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# Unstructured Large Eddy Simulation of the passive control of the flow in a weapon bay

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## Abstract

The control of cavity flows has been investigated by the means of Large Eddy Simulations. The computations have been carried out on unstructured meshes to assess the efficiency of two passive acoustic oscillation suppression devices: the rod-in-crossflow and the flat-top spoiler. Despite a sustained interest and many experiments, a clear explanation for observed reduction in the flow-induced structure load is still missing. This work explores different hypotheses: the modification of the mean field and its linear stability properties, a pure deflection effect of the separated shear layer, or scale coupling between the rod wake and the turbulent mixing layer over the cavity. The aim here is to enhance the experimental database and provide leads towards a better understanding of the phenomena. The selected test-case is a cavity of length/depth ratio equal to 5, at Mach and Reynolds number of $M_\infty = 0.85$ and $Re_L = 7.10^6$, respectively.


*Keywords:* Large Eddy simulation; Rossiter aero–acoustic mode; Flow control; Cavity flow; Turbulence

## 1. Introduction

The flows over cavities are very common in both internal or external aerodynamics, and can be potentially damageable in many cases. If the flow within the recess can be described as the interaction between different well-known phenomena, such as hydrodynamic instabilities, acoustic wave propagation, and aero-acoustic coupling, an important non-linear coupling of these mechanisms occurs. Since Rossiter's (1964) works, the aero-acoustic coupling is known to induce major periodic pressure fluctuations in the case of a subsonic flow over an open cavity. This is the case we are currently interested in. Beside its academic interest, it is also a major concern for aircraft makers since large amplitude aerodynamic loads develop in an open store bay leading to structural vibrations that could endanger the integrity of the aircraft. Depending on the flight altitude, the Rossiter modes can cover a 0–150 Hz range, preventing from a structural answer to the problem. It thus appears as an important problem in an industrial context, which involves complex and still unknown mechanisms.

The aerodynamic loads inside the cavity are driven by a natural flow instability. Schematically (see Fig. 1) the vortex shedding emerging from the mixing layer impinges the downstream corner of the enclosure, arousing pressure waves. These waves go back up to the upstream corner and interact with the mixing layer. Thus, this coupling of a convectively

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**Nomenclature**

| | |
|---|---|
| $\boldsymbol{A}_i$ | $i$th Euler Jacobian matrix |
| $f_n$ | Rossiter tones frequency |
| $\boldsymbol{F}, \boldsymbol{F}^d$ | Euler and diffusive fluxes |
| $\boldsymbol{K} = [\boldsymbol{K}_{ij}]$ | diffusivity matrix |
| $L, W, D$ | cavity length, width and depth, respectively |
| $\mathscr{L}$ | steady compressible Navier–Stokes operator |
| $\mathrm{M}_\infty$ | external Mach number |
| $n$ | mode number |
| $p_i, T_i$ | isentropic pressure and temperature |
| $Q_n$ | space–time slab |
| $\mathrm{Re}_L$ | Reynolds number |
| $\mathscr{S}^h_n, \mathscr{V}^h_n$ | trial and weighting function space, respectively |
| $U_\infty$ | external flow velocity |
| $\boldsymbol{U}, \boldsymbol{W}$ | conservative variables vector and weighting function |
| $\kappa, \gamma$ | constants of Rossiter's formula |

amplifying Kelvin–Helmholtz type shear-layer instability and pressure waves leads to a self-sustained mechanism, inducing aerodynamic loads inside the cavity, pressure drag, and white-noise in the far-field.

Rossiter (1964) proposed the following semi-empirical relation for the prediction of the frequency of the cavity tones:

$$f_n = \frac{U_\infty}{L}\frac{n-\gamma}{M_\infty + 1/\kappa}, \tag{1}$$

where $U_\infty$ and $\mathrm{M}_\infty$ are the external flow velocity and Mach number, respectively, $L$ is the length of the cavity, $n$ is the mode number, and $\gamma$ and $\kappa$ are two parameters adjusted from experiments. $\kappa$ is generally taken equal to 0.57 and $\gamma$ is a function of the length over depth ratio $L/D$ varying from 0 (deep cavity) to 0.57. This above mentioned formula (1) has already been widely and successfully used to predict the frequencies of tones observed in a great variety of cavity flows. Hereafter, the emerging cavity tones will hence be referred to as the Rossiter modes. Beside a very good concordance, the formula also provides an *a posteriori* interpretation of the self-sustained mechanisms based on two phenomena already mentioned: the mixing layer vortices moving downstream at a $\kappa U_\infty$ velocity on the one hand, and pressure waves travelling upstream at the speed of the sound with a $\gamma$ phase shift on the other hand.

Many experimental studies have been devoted to cavity flows (Sarohia, 1975; Knisley and Rockwell, 1987; Gharib and Roshko, 1987; Cattafesta et al., 1997; Lin and Rockwell, 2001; Rockwell et al., 2003; Ziada et al., 2003; Oshkai et al., 2005) but they mostly deal with incompressible or low Mach number flows. An important step was made by Forestier et al. (2003) who performed experiments at high subsonic speed with not only pressure measurements but also PIV, making possible an intensive study of the mechanisms.

The first computations of cavity flows, based on the resolution of bidimensional Navier–Stokes equations with an algebraic model of the turbulence, enable to predict the Rossiter modes frequency and the mean pressure drag on the floor of the recess with a fairly good accuracy. Yet, the overall pressure levels were generally underpredicted by up to 20 dB. Advances occurred in the late 1990s by the use of hybrid turbulence models such as VLES (Sinha et al., 1998), zonal decomposition RANS/LES (Arunajatesan and Sinha, 2001) or using LES (Dubief, 2000; Avital, 2001; Gloerfelt et al., 2002; Rizzetta and Visbal, 2003; Shieh and Morris, 2000). The reader is referred to reference books for detailed descriptions of these approaches (Sagaut, 2005; Sagaut et al., 2006). The best results were provided by the LES method, which is known to be very efficient for separated flows (Manoha et al., 2000; Raverdy et al., 2003; Labbe et al., 2002). The main reasons for that efficient advanced modelling strategies have been proposed during the last decade (Terracol et al., 2001; Quemere et al., 2001; Meyers et al., 2006), which allow for an optimal use of the computational resources. After having assessed the feasibility of its LES approach by computing the flow over a deep cavity, with experimental comparisons including pressure measurements and velocity-field data, Larchevêque and coworkers (Larchevêque et al., 2003, 2004, 2007) provide very accurate results for compressible cavity flows. These authors also provide a large amount of analysis tools and methods.

The control of cavity flows has attracted a lot of interest, and experiments have followed one another since the late 1970s. Previous experiments and computations studied different suppression strategies dealing with the use of ramps, spoilers, rods, air jets, etc. Investigations also dwelt upon active control with vibrating ramps, synthetic or pulsating jets. But the design of effective feedback controller remains problematic. Cattafesta et al. (2003) made a review of active control of flow-induced cavity oscillations comparing different palliatives and describing successes and failures in reducing the pressure levels. Finally, let us note the work of Stanek et al. (2000, 2001, 2002, 2003) who studied high frequency acoustic suppression strategy, including the rod-in-crossflow and the spoiler. The authors stated that high frequency forcing modify the hydrodynamics stability properties thus explaining the oscillations suppression efficiency. In the same way, they explained that the rod provides a high frequency forcing through the induced vortex shedding, unveiling the rod mystery. To conclude, if many varied experiments exist on cavity flow control only a few numerical