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Wall pressure fluctuations induced by transonic boundary layers on a launcher model

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Abstract

Wind tunnel tests on a scaled model of the VEGA aerospace launcher have been performed at transonic Mach numbers and for variable angle of incidence in order to characterize the statistics of the wall pressure fluctuations during different flight conditions. Pressure signals are measured simultaneously in several positions along the model and are analyzed both in the physical domain and in the Fourier space focalizing attention in the region where the payload would be located. The time domain analysis reveals that the propagation of pressure perturbations within the turbulent boundary layer is driven by two different mechanisms, one associated to hydrodynamic pseudo-sound effects and the other to pure acoustic effects. The statistical results are interpreted within the framework of literature spectral models and the physical mechanisms underlying the observed behaviours, in particular the effect of a shock wave moving downstream for increasing Mach numbers, are retrieved with the aid of Schlieren flow visualizations.

Keywords: Launcher testing; Wind tunnel experiments; Transonic flow; Wall pressure fluctuations; Pressure perturbations propagation

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1. Introduction

Flow induced vibrations and interior sound transmission are important issues to be taken into account for the correct design of aerospace launch vehicles. As a matter of fact, vibrations induced in the interior can exceed design requirements and cause costly damages to the Payload while panel vibrations of the external surface must be avoided to prevent fatigue problems and structural damages (see e.g. [1] for an overview). The vibro-acoustic behaviour around a launcher can be accomplished by the knowledge, in a statistical sense, of the pressure fluctuations acting on the external surface (see e.g. [2–4]). The knowledge of the pressure statistics allows for the correct estimation of the excitation induced on the launcher panel surfaces and thus of the forcing functions to be computed into the evaluation of the structural dynamics.

The prediction of the pressure fluctuations around a launcher can be achieved by proper extrapolations of experimental test data. The full-scale extrapolation is usually conducted using reliable semi-empirical models reproducing analytically the spectral properties of the pressure fluctuations at the wall. Cross-spectra represent typical statistical quantities which are needed to estimate the structural response of the surface panel and the interior acoustic transmission as an effect of the external random excitation.

Several theoretical models aimed at predicting the spatio-temporal evolution of the wall pressure fluctuations have been developed in the past (see among many Refs. [5–8]). Extensive reviews have been given by Graham [9] and Bull [10]. Most of the proposed models are based on the original theoretical approach proposed by Corcos [5] and successively modified by Cousin [11]. In this approach the separation of variables

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method is adopted to represent the cross-correlation function dependence upon the streamwise separation (ξ) and the lateral separation (η), assuming that the boundary layer is fully turbulent and that the fluctuating pressure field over the outer surface is statistically steady and spatially homogeneous (see e.g. the recent application in [12]). Without entering into details, the representation of the cross-spectrum, denoted as $S_{pp'}$, is accomplished through the following approximation:

$$S_{pp'}(z_i, \xi, \eta, \omega) = S_{pp}(z_i, \omega)\gamma(\xi, \eta, \omega)\mathrm{e}^{j\frac{\omega\xi}{U_C(z_i)}} \tag{1}$$

where ω is the pulsation and z_i the position along the launcher. S_{pp} denotes the auto-spectrum, and the function $\gamma(\xi, \eta, \omega)$ is commonly defined, even though improperly, as a coherence function. As pointed out above, according to the Corcos-type definition [5], the dependence upon the two space variables ξ and η, can be separated, yielding the following expression:

$$\gamma(\xi, \eta, \omega) = \frac{|S_{pp'}(z_i, \xi, \eta, \omega)|}{S_{pp}(z_i, \omega)} = A(\xi, \omega)B(\eta, \omega) \tag{2}$$

Most of the models suggested to take exponential decaying forms:

$$A(\xi, \omega) = \mathrm{e}^{-|\xi|/L_\xi(\omega)}, \qquad B(\eta, \omega) = \mathrm{e}^{-|\eta|/L_\eta(\omega)} \tag{3}$$

with

$$L_\xi(\omega) = \frac{U_C(z_i, \omega)}{\alpha_C \omega} \tag{4}$$

and

$$L_\eta(\omega) = \frac{U_C(z_i, \omega)}{\beta_C \omega}, \tag{5}$$

α_C and β_C being constant parameters to be determined by the experimental results.

Independently from the details, it is evident that the parameter U_C, i.e. the phase or convection velocity driving the propagation of the pressure perturbations through the turbulent boundary layer, plays an essential role into the theoretical modelling. As pointed out in [13] and [14], the knowledge of the phase velocity is important to clarify the nature of the pressure perturbations and thus the physical behaviours underlying the interior noise generation mechanisms.

To the extent of the aerospace applications of interest for the present purposes, few data obtained in compressible boundary layers are available in literature. Studies on the propagation of pressure perturbations in compressible flows have been conducted in the case of equilibrium boundary layer over flat plates in supersonic flow conditions. It has been shown (see e.g. [15] and [16]) that the Mach (M) and Reynolds numbers (*Re*) have not a relevant influence upon the convection velocity which, at large M, results to be about 0.8 the external free stream velocity. Schneider [17] has also shown that, at supersonic external speed, low wave-number small disturbances can propagate upstream along the boundary layer but with a phase velocity very small in comparison with the sound velocity. A lack of data is instead documented for boundary layers overflowing complex geometries and for the case of transonic M even though this condition represents the most critical situation in terms of local pressure fluctuations amplitude and induced structural excitations and thus it is of greatest interest from the practical viewpoint (see e.g. [18] as an example for the case of a real launcher). As pointed out by Lee [19], unsteady phenomena present at transonic flow conditions, originate interior noise and generate undesirable effects which might affect the durability of the vehicle. As an example, fluctuations of pressure level in shockwaves and in separation areas can induce flow instabilities and then structural vibrations leading to the buffeting phenomenon (see [20] among many), which is not dangerous and destructive, but can increase structural fatigue (see also the recent works in [21] and [22]). Also the overall fluctuating pressure level reaches the maximum amplitude at transonic conditions and thus critical situations from the viewpoint of solicitations levels might be induced on the payload. It is also observed that at transonic conditions the flow physics is very sensitive to the M amplitude. Small variations of the upstream velocity or of other thermodynamic variables, lead to relevant variations of the flow behaviour around the launcher model so that measurements or simulations aimed at reproducing real transonic conditions have to be well resolved in terms of M [23].

The above discussion clarifies the motivation of the present work where the pressure field on the external surface of a 1:30 scaled model of the VEGA launcher, the expendable launch system developed in recent years by the European Space Agency [24], is analyzed experimentally at transonic flow conditions. The present activity was developed under an extended research program aimed at the characterization of the aeroacoustic environment created by the external aerodynamics. The present paper is focalized on the transonic range of flow conditions, and the influence of the most relevant physical parameters, in particular M and the angle of incidence, on the flow physics is analyzed and discussed. The characterization of the pressure fluctuations is accomplished by computing standard statistical indicators retrieved by the acquired signals, and flow visualizations are conducted to contribute to the physical interpretation of the results.

The flow conditions selected for the present analysis are presented in details in the next section together with a brief description of the experimental apparatus. Results and discussions are presented in Section 3 while the conclusive remarks and the related discussions are finally given in Section 4.

2. Experimental configuration and data analysis

2.1. Experimental set up and flow conditions

Measurements have been carried out at the T1500 transonic wind tunnel of FOI (the Swedish Defence Research Agency) in Stockholm. In all cases presented, a 1:30 scaled model in the 4 stages clean configuration, has been considered. Pressure fluctuations were measured through 32 Miniature Pressure Transducer KULITE XCQ-062 flush mounted along the model surface in several positions. The transducers location was organized into clusters in order for cross-correlations and cross-spectra to be computed. The location of the transducers clusters is given in Fig. 1 where a sketch of the model is reported