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Numerical study of three dimensional acoustic resonances in open cavities at high Reynolds numbers ☆

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ABSTRACT

We present two and three dimensional numerical simulations over open cavities at high Reynolds ($Re = 8.6 \times 10^5$) and various Mach numbers ($0.2 < M < 0.8$). Various turbulence closures are compared and the effect of the Mach number and three-dimensionality assessed. Results show that an implicit LES approach provides more accurate results that classic RANS models (e.g. k–epsilon variants) when analyzing the spectra associated to Rossiter's acoustic resonances (regular self-sustained oscillations). In addition, we show that the simulations require relatively high Mach numbers to compare favorably to experimental data, showing the importance of compressibility effects. Finally, to capture qualitatively the dynamical content, we show that 2D simulations are not accurate enough and three dimensional simulations are necessary.

1. Introduction

Predictions of noise generation (or acoustic sources) require the numerical integration of the unsteady compressible Navier–Stokes equations in complex geometries. Acoustic analogies, e.g. Lighthill [17], Ffowcs Williams–Hawkings [36], have enabled a certain degree of decoupling between the generation and propagation of noise. Following these analogies, equivalent acoustic sources can be extracted from the flow. These can be subsequently modeled and injected into a new simulation to predict the propagations of such sources. This decoupling enables fast computations, since source generation that requires highly accurate Navier–Stokes flow computations can be performed separately from the associated computations for the wave propagation. For a review of available techniques to compute aeroacoustic noise generation and propagation, the reader is referred to the monograph of Goldstein [14]. The present work is concerned with the generation of noise which requires accurate temporal and spatial numerical simulations. Indeed, to extract small acoustic scales demands fine meshes and statistically converged solution.

Recently, the numerical community has drifted efforts from classical Reynolds Averaged Navier–Stokes (RANS) turbulent models, towards Large Eddy Simulation (LES) to predict unsteady aeroacoustic sources (e.g. [7,33]). RANS methods consider time averaging of the NS equations where the instantaneous velocities are decomposed into their temporal mean and fluctuating components (see [35] for a detailed description), whilst LES approaches rely on spatial filtering where the large structures are resolved, reducing modeling to the small turbulent structures (i.e. small eddies), which are considered to behave in a homogeneous isotropic fashion.

LES predictions show enhanced accuracy (compared to RANS methods) when computing time evolving flows such as the ones found in aeroacoustic problems [7,25]. However, it is agreed that the computational cost associated to performing LES simulations is still excessive for industrial standards (e.g. fast design cycles) and less computationally demanding solutions are needed. Towards this aim, we compare various turbulence models and asses the effect of three dimensionality when predicting tonal frequencies.

Both RANS and LES methods require adequate turbulence closure models and fine meshes to capture the small fluid structures that generate sound. RANS solvers are generally used for computing steady solutions (i.e. time averaged solution) and have shown good accuracy, at a relatively low cost, when predicting aerodynamic forces for attached and mildly detached flows [35]. For unsteady, or detached flows, the steady RANS approach is no longer valid, but, the unsteady version URANS (i.e. Unsteady RANS) can be used and has shown to provide valuable results [26,35]. Although for unsteady flows, LES approaches have shown to provide better

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prediction capabilities, from a practical point of view URANS may (or may not) be able to capture the main acoustic tones.

Original LES methods derive new filtered equations by applying a spatial filtering to the NS equations [25]. Filtering allows for scale separation: large scales (i.e. large eddies) to be resolved and small scales (i.e. subgrid scale) to be modeled. In recent years a new LES concept has emerged. The Implicit Large Eddy Simulation (ILES) approach [2,15], sometimes referred to as Monotonic Integrated Large Eddy Simulation (MILES). This technique uses the numerical dissipation inherited from the numerical scheme (e.g. from upwinding the non-linear terms) to account for subgrid scale effects. In this method it is not necessary to derive new equations to compute turbulent flows (e.g. filtered NS equations as in explicit LES), but the Direct Numerical Simulation (DNS–NS) equations can handle high Reynolds number flows provided that enough numerical dissipation is present in discretise DNS–NS equations. Indeed, this technique does not require explicit modeling of the turbulent viscosity, as in explicit LES approaches (originally proposed by Smagorinsky [28], see [25] for a review) and provides valuable results even for challenging problems such as the prediction of transitional [31] and detached [10] flows. To obtain valid implicit LES schemes, one needs to ensure a dissipative monotone character (i.e. non-oscillatory) of the discretization which can be provided for example using a Flux-limiting or Total Variation Diminishing (TVD) schemes when discretizing the non-linear terms in the NS equations [2,15]. Note that in a valid implicit LES schemes (if a finite volume discretization is used) the discretization error appears in a divergence form and hence mimics the behavior of explicit subgrid models in explicit LES methods. Further information can be found in the recent review on how to compute high speed flows [22].

A final caveat arises when considering two or three dimensional simulations when using RANS or LES models. Although the 3D nature of turbulent flows is commonly agreed, a large number of 2D computations have managed to successfully predict tonal frequencies [8] at a reduced computational cost. This results partially motivate the work presented hereafter where we compared 3D ad 2D implicit LES simulations. Finally, our work assesses the effect of compressibility effects (varying Mach number) in the prediction of tonal frequencies using Implicit LES models.

To summarize, we present comparisons of two and three dimensional computations for various turbulence models including Implicit LES and URANS models (two k–epsilon variants). These models are compared for the well known but challenging case of an open cavity at Mach $M = 0.8$ and Reynolds number of $Re = 8.6 \times 10^5$ [2,7,12,16,30].

This cavity flow was first experientially analyzed by Forestier et al. [12] and subsequently numerically reproduced using highly accurate LES computation by Larchevêque et al. [16]. These published results will be used for comparison in our work. The underlying physical mechanism responsible of the tonal noise in this configuration has been attributed [12,16] to a self sustained pressure oscillation (i.e. Rossiter modes) with a fundamental frequency of about 2000 Hz. The problem is described in details in the following section but the interested reader is referred to the more complete overview of Gloerfelt [13].

The cavity flow problem has been studied previously but a few questions are still unanswered. The following bullet points summarize the main novelties, aims and clarifications included in our work:

- We clarify the effect of turbulence modeling and show that only the ILES computations are able to predict the complex flow of this challenging case.
- We show that both 2D and 3D ILES computations are able to predict the experimental frequencies but that the tonal amplitudes are only accurately predicted using 3D computations.
- We show that eddy viscosity models (also with anisotropic corrections) are unable to capture the feedback mechanism described by Rossiter.
- We show that for Mach numbers below 0.5, the cavity physics are different. Hence compressibility effects are crucial to predict accurately the experimental frequencies.

This paper is organized as follows, in Section 2 a short review of the physical phenomena and the experimental set-up is introduced. The computational method and turbulence modeling strategies are described in Section 3. Finally, Sections 4 and 5 present and analyze the numerical solutions, which are compared to published experiential data. In Section 5, we first discuss the influence of the turbulence model to then analyze the compressibility effects and Mach number influence in the results.

2. Problem description

Open cavity flows have received a great deal of attention [8,13], partially because the configuration is relatively simple but also because the resulting flow presents interesting and complex behaviors. In addition, this configuration presents an interesting framework for the development of active and passive flow control strategies [4,8,20].

The physical phenomenon at play is a closed loop (feedback) mechanism of self sustained oscillation. The flow leaving the leading edge (left top corner) of the cavity presents a sheared velocity profile (or a set of vortices) along the top of the cavity that impinges at the trailing edge (right top corner). When this sheared profile interacts with the corner, a hydraulic pressure wave bounces back and excites the sheared profile near the leading edge (a region of high receptivity) producing or enhancing instabilities of Kelvin–Helmholtz (K–H) type in the sheared profile. This is a two dimensional self exiting mechanism named after Rossiter [24], that leads to well defined tonal frequencies (see Eq. (4) in following sections). In addition, global cavity modes (e.g. depth-modes, spanwise modes or tunnel modes) that may be either two or three dimensional can be excited within the cavity (depending on the flow conditions) [8,38] and may interact with the previous Rossiter phenomenon.

Two very recent contributions have analyzed open cavity flows in terms of linear global stability analysis [20,38]. The first has focused on the Mach number effects in laminar flow conditions, showing that K–H instabilities are weakened for high Mach numbers. This conclusion is in accordance with our non-linear results as will be shown hereafter. In [20], Mettot et al. study for the first time the linear stability associated to the high Reynolds and Mach $M = 0.8$ using a k–omega and Spallart–Almaras turbulence models. In their work, URANS computations compare favorably with linear stability results showing that the latter technique is appropriate to shed light in this type of complex Rossiter's mechanism. In addition, linear stability shows that when the frequencies of the K–H phenomenon and the acoustic waves coincide (i.e. resonance or lock-on state), the amplification of the power spectra is maximum. However, in our work (see following sections) we find that URANS methods are unable to capture the dynamical content for this configuration.

A sketch of the geometry selected for the simulations is shown in Fig. 1. The geometry described here is a cavity of length $L = 50$ mm, depth $D = 120$ mm and width $l = 120$ mm, resulting in low aspect ratios: $L/D = L/l = 0.42$. This cavity may be considered deep ($L/D < 1$) and two-dimensional ($L/l < 1$).