Large-Eddy Simulation of the Acoustic Response of a Perforated Plate

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I. Abstract

An original numerical configuration is designed to compute the acoustic response of a multi-perforated plate submitted to normal acoustic excitation with Large-Eddy Simulation (LES). It consists in simulating an infinite perforated plate, the periodicity of the geometry allowing to reduce the computational domain to a periodic configuration containing only one perforation. The numerical configuration is adapted from the experimental set up studied by Bellucci *et al.* A low Mach and low Reynolds numbers bias flow is imposed through the perforated plate, resulting in a jet issuing from the hole, but no grazing flow is considered. Flow and acoustic results from LES are presented. The dynamic results show that the jet does not respond in the same way for every frequencies, resulting in different acoustic responses. Acoustic results are compared with available experimental measurements and to three existing analytical and numerical models. The overall agreement between all data is very good, in particular at low frequencies. Excellent agreement is observed with the most sophisticated model, developed by Jing & Sun. Notably, the LES results show the relevance of the hypotheses of this model concerning the shape of the jet separation at the aperture inlet.

II. Introduction

Nowadays, competitive gas turbines have to prove a low pollutant emission capability. This is often obtained by using lean combustion, for example in Lean Premixed Prevaporized (LPP) systems. However, this class of LPP burners are likely to be subject to combustion instabilities,[1,2] which consists in an unfavorable coupling between acoustics and combustion. Hence, the prediction of combustion instabilities necessitates an accurate description of both the unsteady combustion process and the acoustic modes in the chamber. Notably, in aeronautical gas turbines, one needs to consider the fact that liners are often perforated. Indeed, to ensure their thermal protection, combustion chamber liners are often perforated with thousands of small holes (of diameter approximately 0.5 mm), through which air flowing in the casing is injected.[3] In the combustion chamber, the jets issuing from the holes coalesce in the vicinity of the wall, resulting in a cooling film that isolates the plate from the hot gases. This cooling system is known as effusion cooling.

From an acoustic point of view, the behavior of perforated plates is known to be very different from the one of a solid wall, even at small open-to-total area ratio. It has been demonstrated, both analytically,[4,5] experimentally[6–8] and numerically[9,10] that perforated plates have a damping effect on incident acoustic waves and thus potentially on combustion instabilities. The sound attenuation mechanism consists in the conversion of acoustic energy into vortical energy: incident waves interact with the shear layers formed at the apertures rims; submitted to pressure fluctuations, the shear layers destabilize to form vortex rings. The vortices are then dissipated without sound production. For certain frequencies, depending on the geometrical and operating characteristics, an incident acoustic wave can be almost completely damped by a system composed

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by a perforated liner and a back wall,[6,11] which is exactly what is encountered in combustion chambers, the back wall being the wall bounding the casing.

Recently, the ability of Large-Eddy Simulations (LES) and Helmholtz solvers to study combustion instabilities has been proven.[12–18] In any of these approaches, the acoustic impact of multi-perforated liners is generally neglected: the direct representation of effusion cooling is out of reach in numerical simulations, due to the size of the perforations. The problem is exactly the same from the dynamical point of view: to account for effusion cooling, Boudier *et al.*[16] have used a uniform model recently developed from wall-resolved LES,[19] avoiding the resolution of the effusion holes. Similarly, to improve the acoustics prediction, the influence of the perforated plate should be modeled in the numerical simulations. This objective can be reached in two steps:

- Perforated plates models have to be adapted to the configuration encountered in combustion chambers. This configuration involves a mean flow through the plate (bias flow) and a crossflow tangential to the plate on each side of it (grazing flow). Some existing models include the presence of bias flow through the plate.[4,6,11,20–22] Among them, some also account for the grazing flow.[20–22] However, these models are not *a priori* adapted to the geometry of the effusion cooling holes. In combustion chambers, perforations are generally inclined and the length-to-diameter ratio is more than unity: typically, perforations are inclined at 30° to the wall, with a diameter of approximately 0.5 mm and a plate thickness of 1 mm. To the authors' knowledge, this kind of configuration have only received recent interest.[9,10] In effusion cooling, high temperature gradients are also observed in the apertures and the frontiers of the jets. This may also have an influence on the acoustic-vortex interaction.
- Once an appropriate model is available, it is necessary to implement it in the target numerical code. This is not necessarily easy and depends on the nature of the code. Notably, impedances of perforated plates are complex and depend on the frequency of the acoustic excitation, which is difficult to reproduce in temporal codes.[23] As far as Helmholtz solvers are concerned, this increases the non-linearity of the eigen value problem to be solved.

This paper focuses on the first point. In order to build models adapted to combustion chamber situations, it proves useful to rely on relevant data. The long-term objective of this study is to use wall-resolved Large-Eddy Simulations to generate numerical data for the development of acoustic models. The objective of this paper is thus to establish the ability of wall-resolved LES to produce numerical data for perforated plate-acoustic interaction problems. This is achieved by calculating a classical configuration of acoustic-vortex interaction in perforated plates, corresponding to the analytical and experimental study by Bellucci *et al.*[11]

In next section, the LES code is presented and details are provided about the numerical configuration, that has to be adapted from the experimental geometry. Section IV briefly presents two analytical and one numerical models found in the literature that assess the reflection of an acoustic wave on a perforated plate. In section V, the LES results are presented. Acoustic and flow results are displayed. The acoustic data are compared to the measurements of Bellucci *et al.*[11] and to the data coming from the models presented in section IV.

III. Numerical information and configuration of interest

All simulations are carried out with AVBP (www.cerfacs.fr/cfd/avbp_code.php), an LES code developed at CERFACS. It is explicit in time and solves the compressible Navier–Stokes equations on unstructured meshes for the conservative variables. AVBP has been widely used and validated in the past years in all kinds of configurations[15,24,25] including perforated liners.[19] LES are based on the WALE sub-grid model.[26] The numerical scheme is the TTGC scheme,[27] an essentially non dissipative scheme – third order accurate in both space and time – which was specifically developed to handle unsteady turbulent flows.

The configuration of interest is inspired by the experimental test rig studied by Bellucci *et al.*[11] In their experiment, a cylindrical tube is closed at one of its ends by a wall. At a distance l from this wall, is placed a perforated plate, parallel to the back wall (normal to the tube axis). A bias flow through the perforated plate is generated by injecting air in the cavity formed by the perforated plate and the back wall, through the lateral wall of the tube. On the other side of the tube, four acoustic drivers generate an acoustic wave. Six microphones are used to measure the acoustic wave reflected by the plate. In a combustion chamber, the perforated plate is the chamber liner and the back wall is the wall bounding the casing. The perturbation generated by the loud speaker would correspond to an acoustic perturbation coming from the chamber, for example due to unsteady combustion.

Calculating exactly this configuration is out of reach because of the number of holes of the perforated plate. To calculate this case, it has thus been decided to consider the situation where the perforated plate and the back wall are infinite. In this case, due to the periodicity of the perforations and their in-line arrangement, the infinite configuration allows the use of periodic boundary conditions in the lateral frontiers of the computational domain. We then consider a unique perforation as shown in Fig. 1. Except from the periodicity in the calculation, the geometrical characteristics of the experiment are reproduced.

The geometrical characteristics of the plate are the following: the thickness of the plate is $h = 1.5$ mm, the holes diameter is $2a = 6$ mm and the perforations are separated by $d = 35$ mm in both directions. The porosity of the plate is thus $\sigma = \pi a^2/d^2 = 0.0231$. The holes direction is normal to the plate. In the experiment, the back wall is located at $l = 95$ mm from the perforated plate. In the operating point we consider, a bias flow is present through the perforated plate. The bulk velocity in the holes is denoted by U.

In the reference experiment, fluid is injected laterally, through the walls of the tube. In the calculations, this cannot be done. The back wall is replaced by an inlet boundary condition. To ensure a bias flow through the hole at bulk velocity U, the air is injected at $u^{\infty} = U\sigma$ through the inlet boundary condition. The inlet being fully reflecting, it behaves like a wall for the acoustics. An outlet boundary condition closes the domain at $x = L = 3l$. L is chosen large enough to avoid spurious interactions between the outlet condition and the zone of interest. The computational grid is composed by 280,000 tetrahedra, 20 points describing the diameter of the hole.

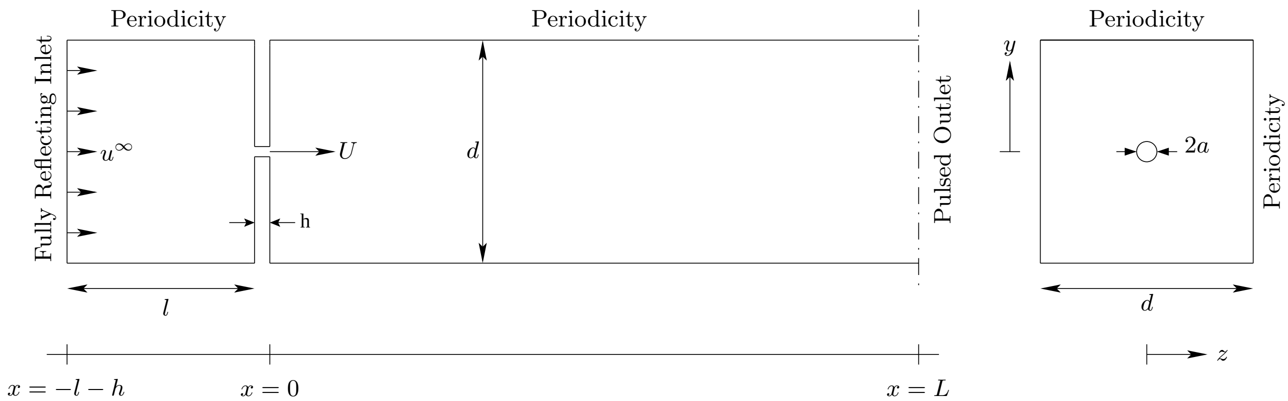


Figure 1. Schematic of the configuration of interest. Computational domain for the LES.

The operating point is such that $U = 5$ m.s^{-1}, so that $u^{\infty} \approx 0.115$ m.s^{-1}. For this operating point, the pressure loss in the perforation is 37 Pa. To assess the acoustic response of the system, the pressure at the outlet condition is pulsed by adding a sinusoidal perturbation to the reference state, with an amplitude of 5 Pa and at a frequency $f \in [250, 500\,\text{Hz}]$ (one simulation every 50 Hz). The Strouhal number of the configuration is defined from the frequency of excitation and the bulk velocity in the hole: $St = \dfrac{2\pi f\, a}{U}$. Pulsed simulations last 30 excitation periods and the last 20 periods are used for post-processing purposes.

IV. Acoustic models

In the next section (section V), the computational results will be presented. The numerical simulations will be compared to several data, either coming from experimental, numerical or analytical work. In particular, three models will be used. In the present section, the aim is to briefly summarize the hypotheses and the results of these models.

All the three models presented in this section are related to the work of Howe.[4] Howe proposed a model for linear sound absorption through a perforated plate. Indeed, in presence of bias flow and for acoustic perturbations of small amplitude, the mechanism is linear. Note that sound absorption occurs with and without mean flow through the aperture. In absence of mean flow through the aperture, the interaction is non-linear, the shear layer being created by the acoustic perturbation itself.[28,29]

Assuming that acoustic-vortex interaction was the mechanism responsible for sound absorption, Howe built a model to evaluate the amount of energy transferred from acoustic to vortical energy. His results were notably confirmed by the posterior experiments of Hughes & Dowling.[6] Three models are presented in the next paragraphs. First, the Howe model is discussed. Then a modified version[30] of this model is presented, accounting for the thickness of the plate, supposed to be zero in the Howe model. At last, the numerical model of Jing & Sun[31] is presented. This model solves the equations derived by Howe but in a more complex domain: Jing & Sun include a finite plate thickness and a complex form for the jet separation at the aperture inlet. All these models give satisfactory results in the cited references.

A. Howe model (HM)

This is the most classical model for linear sound absorption by perforated screens and is very often used for the construction of more elaborated models. The model developed by Howe[4] (HM) assumes an infinitely thin wall and a high Reynolds number in the aperture. It also considers that d/a (hole spacing-to-radius ratio) is large so that apertures do not interact with each other. The acoustic behavior of an aperture is described through its Rayleigh conductivity K_R, which is defined as

$$K_R = \frac{i\rho\omega\hat{Q}}{\hat{p}_+ - \hat{p}_-}, \tag{1}$$

where ρ is the mean density near the aperture, $\omega = 2\pi f$ the angular frequency of the perturbation, $\hat{Q}$ the amplitude of the flow rate fluctuations through the aperture and $\hat{p}$ the amplitudes of pressure fluctuations, measured below ($x < 0$, $\hat{p}_-$) and above the aperture ($x > 0$, $\hat{p}_+$).

At the rim of the aperture, the flow separates, forming a jet. The vorticity is supposed to be concentrated in an axisymmetric vortex sheet separating two regions of potential flow, the jet and the rest of the domain. The acoustic perturbation pulses the vortex sheet, resulting in the periodical shedding of vortex rings. The vortex shedding is supposed to have the following characteristics: the vortex rings shed are assumed to have the diameter of the aperture and to be convected at the mean velocity in the aperture, U. Under these hypotheses and assessing the vortex sheet strength by using a Kutta condition, Howe determined the following expression of the Rayleigh conductivity:

$$K_R = 2a\,(\gamma - i\delta) \qquad \text{with} \qquad \gamma - \mathrm{i}\delta = 1 + \frac{\frac{\pi}{2}\mathrm{I}_1(\mathrm{St})\mathrm{e}^{-\mathrm{St}} - \mathrm{i}\mathrm{K}_1(\mathrm{St})\sinh(\mathrm{St})}{\mathrm{St}\left[\frac{\pi}{2}\mathrm{I}_1(\mathrm{St})\mathrm{e}^{-\mathrm{St}} + \mathrm{i}\mathrm{K}_1(\mathrm{St})\cosh(\mathrm{St})\right]}, \tag{2}$$

where I_1 and K_1 are modified Bessel functions of the first and second kinds.

B. Howe model: modified version to account for the plate thickness (MHM)

This model can be found in several references, notably in papers by Jing & Sun.[30,31] As already stated, the model developed by Howe is relevant to infinitely thin plates. To account for the finite (but small) thickness of the plate, the Rayleigh conductivity derived by Howe is modified by adding a term representing the effect of plate thickness. This model gave good results in several previous studies,[30,31] including with tilted apertures.[10] The Rayleigh conductivity in the modified version of the Howe model (MHM) is written:

$$K_R = 2a\left(\frac{1}{\gamma - i\delta} + \frac{2}{\pi}\frac{h}{a}\right)^{-1}. \tag{3}$$

C. Jing & Sun numerical model (JSM)

This model is a numerical model that solves the equations derived by Howe within a more complex geometry. In particular, the absence of plate thickness and the assumption of a cylindrical vortex sheet of diameter $2a$ allows Howe to find an analytical expression for K_R. The model proposed by Jing & Sun[31] includes a finite plate thickness and assumes a complex form for the vortex sheet. They used a previous study assessing the trajectory of the jet separation through axially symmetrical orifices.[32] By interpolation of the profiles given by this study, Jing & Sun know the form of the vortex sheet, that is no more cylindrical. As a consequence, it is no more possible to derive an analytical solution. The governing equations are solved with the boundary element method. In this model, the convection velocity of the shed vortices is still supposed to be equal to the bulk velocity in the orifice, U. Results of the JSM for the case of interest ($h = 0.5a$) can be found in the recent study by Lee *et al.*[33]

From the Rayleigh conductivity, one can build the impedance of the perforated plate through:

$$z_p = \frac{i\omega\rho\, d^2}{K_R}. \tag{4}$$

Assuming plane wave propagation between the perforated plate and the back wall, the cavity impedance reads:

$$z_c = -\frac{i\rho c}{\tan(kl)}, \tag{5}$$

with k the wave number of the perturbation and c the speed of sound. The total impedance of the system perforated plate-back cavity is thus

$$z_t = z_p + z_c = \frac{i\omega\rho\, d^2}{K_R} - \frac{i\rho c}{\tan(kl)} = i\rho\omega\left(\frac{d^2}{K_R} - \frac{1}{k\,\tan(kl)}\right). \tag{6}$$

The reflection coefficient of the whole system is derived from this expression using

$$R = \frac{z_t + \rho c}{z_t - \rho c}. \tag{7}$$

The reflection coefficient is the quantity measured in the calculations, comparing the wave reflected by the system and the perturbation wave, imposed at the outlet boundary condition. These results are also compared to the experimental data of Bellucci *et al.*[11]

V. Results

Figure 2 presents velocity and vorticity fields, the outlet pressure being pulsed at $f = 250$ Hz and $f = 400$ Hz respectively. Due to the section restriction, a jet is formed in the hole. At the hole inlet, the flow separates, forming a small recirculation close to the aperture edges (Fig. 2a). An axisymmetric shear layer is formed between the jet and the remainder of the flow. In both calculations, the jet issuing from the hole is pulsed and vortices are formed at the edges of the jet: the shear layer rolls up and forms vortices that are advected by the jet. This mechanism, responsible of the acoustic absorbing behavior of the perforated plate is reproduced in our simulations.

The global behavior at the two frequencies are identical but Fig. 2 shows that the jet does not react in the same manner, depending on the frequency of the forcing. At $f = 250$ Hz, the jet remains more coherent and is less sensitive to the pressure fluctuations. In Fig. 2b, the shear layer rolls up $6\,a$ apart from the plate at $f = 250$ Hz and only $4\,a$ apart from the plate at $f = 400$ Hz. The same behavior is observed in Fig. 2a. The jet destabilizes more easily at $f = 400$ Hz. The fields presented in Fig. 2 are instantaneous snapshots but they are representative of the general flow behavior. The differences in the hydrodynamic behaviors also induce differences in the acoustic response.

Far enough from the plate, the acoustic waves reflected by the system perforated plate-back cavity are plane. The reflection coefficient is calculated at four positions above the aperture center, at $x = 70\,a$, $x = 80\,a$, $x = 90\,a$ and $x = 95\,a$. The results are then shifted, assuming plane waves, and averaged together (differences between the results coming from the four stations are less than 0.3%) to obtain R at $x = 0$ (at the aperture outlet plane).

Figure 3(left) presents the absorption coefficient[6] A of the perforated plate as a function of the pulsing frequency f. A is related to R, the reflection coefficient of the whole system, through $A = 1 - |R|^2$. The present LES results are reported, together with the experimental results of Bellucci *et al.*[11] and the numerical data of the Jing & Sun model.[31] The theoretical Howe model[4] is also plotted, together with its modified version accounting for the plate thickness.[30]

All data provide the same form for the absorption coefficient. The presence of the perforated plate induces an acoustic absorption that depends on the frequency. The absorption is maximum around $f_m \approx 400$ Hz,

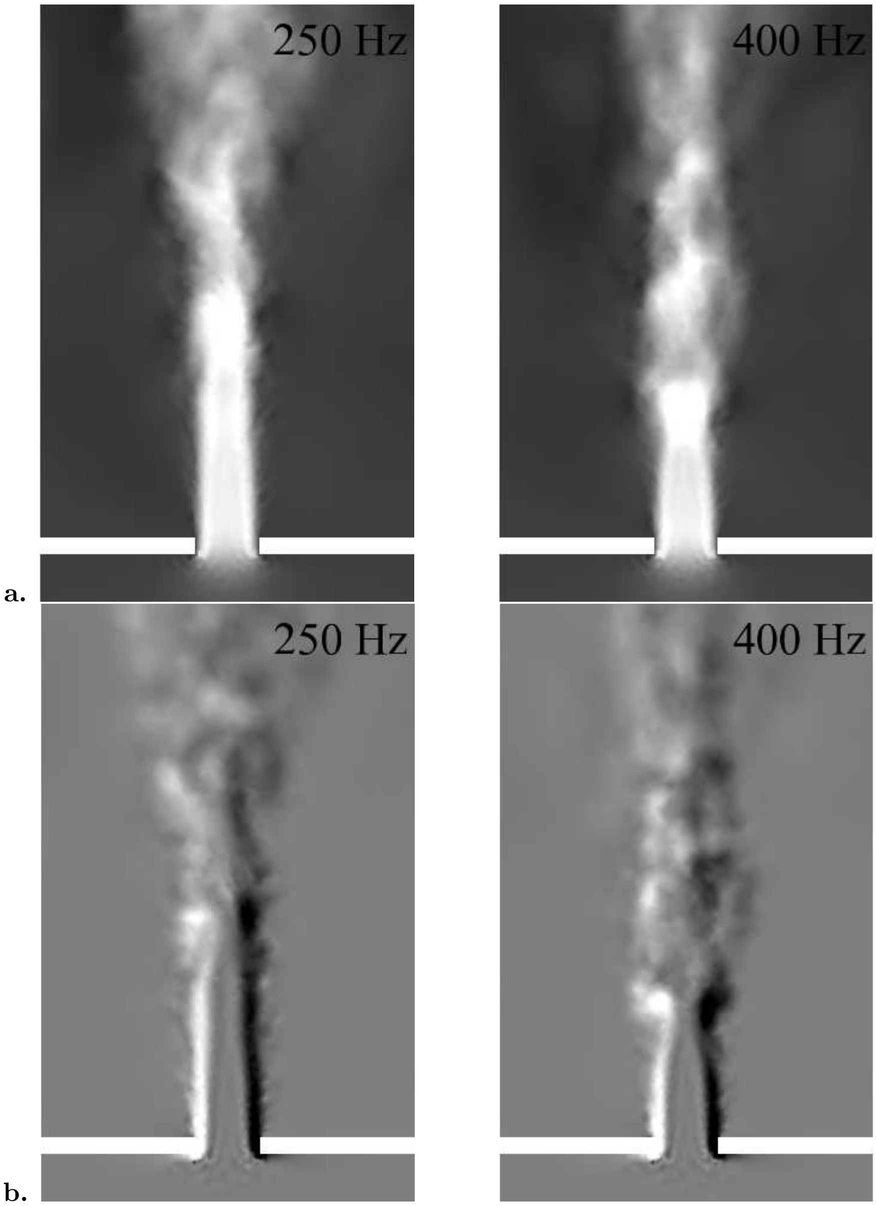
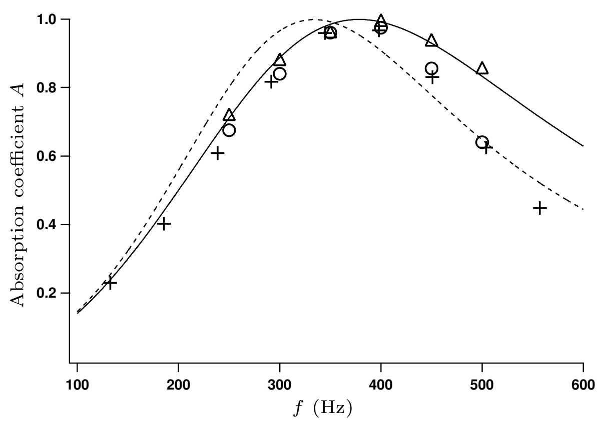


Figure 2. Instantaneous solutions from the runs pulsed at 250 Hz and 400 Hz: cutting plane $z = 0$. a. Velocity field in the x direction from $-0.5\,U$ (black) to $1.5\,U$ (white). Vorticity field in the z direction from $-3\,U/a$ (black) to $3\,U/a$ (white).

resulting in an absorption peak in Fig. 3(left). For this frequency, almost all the incident acoustic wave is absorbed by the system. The LES results show the same behavior.

If the general form is the same for all the results and models, a more detailed comparison allows to highlight differences. It is possible to divide the results into two regions, depending on the frequency of excitation:

- For $f \leq f_m$, almost all data collapse. The HM and JSM give very similar absorption coefficient. The agreement with the experimental measurements of Bellucci *et al.* is very good. At these low frequencies, the LES give values of absorption coefficient in excellent agreement with all these data. The MHM is the only one to give different results. In particular, the MHM under-predicts in this case the frequency of the absorption peak. At least for low frequencies, it is possible to conclude that the LES can provide the good absorption coefficients.



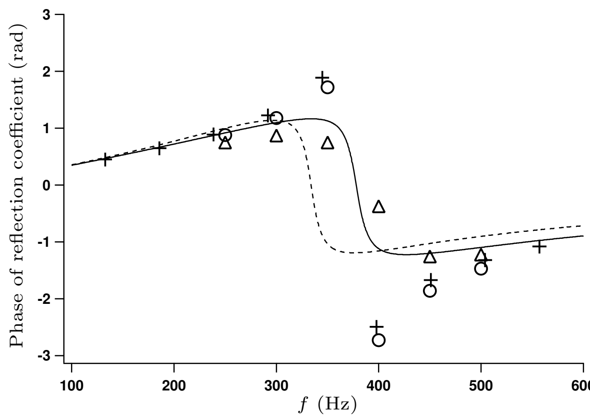


Figure 3. Acoustic behavior of the system (perforated plate + cavity). Left: absorption coefficient. Right: phase of the reflection coefficient. —— : HM,[4] ---- : MHM,[30] + : results adapted from JSM,[31] △ : results adapted from Bellucci *et al.*,[11] ○ : present LES results.

- For $f > f_m$, two kinds of results are observed. The HM gives high values of absorption coefficient, in agreement with the results of Bellucci *et al.* On the contrary, the JSM and the MHM predict values of the absorption coefficient approximately 25 % lower. Concerning the models, it appears clearly that the plate thickness has a much higher effect on the results at high frequencies. Note that even if the plate thickness is moderate ($h/a = 0.5$), the correction in the MHM model is important after the absorption peak. The LES results show a very good agreement with the JSM, that accounts for the jet shape and the plate thickness. Surprisingly, even if the plate has a finite thickness, the experimental results of Bellucci *et al.* are very close to the Howe model, that neglects this thickness.

Figure 3(right) displays the phase of the reflection coefficient. The phase is close to zero at low frequencies, and increases almost linearly with the frequency. Near the absorption peak, variations are larger and the phase sign changes. Above f_m, the phase increases slowly. Again, all data give the same behavior, including the LES results. As for the absorption coefficient, all data give very similar results al low frequencies. However, near f_m, phase variations are much larger for the JSM and the LES results, which are in very good agreement for all the frequencies tested.

As a conclusion about acoustic reflection, the present LES give results very similar to the numerical model developed by Jing & Sun, that is the most sophisticated one (section IV). Compared to the data of the reference experiment, the results also collapse for low frequencies, but discrepancies are observed at higher frequencies. This might be due to the difference of configuration between the experimental test rig and the numerical simulations which consider an infinite plate. However, the agreement with the JSM, both for the modulus and phase of the reflection coefficient, supports the quality of the present LES results.

The acoustic models presented in section IV are based on several hypotheses that can be verified in the numerical simulations. In particular, the HM, MHM and JSM assume a particular form for the jet. Figure 4 displays the azimuthal-averaged jet profile coordinates in the LES. The jet profile is determined from the position of the maximum of azimuthal vorticity. It is compared with the hypothesis of Howe (cylindrical vortex shedding) and the hypothesis of Jing & Sun (jet profile interpolated from the data provided by Rouse & Abul-Fetouh[32]). The abscissa is the axial distance from the hole inlet. At the hole inlet, the jet separates from the rim and contracts. At the minimum, the jet radius corresponds approximately to $0.78a$. Further downstream, the jet progressively expands and then becomes turbulent (not shown). The agreement between the LES results and the Rouse & Abul-Fetouh profile is very good. This figure allows to explain the good agreement between the LES results and the JSM observed in Fig. 3. On the contrary the the LES jet profile clearly departs from the form assumed by Howe for the vortex sheet separating the jet from the remainder of the flow.

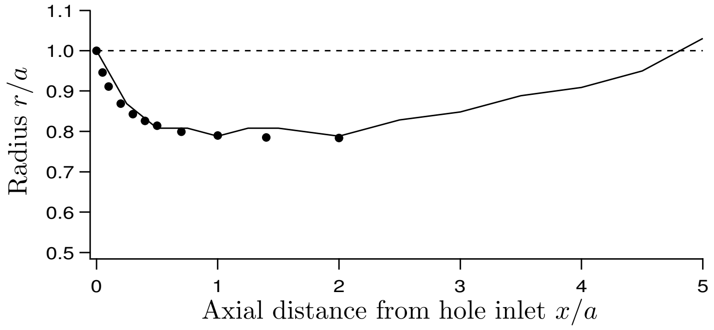


Figure 4. Jet profile coordinates. Comparison of the numerical profile at $f = 400Hz$ (——) with the profile of Rouse & Abul-Fetouh[32] for a perforated plate porosity $\sigma = 0.0231$ (. . .) and the jet profile assumed by Howe[4] (- - - -).

VI. Conclusion

Large-Eddy Simulation proves to be able to reproduce the acoustic behavior of a perforated plate. The present results show the strong relation between the dynamic field and the acoustic response of the system. The acoustic results are in excellent agreement with the numerical model of Jing & Sun, that accounts both for the finite thickness of the plate and the particular shape of the jet after its separation from the aperture inlet rim. From the LES results, it is possible to get insight into the mechanisms that lead to acoustic absorption and to verify the assumptions made by the theoretical models. This is very interesting in the context of small apertures, for which experiments are unable to provide detailed measurements. For example, our simulations show that the hypothesis of the Jing & Sun model concerning the jet shape seems to be relevant, at least at moderate Reynolds numbers.

Wall-resolved LES can also be used to assess the effect of different parameters such as the plate thickness or the hole angle, as in Eldredge *et al.*[10] This will be developed in the following of this study. Detailed flow-field information is missing about vortex-acoustic interactions in the case of perforated plates and numerical simulations offer a way to a deeper understanding of the small-scale flow physics.

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References

[1]Lieuwen, T. and Yang, V., *Combustion Instabilities in Gas Turbine Engines. Operational Experience, Fundamental Mechanisms and Modeling*, Vol. 210, Progress in Astronautics and Aeronautics AIAA, 2005.

[2]Poinsot, T. and Veynante, D., *Theoretical and numerical combustion*, R.T. Edwards, 2nd edition., 2005.

[3]Lefebvre, A. H., *Gas Turbines Combustion*, Taylor & Francis, 1999.

[4]Howe, M., "On the theory of unsteady high Reynolds number flow through a circular aperture," *Proceedings of the Royal Society of London, Series A: Mathematics and Physical Sciences* , Vol. 366, 1979, pp. 205–223.

[5]Howe, M., *Acoustics of Fluid-Structure Interaction*, Cambridge University Press, 1998.

[6]Hughes, I. and Dowling, A., "The absorption of sound by perforated linings," *Journal of Fluid Mechanics* , Vol. 218, 1990, pp. 299–335.

[7]Eldredge, J. D. and Dowling, A. P., "The absorption of axial acoustic waves by a perforated liner with bias flow," *Journal of Fluid Mechanics* , Vol. 485, 2003, pp. 307–335.

[8]Tran, N., Ducruix, S., and Schuller, T., "Analysis and control of combustion instabilities by adaptive reflection coefficients," *13th AIAA/CEAS Aeroacoustics Conference, Rome, 21-23 May 2007*, 2007.

[9]Eldredge, J. D., Shoeybi, M., and Bodony, D. J., "Numerical investigation of the acoustic behavior of a multi-perforated liner," *Proceedings of the Summer Program CTR, NASA Ames - Stanford University* , 2006.

[10]Eldredge, J. D., Bodony, D. J., and Shoeybi, M., "Numerical Investigation of the Acoustic Behavior of a Multi-perforated Liner. AIAA Paper 2007-3683," *13th AIAA/CEAS Aeroacoustics Conference, Rome, 21-23 May 2007*, 2007.

[11]Bellucci, V., Flohr, P., and Paschereit, C. O., "Numerical and Experimental Study of Acoustic Damping Generated by Perforated Screens," *AIAA Journal* , Vol. 42, No. 8, 2004, pp. 1543–1549.

[12]Pierce, C. and Moin, P., "Progress-variable approach for large eddy simulation of non-premixed turbulent combustion," *Journal of Fluid Mechanics* , Vol. 504, 2004, pp. 73–97.

[13]Sommerer, Y., Galley, D., Poinsot, T., Ducruix, S., Lacas, F., and Veynante, D., "Large eddy simulation and experimental study of flashback and blow-off in a lean partially premixed swirled burner," *J. of Turbulence*, Vol. 5, 2004.

[14]Selle, L., Lartigue, G., Poinsot, T., Koch, R., Schildmacher, K.-U., Krebs, W., Prade, B., Kaufmann, P., and Veynante, D., "Compressible Large-Eddy Simulation of turbulent combustion in complex geometry on unstructured meshes," *Combustion and Flame* , Vol. 137, No. 4, 2004, pp. 489–505.

[15]Schmitt, P., Poinsot, T., Schuermans, B., and Geigle, K., "Large-eddy simulation and experimental study of heat transfer, nitric oxide emissions and combustion instability in a swirled turbulent high-pressure burner," *Journal of Fluid Mechanics* , Vol. 570, 2007, pp. 17–46.

[16]Boudier, G., Lamarque, N., Sensiau, C., Staffelbach, G., Poinsot, T., and Moureau, V., "Investigating the Thermo-Acoustic Stability of a Real Gas Turbine Combustion Chamber Using Large-Eddy Simulations," *11th CEAS-ASC Workshop and 2nd Scientific Workshop of X3-NOISE 27–28 September 2007, Lisbon, Portugal*, 2007.

[17]Martin, C., Benoit, L., Sommerer, Y., Nicoud, F., and Poinsot, T., "LES and acoustic analysis of combustion instability in a staged turbulent swirled combustor," *AIAA Journal* , Vol. 44, No. 4, 2006, pp. 741–750.

[18]Nicoud, F., Benoit, L., and Sensiau, C., "Acoustic Modes in Combustors with Complex Impedances and Multidimensional Active Flames," *AIAA Journal* , Vol. 45, No. 2, 2007, pp. 426–441.

[19]Mendez, S. and Nicoud, F., "Large-eddy simulation of a bi-periodic turbulent flow with effusion," *Journal of Fluid Mechanics* , Vol. 598, 2008, pp. 27–65.

[20]Jing, X., Sun, X., Wu, J., and Meng, K., "Effect of Grazing Flow on the Acoustic Impedance of an Orifice," *AIAA Journal* , Vol. 39, No. 8, 2001.

[21]Howe, M. S., Scott, M. I., and Sipcic, S. R., "The influence of tangential mean flow on the Rayleign conductivity of an aperture," *Proceedings of the Royal Society of London, Series A: Mathematics and Physical Sciences* , Vol. 452, 1997, pp. 2303–2317.

[22]Sun, X., Jing, X., Zhang, H., and Shi, Y., "Effect of Grazing-Bias Flow Interaction on Acoustic Impedance of Perforated Plates," *J. Sound Vib.* , Vol. 254, No. 3, 2002, pp. 557–573.

[23]Fung, K., Ju, H., and Tallapragada, B., "Impedance and Its Time-Domain Extensions," *AIAA Journal* , Vol. 38, No. 1, 2000, pp. 30–38, NL.

[24]Schönfeld, T. and Rudgyard, M., "Steady and unsteady flows simulations using the hybrid flow solver AVBP," *AIAA Journal* , Vol. 37, No. 11, 1999, pp. 1378–1385.

[25]Moureau, V., Lartigue, G., Sommerer, Y., Angelberger, C., Colin, O., and Poinsot, T., "Numerical methods for unsteady compressible multi-component reacting flows on fixed and moving grids," *Journal of Computational Physics* , Vol. 202, No. 2, 2005, pp. 710–736.

[26]Nicoud, F. and Ducros, F., "Subgrid-scale stress modelling based on the square of the velocity gradient tensor," *Flow, Turbulence and Combustion* , Vol. 62, No. 3, 1999, pp. 183–200.

[27]Colin, O. and Rudgyard, M., "Development of high-order Taylor-Galerkin schemes for unsteady calculations," *Journal of Computational Physics* , Vol. 162, No. 2, 2000, pp. 338–371.

[28]Cummings, A. and Eversman, W., "High amplitude acoustic transmission through duct terminations: Theory," *J. Sound Vib.* , Vol. 91, No. 4, 1983, pp. 503–518.

[29]Tam, C. K. W., Kurbatskii, K. A., Ahuja, K. K., and Gaeta, R. J., J., "A numerical and experimental investigation of the dissipation mechanisms of resonant acoustic liners," *J. Sound Vib.* , Vol. 245, No. 3, 2001, pp. 545–557.

[30]Jing, X. and Sun, X., "Experimental investigations of perforated liners with bias flow," *Journal of the Acoustical Society of America* , Vol. 106, No. 5, 1999, pp. 2436–2441.

[31]Jing, X. and Sun, X., "Effect of Plate Thickness on Impedance of perforated plates with Bias Flow," *AIAA Journal* , Vol. 38, No. 9, 2000, pp. 1573–1578.

[32]Rouse, H. and Abul-Fetouh, A., "Characteristics of irrotational flow through axially symmetric orifices," *J. Appl. Mech*, Vol. 17, 1950, pp. 421–426.

[33]Lee, S., Ih, J., and Peat, K., "A model of acoustic impedance of perforated plates with bias flow considering the interaction effect," *J. Sound Vib.* , Vol. 303, No. 3-5, 2007, pp. 741–752.