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Analytical model for the prediction of pulsations in a cold-gas scale-model of a Solid Rocket Motor

L. Hirschberg [a,b,c,*], T. Schuller [a,d], J. Collinet [c], C. Schram [e], A. Hirschberg [f]

[a] Laboratoire EM2C, CNRS et CentraleSupélec, 3 Rue Joliot Curie, 91190, Gif-sur-Yvette, France
[b] Environmental and Applied Fluid Dynamics Dept, von Karman Institute for Fluid Dynamics, 72 Chaussée de Waterloo, 1640, Rhode-St-Genèse, Belgium
[c] ArianeGroup, 51-61 Route de Verneuil, BP 3002, 78133, Les Mureaux Cedex, France
[d] Université Paul Sabatier, IMFT, CNRS, 2 alle du Professeur Camille Soula, 31400, Toulouse, France
[e] Aeronautics and Aerospace Dept / Environmental and Applied Fluid Dynamics Dept, von Karman Institute for Fluid Dynamics, 72 Chaussée de Waterloo, 1640, Rhode-St-Genèse, Belgium
[f] University of Twente, Faculty of Engineering Technology, Engineering Fluid Dynamics, P.O. Box 217, 7500, AE Enschede, The Netherlands

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ABSTRACT

Cold gas scale model experiments (1/30) demonstrate that coupling of vortex shedding with acoustic standing waves can produce pressure oscillations of the same level as observed in large Solid Rocket Motors. An analytical acoustical energy balance model is proposed in which the system is described as a single mode acoustic resonator and the pulsations are assumed to be purely harmonic. The selected acoustic mode number is an input to the model. Quasi-steady linear models are used to describe losses of acoustic energy by vortex shedding at a thermal inhibitor ring, radiation at the nozzle and friction within the porous injection wall used for gas injection. The sound production is predicted by using a 2-D planar point vortex model combined with the Vortex Sound Theory. The model demonstrates that the sound production due to interaction of the vortex with the cavity surrounding the integrated nozzle is dominant, explaining previous results of cold gas and hot-gas scale models. The effect of vortex ingestion by the nozzle is negligible. Aspects of the nozzle geometry, other than the cavity volume, are not critical. The model predicts pressure pulsations within a factor 2, when the circulation of the vortices is taken one third of the maximum available circulation. This reduction factor of the circulation is assumed to be a consequence of turbulence. The Mach number corresponding to the maximum of pulsation is predicted within 20% in a range comparable to results obtained by axis-symmetrical numerical flow simulations.

1. Introduction

Solid Rocket Motors (SRMs) can display strong acoustic oscillations [1–3]. For small engines these are often driven by a coupling between the combustion and acoustic standing waves in the engine [4,5]. In large SRMs the oscillations can be sustained by coupling between vortex shedding and acoustic standing waves [6,7]. A modulation of the combustion rate by the acoustic field may also alter these pulsations, but is not absolutely necessary to sustain pulsations.

Detailed numerical simulations (CFD) of these sustained pressure oscillations in SRMs stil remain challenging and were recently reviewed in Ref. [3]. This makes systematic parametric CFD studies of this phenomenon in SRMs wildly impractical. Thus, there is a need for simplified models to accompany these numerical investigations, providing fast results which can suggest

* Corresponding author.
E-mail address: l.hirschberg@me.com (L. Hirschberg).

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if an envisioned numerical run is beneficial and providing a framework for interpretation of simulation results. These could eventually be used for interpolation or extrapolation of experimental or numerical results.

Most of the past analytical research effort focuses on growth of instabilities [8–10] which is described using linear theory and as such is not capable of predicting limit cycle amplitudes. The main results were also derived for combustion related instabilities with limited progress made for instabilities triggered by hydrodynamic interactions [8].

Originally [11] it was believed that vortex shedding at thermal inhibitor rings between segments of the propellant, so called Obstacle Vortex Shedding (OVS), was the only possible cause of vortex shedding. However, Vuillot [6] and Dotson et al. [12] showed that vortices can be formed in the absence of inhibitors. This is due to the intrinsic instability of the so-called Taylor flow generated by the combustion [13,14] and is referred to as Surface Vortex Shedding (SVS). Vortex shedding can also occur at the edge of an abrupt expansion in the combustion chamber cross-section. This is called Angle Vortex Shedding (AVS) and this process is similar to OVS. In this paper OVS is focused on as a mechanism for vortex shedding and a model is developed to understand how OVS vortices interact with the sound field in a SRM.

The experimental results display oscillation bursts in specific Mach number ranges corresponding to a particular acoustic mode and a hydrodynamic mode. At the pulsation maximum the oscillation frequency coincides with the acoustic mode eigenfrequency. Within such a burst the oscillation frequency increases with increasing Mach number as observed in actual SRMs [12,15,16]. A famous example of such data is shown in Fig. 1.

Fig. 1 is a reproduction of the high amplitude pulsations detected in Titan 4 SRM. One observes bursts of pulsations around the eigenfrequency of the first acoustic mode corresponding to a standing wave of approximately one half wavelength along the combustion chamber. The Mach number at the nozzle inlet decreases with time as the combustion chamber diameter increases due to combustion while the chocked nozzle throat remains almost constant. Within one burst, the frequency decreases as a function of time, hence it increases with increasing Mach number. This frequency signature is a consequence of the time delay in the convection of vortices between the vortex shedding position in the combustion chamber and the nozzle, where sound is generated. Fig. 1 has motivated investigations of OVS as a strong source of instabilities [15–19] in SRMs.

It is known that vortical structures will produce sound by hydrodynamic interaction with the nozzle, but can also as suggested by Matveev and Culick [20] generate sound by a modulation of the combustion. The focus here is on the hydrodynamic interaction with the nozzle.

Anthoine et al. [17–19] confirmed the importance of vortex nozzle interaction in sound production. In the cold gas experiments [17] the combustion is replaced by injection of air through a porous wall to reproduce the flow at a 1/30 scale in a Ariane 5 SRM. Anthoine [17] found, ratios p_{rms}/p of the root-mean-square (rms) acoustic pulsation amplitude p_{rms} to static pressure p of the order of 10^{-3}. This corresponds to the amplitudes observed in full scale firing test [15] and scale models with combustion [15,21]. Anthoine observed the characteristic frequency signatures observed in SRMs [12,15,16], an increasing frequency around the acoustic mode frequency with increasing Mach number around each maximum of pulsation amplitude. This confirms that these signatures can be accounted for by convective delay of vortices.

Anthoine et al. [17,18] proposed an analytical model to estimate the pulsation amplitude by balancing the vortex sound power to radiation losses at the nozzle. In the present paper an improved analytical model is provided based on the Vortex Sound Theory in which the losses are estimated using quasi-steady linear models. This includes radiation at the nozzle, the effect of the vortex shedding at the inhibitor [22] and the sound absorption by the porous wall [23]. The effect of convection in the nozzle radiation model, ignored by Anthoine [17], is also included using the expressions from Marble and Candel [24] and

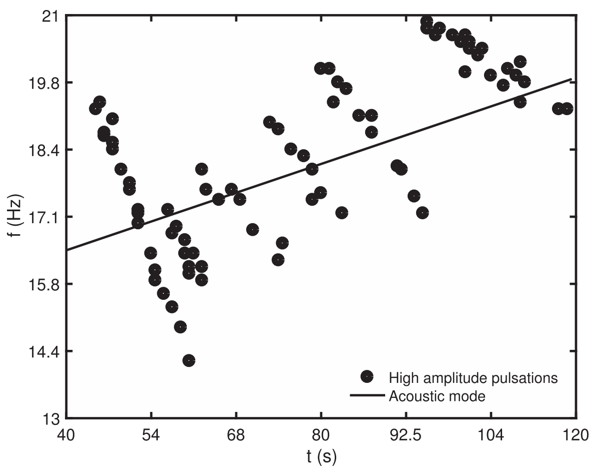

Fig. 1. Time dependence of the frequency of pulsations observed in a SRM. Titan 4 data, Figure after Fig. 4 in Ref. [12]. One observes six sets of measurements corresponding to bursts of high amplitude pulsation. Within each burst the frequency of oscillation decreases with increasing time, corresponding to an increase of oscillation frequency with increasing Mach number.