WT wall creating a flow field distortion in some part of the panel. The computational model does not consider the WT wall so does not predict such effect. Thus, the discrepancies in the results come from the difference in the experimental and computational model so the results at Ma=1.529 do not affect the reliability of the test.

The complete report of the results concerning this activity can be found in the documentation of the project [19, 20, 21].

The 1/2 Active Model (AM) had the aim to assess the Fluid Structure Interaction (FSI) capabilities of the computational tool around the half cylinder configuration.

The geometry is the same used in the 1/2 RM but the panel has been built by a thin skin, the boundary condition are those from the VTI panel (pinched point supported). An actuator has been put in the cavity under the panel in order to create some periodical deformation on the panel during the test.

The most interesting regime is the regime at M 0.86 (see Figure 6a) where all the three contribution can be detected. A peak of pressure close to the excitation frequency (5912 Hz, 9072 Hz, 10389 Hz). A peak due to a possible aeroelastic phenomena at about 10KHz. The same problem at the same regime has been investigated by LKE.

The results from the WT test showed that the model was able to predict some aeroelastic instabilities with a frequency equal to 10KHz.

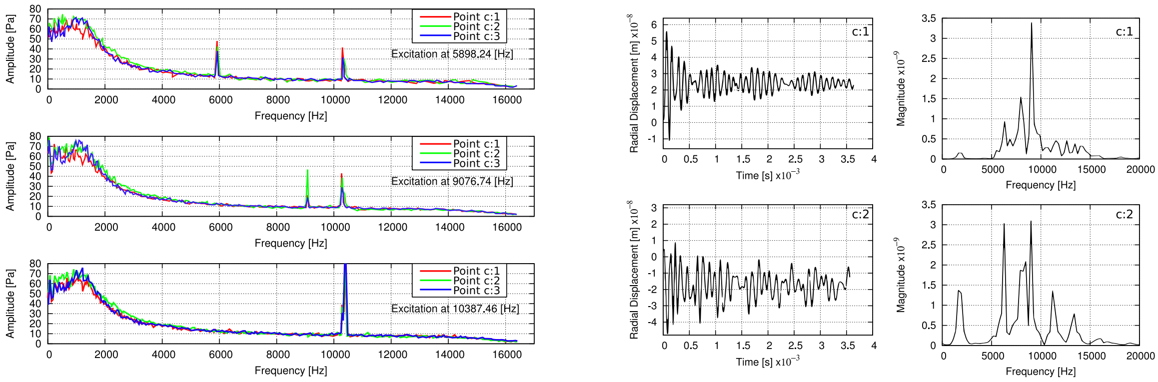
The results (Figure 6b),from the computational analyses, show a peak at 9-10KHz, a frequency close to the one see in the WT test.

From the results of the 1/2 AM it is possible to state that the computational tool is able to predict the aeroelastic behaviour observed in the WT test.

3.4 Full scale VTI panel analysis

The approach proposed by LKE is able to include any external load and can be used in all Mach regimes, but the full coupled approach is very time consuming and requires a big computational effort.

The approach proposed by VZLU introduces some strong approximations in



(a) WT results of the 1/2 Active model At M=0.86, Power Spectral Density in three different points.

(b) Computational Analysis results of the 1/2 Active model At M=0.86, Case 3. Time response and Power Spectral Density in the point c:1 and c:2

Figure 6: Response of the 1/2 Active Model at M=0.86.

	Stability Margin Factor			
	M=0.78	M=0.96	M=1.01	M=1.19
BLM	1.5–2.0	1.0–1.25	1.0–1.25	3.0–4.0
BLM1	–	1.5–2.0	–	–
BLM2	–	0.5–1.0	–	–
BLM3	–	1.0–1.25	–	–
BLM4	–	1.0–1.5	–	–
VTI	–	2.0–2.5	2.0–2.5	–

Table 4: Stability Margin Factor (SMF) at for different Models at different flight conditions.

the fluid domain (the pressure is split in the steady contribution evaluated by means of the CFD tool and a pressure perturbation evaluated by means of the potential linearised theory) and does not allow to introduce easily the external loads, but is less computationally expensive.

In order to built a representative computational model, the first part of the activity was devoted to the analysis of the different external load and their effects on the panel dynamics.

The Base Line Model (BLM) has the half cylinder geometry, the VTI boundary conditions. Starting from this model the following effects has been investigated: BLM1(Shrinkage and thermal effects), BLM2(Modified BC, one pinched point has been removed), BLM3(Gap effects, the gap between the panel and the tank has been considers by an acoustical model), BLM4(Viscosity), VTI (BLM, Gap effects, viscosity, thermal load, shrinkage).

The shrinkage is the initial displacement due to the deformation of the tank where is attached the panel. In Table 4 the Stability Margin Factor (SMF) are reported for the different models and for different Mach numbers. The stability margin has been investigated by considering fixed the Mach number and increasing the density (ρ) up to the critical condition (ρ_f). The stability margin factor is the multiplication factor necessary to reach a unstable condition.

The final results obtained by LKE and VZLU can be represented in only one graph that collect all the informations about the VTI panel flutter behaviour (see Figure 7). Figure 7 shows the different flutter boundaries obtained with the different approaches. The parameter λ represents the non-dimensional flutter parameter.

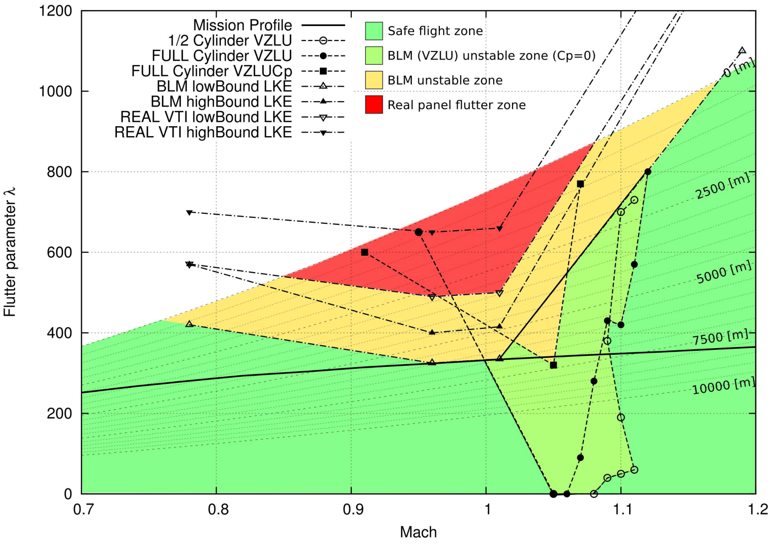


Figure 7: VTI-panel flutter stability regions for different computational models.

4 Conclusions

In the present paper the aeroelastic design of a Versatile Thermal Insulation panel has been analysed.

From the results the following considerations can be made:

- The computational tool proposed by LKE is able to predict many of the aeroelastic phenomena investigated. It was successful in the benchmark analysis.

- The full scale model analysis was performed by LKE using the FEM+CFD approach assessed with the WT tests. The LKE approach considered many effects such as shrinkage and boundary layer and the results show that the panel in its base line configuration has a stability boundary close to the mission profile in the transonic regimens.

- The full scale analysis was performed by VZLU by using the ZAERO+EDGE codes. When the steady Cp distribution is considered different from 0, the results are very similar to the results from LKE. In both cases the stability boundary in the transonic range is close to the mission profile.

The outputs of the present research activity show that the VTI panel can be affected by aeroelastic instability not far from the flight conditions, so the VTI-panel design should consider aeroelastic loads. The present work provide a basis for future developments of VTI-panel design and provides a reliable computational approach for the analysis of panel flutter phenomena.

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