AEROACOUSTICS ANALYSIS OF THE FLOW FROM SINGLE NOZZLES OPERATING AT SUBSONIC SPEEDS

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Abstract. *The main goal of the present work was the aeroacoustics analysis of the flow from single nozzles operating at subsonic speeds (Mach = 0.6 and 0.9) with focus on the understanding of methodologies for aerodynamic noise radiated by subsonic single jets. This is a recent area of knowledge evolving in Brazil and then an ample bibliography survey has been reviewed during this work. One of the most recent commercial codes in aeroacoustics (CAA++ software) was applied for all the numerical simulations. Different methodologies available in CAA++ were employed for the numerical analysis in order to predict and compare the farfield radiated sound. First of all, a study of influence parameters was conducted, including boundary conditions, grid independence and time step to advance the acoustic solution. 2D axisymmetric and 3D simulations were carried out to characterize both flow dynamics and acoustics of the jet. Experimental data available were used to corroborate the numerical results. At the end, for each methodology studied, limitations and flaws were identified and discussed. The final results showed strong dependence of time step size and mesh resolution.*

Keywords*: single nozzles, jet flow, fluid dynamics, aeroacoustics*

1. INTRODUCTION

Restrictions of noise levels in the surroundings of airports have made the reduction of near ground operation noise an important issue for aircraft and engine manufacturers and as a result, noise generation has now become an important design factor taken into consideration in the project phase definition. As an example, many commercial operators do not have permission to operate at Heathrow and John F. Kennedy airports located at London and New York, respectively, due to the high noise levels generated by their aircrafts. Hence they lose space on the competitive airspace business. More details about the airplanes certifications noise limits can be found at ICAO Chapter 4 and FAR 36 Chapter 4.

Accordingly to Lilley (1996), the problem represented by the noise radiated from aircrafts and its effects on the environments were realized, soon after the Second World War, by many aircraft engineers and scientists that the introduction of the jet engine as the power plant for civil air transport would be dependent on limiting the noise from its jet exhaust.

Nowadays, it's known that a primary component of the measured noise during the takeoff phase of an aircraft is jet noise, produced by the strong turbulent mixing of the engine flow with the ambient, or external, air stream. Even modern engines as turbofans with high by-pass ratio have high noise levels associated to the pattern of the jet flow in the nozzles.

Until recently, in the aeronautic industry, the design and development of low-noise exhaust systems were based on "trial" experiences with modification of the nozzle geometry and acoustics tests in engine's test-stands. Obviously, this is a very expensive process and many times aside the optimum trade-off point between noise reduction and performance of the engine (specific fuel consumption and thrust).

To overcome this difficulty of finding tools for low-noise design of nozzles, empirical methods gained importance in 70's and 80's decades. These methods, based on experimental databases, are largely used in the aeronautic industry. For instance, methods as ESDU 98019 and SAE ARP 876D still today play an important role in the design phase.

Due to the inherent geometrical and physical complexity of the problem, CFD techniques have traditionally had little impact on the design process of exhaust systems. This is largely due to limitations from available computational power, grid generation techniques, reliable CFD solvers as well as the lack of a good understanding of the dominant flow mechanisms. As more powerful computers and improved computational methods have become available, CFD techniques have been applied in the design process still under certain amount of limitations.

In principle, the entire jet nozzle flow prediction could be accomplished by a full unsteady CFD calculation, but the complexities associated with such a task for high Reynolds number jet flows (computational cost) mean that this is unlikely to be practical for several years to come in industry. Alternatives for solving this problem led to a new area of research, actually known as Computational Aeroacoustics (CAA).

As a former definition, Computational Aeroacoustics (CAA) is the process of calculating numerically the acoustic signature of aerodynamic generated noise. Such principle had already been exposed by Sir James Lighthill (1952 and 1954) in early 50's, and since then evolved progressively throughout the last five decades. However, even considering the advances in numerical methodologies and computing resources, CAA applications are still related to very simple problems, due to numerical limitations when dealing with the physics of wave generation and propagation.

Such critical numerical issues can limit the calculation of noise generated and radiated from a three-dimensional unsteady flow, as subsonic jets. One of the most restringing factors is imposed by the magnitude of acoustic-pressure fluctuations which are about five orders of magnitude smaller than the variation of the mean flow variables. Indeed, this imposes challenges to current CFD techniques. Another point is the acoustic frequencies of interest in an industrial problem, which likely lies in the range of 50 Hz-20 kHz and are much larger than normal for CFD. In this case, finite meshes acts as filter to high frequency disturbances and are not numerically resolved.

Most recent computational aeroacoustics researches are focused on improving numerical schemes for spatial and temporal discretization, as well as boundary conditions – Bridges and Hussain (1995), Colonius and Lele (2004) and Tam (2004), among others. Another class of researches are focusing in the creation and/or application of different mathematical formulation for solving the Navier-Stokes equations in a form of disturbance equations – Uzun (2003), Batten *et al* (2004), Billson (2004) among others.

One alternative to resolve the difficulties previously mentioned is to use a relatively fast-running CFD code, such as a Reynolds-averaged Navier–Stokes (RANS) scheme, to generate input data for acoustic source and propagation models used in CAA. In this case, there is a natural separation in the numerical approach. It means that, the acoustic source is firstly evaluated by traditional CFD techniques. Primitive flow variables, as pressure, velocities and turbulence quantities are used to characterize the noise source. Such parameters are then exported (as input) to an aeroacoustics module which will use this information to feed a propagation model.

Currently, these tools are being developed for simple industrial problems as cavity flows, airfoil and axis-symmetric jets. The methodology is used to combine advantageous features from both conventional acoustic analogy frameworks and hybrid Reynolds-averaged Navier-Stokes (RANS)/Large Eddy Simulation (LES) methods. It turns to an alternative framework for partially resolving, and partially modelling, flow-generated acoustics – Batten *et al.* (2004).

This paper deals with the aeroacoustics validation of radiated sound from a subsonic jets operating at Mach numbers equal to 0.6 and 0.9. The focus of this work was on the understanding of methodologies for aeroacoustics, as well as the use of CAA software to solve the proposed problem. To accomplish these tasks, numerical simulations have been performed using the commercial software CFD++ in conjunction with CAA++, which employs two distinct methods for noise prediction: a) an analytical propagation solver via Curle's equation solution (1970); b) a non-linear acoustic solver (NLAS) and Ffowcs-Williams/Hawking equation. Such numerical results have been compared to experimental acoustic data. First of all, a study of influence parameters was conducted, including boundary conditions, grid independence and time step to advance the acoustic solution. 2D axis-symmetric and 3D simulations were carried out to characterize both flow dynamics and acoustics of the jets. Experimental data available were used to corroborate the numerical results. At the end, for each methodology studied, limitations and flaws were identified and discussed.

Finally, it's important to emphasize that prediction tools are most useful when they can be integrated into the design optimization process in industry. To be able to do this, the jet noise prediction tool should be able to provide results in a reasonable time, for example within a day. Of course, the accuracy and ability to predict complex installed configurations are also equally important. Such jet noise design tools are expected to be a hybrid combination of some or all of the following: CFD, CAA, analytical, and empirical based techniques.

2. PROBLEM DESCRIPTION AND FORMULATION

Two subsonic cold jet flows in a single nozzle (Mach 0.6 and Mach 0.9) are considered in this work in order to evaluate the computational aeroacoustics tools available in the commercial code CAA++. The physical flow problems of these jets have already been studied by Simonich *et al* (2000), where experimental data were gathered. These results are used herein for comparison purposes.

The flow is modeled as compressible and turbulent, and for the bidimensional simulations the flow is also taken as axis-symmetric. The computational domain used for the 2D simulations is presented in Figure 1. The boundaries (Fig. 1) has been modeled as Pressure-Temperature Inflow/Outflow using Inside Velocity (available on the commercial code CFD++) which acts as a reservoir boundary condition (BC), but also allows for reversed flow. The velocity normal to the boundary is computed from the interior and user to determine whether there is inflow or outflow. For inflow, this BC imposes the user-specified pressure and temperature as stagnation conditions. For outflow, the BC imposes the input pressure as a static back pressure (or, optionally, the imposed pressure can be interpreted as a stagnation pressure and the static pressure determined using the local flow velocity). The inlet conditions for the subsonic jets are given in Table. 1. The ambient conditions are 101 kPa and 300 K for the static pressure and temperature, respectively. The nozzle diameter (D_j) is 0.0822706 m.

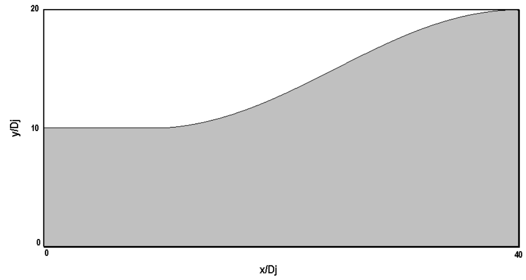


Figure 1. 2D Computational Domain utilized on the simulations.

Table 1. Inlet Conditions for the subsonic jets.

Mach Number	T_j [K]	U_j [m/s]	Total Pressure [kPa]	Total Temperature [K]
0.6	295	206	129.24	316.5
0.9	298	310	171.37	346.3

2.1. Grid Independancy Study

In order to establish the grid independence of the solution for the 2D axis-symmetric simulations, it was performed calculations on two different grids - a fine grid with 45000 cells and a grid with 35000 cells. There was no significant variation in the axial velocity profiles obtained on the grid with 35000 cells and those obtained from the fine grid. Hence, the grid with 35000 cells was used for all the subsequent calculations. Figure 2 illustrates the 2D grid resolution. Figure 3 depicts the 3D computational RANS mesh.

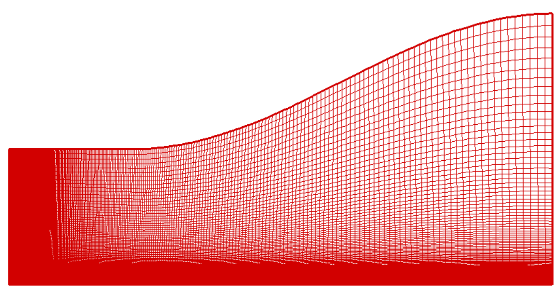
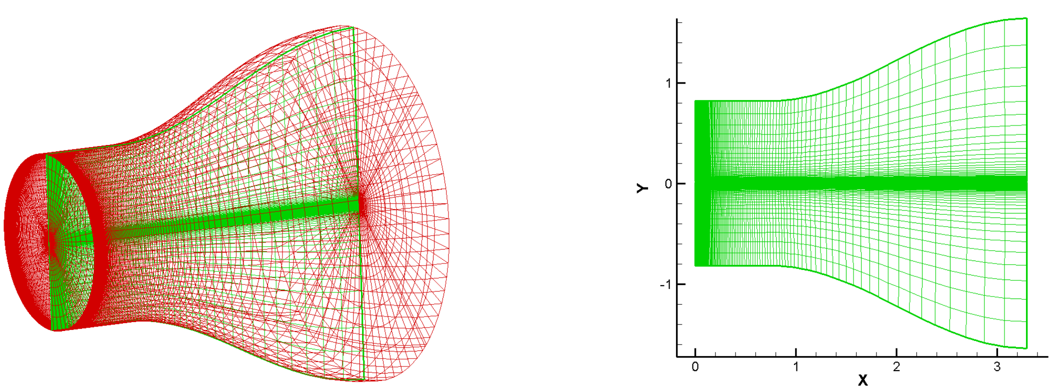


Figure 2. Computational 2D RANS mesh resolution (35000 cells).



(a) (b)

Figure 3. (a) Three-dimensional computational domain. (b) 3D computational slice.

2.2. Turbulence Modelling

In order to determine the most appropriate turbulence model for the compressible jet, a set of numerical experiments with the subsonic cold jet at M=0.9 were carried out using the turbulence models available in CFD++. The variation of the axial velocity along the centerline obtained from each of these turbulence models has been compared with the experimental data to determine the most suitable model. Figure 4 depicts the results obtained with the two equation non-linear (cubic) k-epsilon model and with the Reynolds-Stress Transport Model (RSTM).

From Figure 4 it can be concluded that for both simulated cases (Mach 0.6 and 0.9 jet) the results obtained for the variation in the axial velocity profiles the RSTM (Reynolds Stress Transport Model), considering the Vortex Stretching Correction proposed by Pope (1978), provides a more efficient spreading rate of the jet when compared with the k-ε cubic model. Basically, the correction proposed by Pope takes into consideration modifications on the model constants in order to take into account the vortex stretching effects. More details about turbulence modelling for subsonic jets can be found in the work of Nallasamy (1999).

According to Senesh and Babu (2002), the turbulence intensity of the jet at the nozzle exit plane is an important parameter which affects the potential core length of the jet. The turbulence intensity set in this work was 10% for both of the jets.

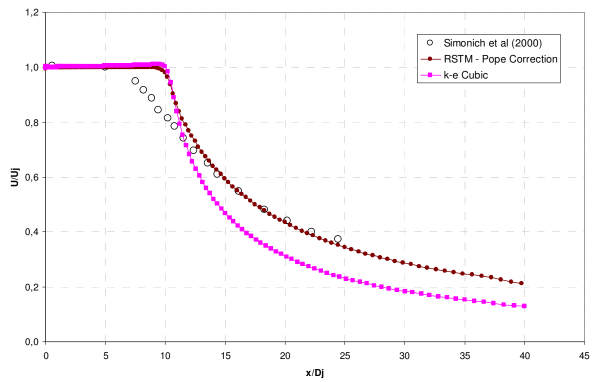


Figure 4. Turbulence influence in the axial velocity profile.

3. NUMERICAL METHOD FOR AEROACOUSTICS

Once the flow field was well characterized the identification of jet's noise sources could be evaluated by two distinct methodologies both available in CAA++ software: a) an analytical propagation solver via Curle's solution; b) a non-linear acoustic solver (NLAS) and Ffowcs Williams-Hawkings (FWH) propagation model.

For the first approach, the 2D axis-symmetric RANS mean field, Reynolds-stress and dissipation rate data are interpolated onto an acoustics 3D mesh (Figure 5a) and Farfield data at the outer boundaries are then set from the interpolated RANS mean field data at those locations. Then, the empirical wave propagation solver is used to evaluate the volumetric noise sources and to propagate acoustics perturbations to the Farfield – section 3.1.

In the second approach, two possibilities are available for taking into account the RANS solution. It's possible to get the 2D axis-symmetric RANS results (mean field, Reynolds-stress and dissipation rate) and interpolate onto a 3D acoustics mesh for NLAS. On the other hand, it's also possible to get a 3D RANS result and interpolate onto a 3D acoustics mesh. In this paper only the empirical wave propagation solver has been used.

3.1 Empirical Wave Propagation Solver (waveprop1)

The empirical wave propagation solver provides an approximate but rapid means of evaluate Farfield noise from conventional RANS solutions. This solver can be considered an analytical model which works by reconstructing the sound-generating velocity fluctuations from the statistics contained within the given turbulence solution. Since these statistics describe the full spectrum of turbulence, there is no limit to the frequencies that can be extracted using an analytic wave propagation model. The proposed model can therefore be used as a stand-alone tool to provide full-spectrum predictions, or in conjunction with a separate numerical solver, to provide a description of the unresolved frequencies. The model is based on a form of Lighthill's equation, according to Eq. (1) and Eq. (2).

$$\frac{\partial^2 \rho'}{\partial t^2} - c_0^2 \frac{\partial^2 \rho'}{\partial x_i^2} = \frac{\partial^2 T_{ij}}{\partial x_i \partial x_j} \tag{1}$$

where:

$$T_{ij} = \rho u_i u_j - \tau_{ij} + (p - c_\infty^2 \rho)\delta_{ij} \tag{2}$$

The right-hand side terms are assumed to be known and independent of the left-hand side, which then simply represents a wave-propagation operator. A solution to this equation was proposed in 1970 by Curle (1970):

$$\rho(x_j, t)' = \frac{1}{4\pi c_\infty^2} \iiint \frac{1}{r} \frac{\partial^2 T_{ij}}{\partial y_i \partial y_j} dV - \frac{1}{4\pi} \iint \left(\frac{1}{r}\frac{\partial \rho}{\partial n} + \frac{1}{r^2}\frac{\partial r}{\partial n}\rho + \frac{1}{c_\infty r}\frac{\partial r}{\partial n}\frac{\partial \rho}{\partial \tau}\right) dS \tag{3}$$

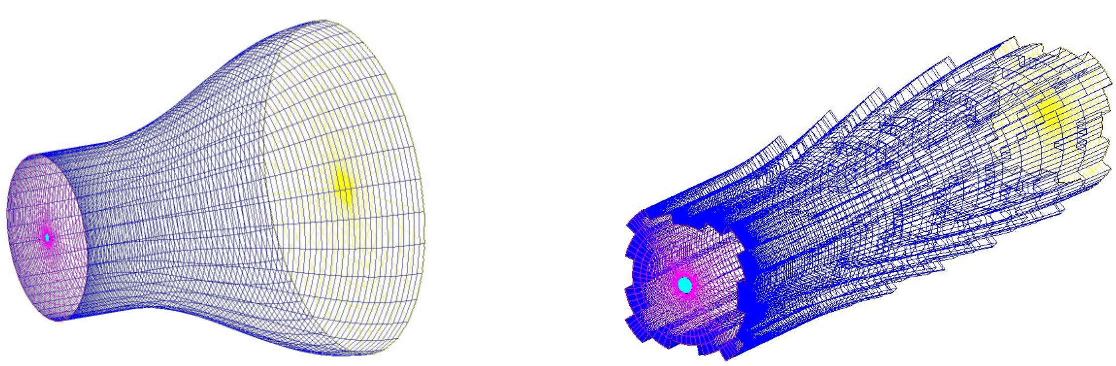
where n defines the local surface normal. A solution to Curle's equation, which is valid for arbitrary r can be written as (see, for example, Larsson (2002)):

$$p'(x_i, t) = \frac{1}{4\pi} \iiint \left[\frac{l_i l_j}{c_\infty^2 r} \frac{\partial^2 T_{ij}}{\partial t^2} + \frac{3 l_i l_j - \delta_{ij}}{c_\infty r^2} \frac{\partial T_{ij}}{\partial t} + \frac{3 l_i l_j - \delta_{ij}}{r^3} T_{ij} \right] dV + \frac{1}{4\pi} \iint l_i n_j \left[\frac{1}{c_\infty r} \left(\frac{\partial p}{\partial t} \delta_{ij} - \frac{\partial \tau_{ij}}{\partial t} \right) + \frac{p \delta_{ij} - \tau_{ij}}{r^2} \right] dS \tag{4}$$

Given a suitable mathematical model for the terms on the right-hand side, the previous equation can be used to determine the resulting acoustic pressures as a function of position (x_i) and time (t). These sources are determined in the model using an assumption that the pressure fluctuations on the right-hand side, corresponding to monopole sources (such as mass sources/sinks) and dipole sources (such as oscillating surfaces) are zero. The quadrupole terms, corresponding to the fine-scale turbulent fluctuations are determined by a mathematical model that reconstructs the fluctuating velocity field from a given set of turbulence statistics (the details of this reconstruction are given in the section below). It's worth noting that an important limitation of this model is that it ignores the presence of walls, implying that waves are not blocked, reflected from, or refracted around solid obstacles. The proposed model is therefore best suited for problems involving free shears or jets.

In order to run this model a 3D mesh is required since Eq. (4) is integrated over discrete volumes. As stated above, the presence of walls was ignored, i.e. the simulations were run without the nozzle geometry. To accomplish this task, a separate acoustics mesh was generated through a cutting process from the original 3D RANS mesh.

Figure 5 illustrates two of the 3D mesh (named acoustics mesh) utilized in order to run the waveprop1 solver.



(a) (b)

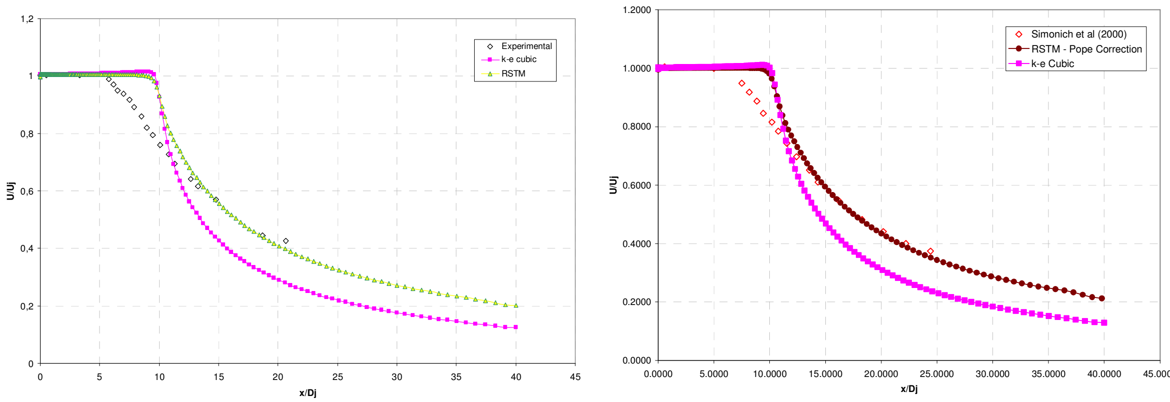
Figure 5. 3D Acoustics Meshes. (a) 310.000 cells. (b) 460.000 cells.

4. RESULTS

The results obtained in this work are divided into two main parts: Fluid dynamics and Acoustics. The first part presents the solution obtained by applying the conventional Computational Fluid Dynamics approach which provides all the information related to the flow field of the single nozzle (velocity, pressure, turbulence, etc). The acoustics section shows the sound pressure level obtained for the Farfield region with the computational aeroacoustics simulation procedure.

4.1 Fluid Dynamics

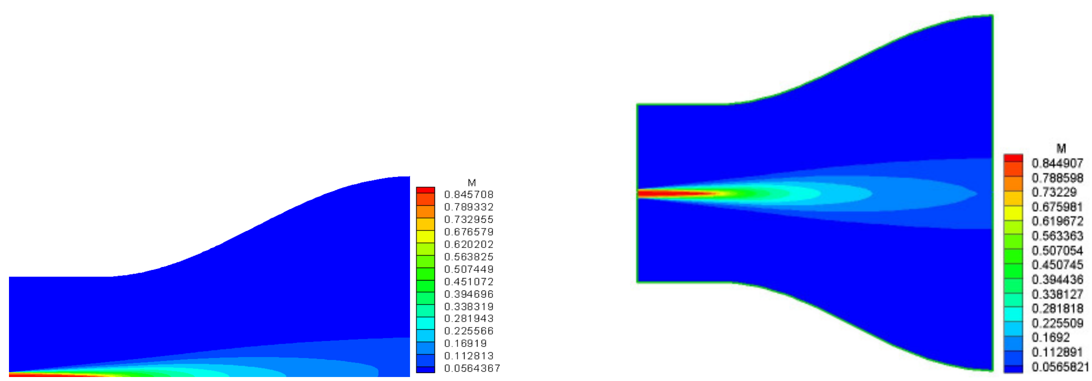
Figure 6 shows the centerline velocity distribution for the 2D axis-symmetric nozzle simulation for both of the Mach numbers jets.



(a) (b)

Figure 6. Jet centerline velocity distribution. (a) Mach = 0.6; (b) Mach = 0.9

Figure 7(a) and Fig. 7(b) depict the Mach numbers distribution obtained from the numerical simulations of the single nozzle flow (Mach 0.9 jet) for a bidimensional and three-dimensional computational mesh, respectively.



(a) (b)

Figure 7. (a) 2D axis-symmetric. (b) 3D simulation (slice).

4.2. Acoustics

This section presents the acoustics results obtained by applying the computational aeroacoustics approach. The numerical software utilized on the simulations was the CAA++ distributed by Metacomp Technologies Inc. In order to acquire a better understanding of the acoustic phenomena and the principal acoustics parameters involved in the flow simulation inside of single nozzles there were conducted a great amount of analyzes (time step size, mesh independence, etc). The numerical results are compared with the experimental data and with the SAE Aerospace Recommended Practice ARP867D (1994) which gives a prediction methodology for both single and coaxial jets.

All the results presented herein refer to One Third Octave Band of the sound pressure level (SPL) predictions for the Farfield region, which is the region far from the noise sources of the flow. In this region, the main sources of sound are due to the shear stress flow.

The results refer to a probe positioned at 90º and 29.5 nozzle diameters from the nozzle centerline. Figure 8 shows the probe location on the farfield with D=2.46 m.

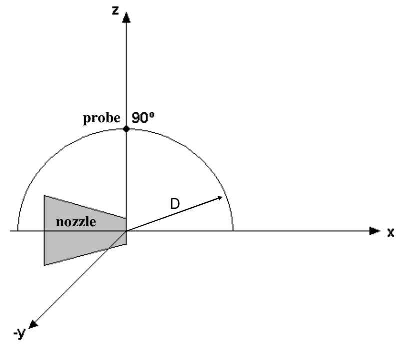


Figure 8. Acoustic Probe Position.

Figure 9 illustrates the acoustic mesh influence in the sound pressure levels for the Mach 0.9 jet. As can be seen, the results are strongly dependent on the resolution of the acoustic mesh.

Figure 10 shows the influence of the time step size of the method in the numerical simulations. The results show that the for large time steps the data resolution is kind of lost for high frequencies, that is, high frequency acoustic waves will not be captured. With lower time steps (ex: $\Delta t = 1 \times 10^{-5}$s), the results provide better time resolution of the signal however, the computational cost of the simulation increases which could turn the calculations unfeasible.

Figure 11 depicts the influence of the time sample on the acoustics results. This is an important issue because it is necessary to choose an optimized relation of computational cost and precise acoustics results. According to Figure 11, when the time sample of the simulation is relatively big, the results tend to be more accurate.

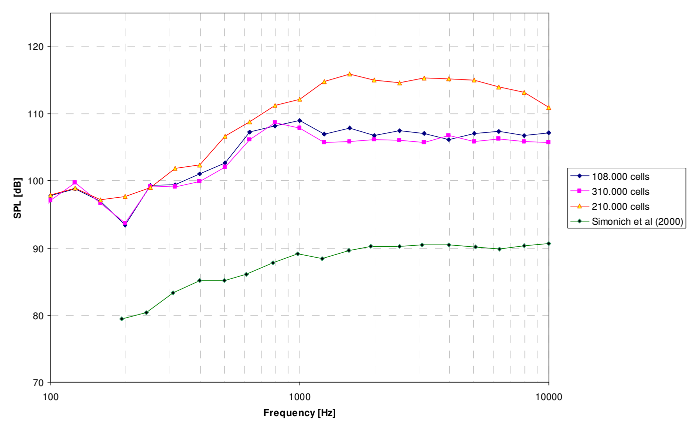


Figure 9. Acoustic Grid Independency Study.

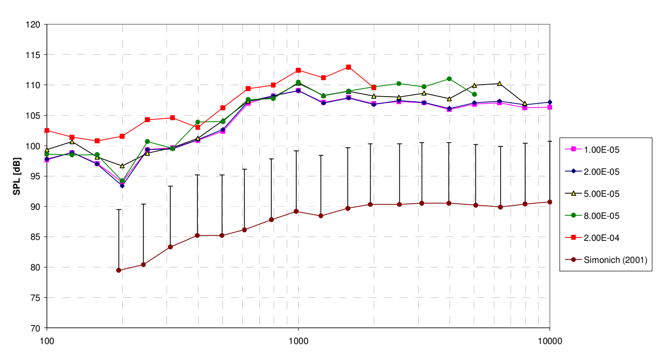


Figure 10. Time Step Size Influence Study.

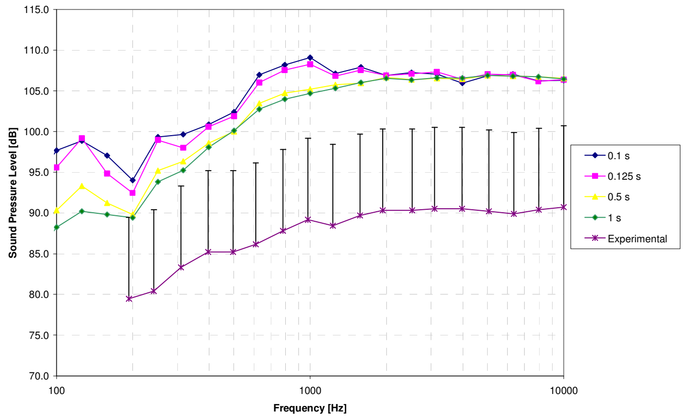


Figure 11. Total Time influence study.

Figure 12 presents the comparison of the bidimensional and three-dimensional results for the SPL prediction using the same parameters for both simulations except, obviously, for the dimensional of the mesh. In order words, the 2D results presents in the figure below were generated by using the acoustics input (noise sources) from the 2D axis-symmetric RANS simulation and for the 3D results, the acoustic input is from the 3D RANS calculations. The results show that the 3D simulations gave better predictions for the SPL, this is mainly because of the turbulence influence.

Figure 13 illustrates the influence of the boundary condition for the inlet of the jets. It can be noticed a significant difference in the SPL when utilizing a flat constant velocity profile or a variable velocity profile (simulating the boundary layer generated by the flow inside the nozzle) for the BC regarding the exhaust jet region. For the flat profile, the transfer of kinetic energy of the fluid motion into acoustic energy is greater than it should be, that is because the core of the jet is overestimated given rise to more noise sources (Ligthhill stress tensor) and hence over-predicting the SPL. This result evidence once more the need of a good RANS simulation of the flow problem.

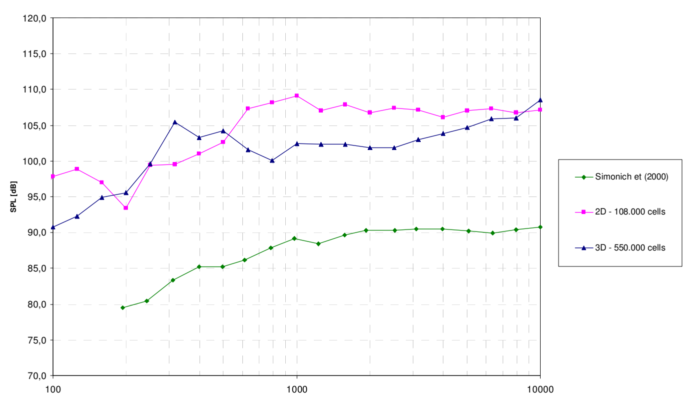


Figure 12. 2D vs 3D simulation.

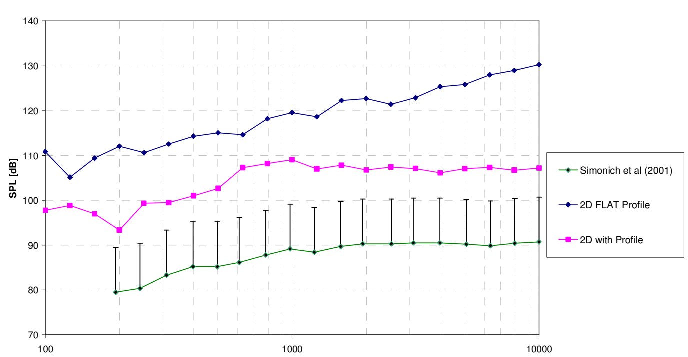


Figure 13. Jet Inlet Boundary Condition influence.

Figure 14 presents the acoustics results obtained with the two equation cubic k-epsilon model and with the RSTM (with Pope correction). The results obtained with the RSTM shows better sound pressure level predictions when compared with the cubic k-epsilon model. This can be understood when analyzing Fig. (6) once more, which presents the axial velocity distribution of the jet. The RSTM provided, for this flow problem, better predictions for the fluid dynamics of the jet flow (spreading rate) and hence identified (modeled) the noise sources more accurately for this simulation.

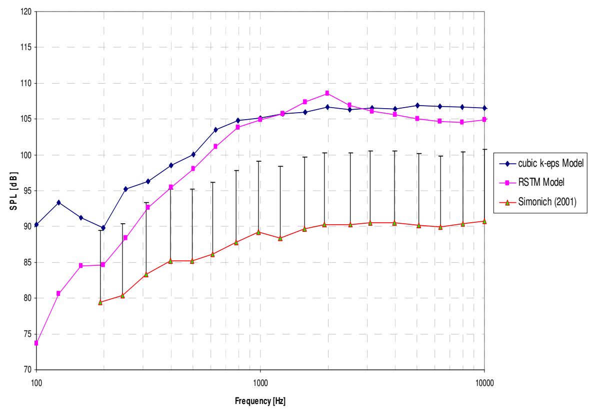


Figure 14. Turbulence modeling influence on the SPL.

Figure 15 presents the final results obtained with the wave propagation solver (waveprop1) available on the commercial software CAA++ for the subsonic jet Mach 0.9. These results were obtained by using the optimized parameters studied on this work (ideal mesh, $\Delta t = 2 \times 10^{-5}$s, total time of 1 second). The numerical results were compared against the experimental results obtained by Simonich *et al.* (2000) and with the SAE model.

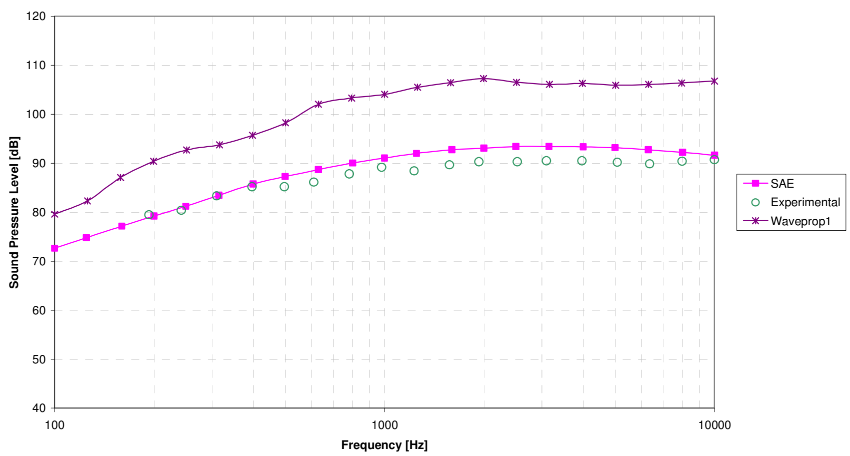


Figure 16. One third octave band for Mach 0.9 jet.

5. CONCLUSIONS

In the present work, an aeroacoustics analysis of the flow from single nozzles operating at subsonic speeds (Mach = 0.6 and 0.9) were conducted. In addition, an analytic wave propagation solver proposed by CAA++ has been presented in which a RANS solution is the basis of synthesized turbulence which is then used to evaluate source terms.

This work was focused on the understanding of methodologies for aerodynamic noise radiated by subsonic single jets. The results presented herein are preliminary, a more detailed study of the influences regarding the correct prediction of the fluid dynamics of the jet flow and the numerical are being conducted. However, the results presented in this paper provided the authors a relatively good insight of the phenomenology of noise generation by fluid flow. Additionally, most of the parameters influence on the numerical noise predictions were analysed (boundary conditions, mesh independency, turbulence modelling).

Although the numerical results presented in this work are not quantitatively representative of the experimental data (they are overpredicted by a constant value of approximately 10 dBs), qualitatively the behavior of the numerical curves was pretty similar to the experimental. This can be explained by the methodology concept utilized in this work, that is, the empirical wave propagation solver (waveprop1) is only an analytical wave propagator (it does not solve any transport equation). This implies that if the noise sources, which are calculated by the statistical information of the turbulence modeling, are not well predicted from RANS calculations the sound pressure level at a specific listener position will be not correctly. Even today, there is a need for more reliable turbulence models for the problem represented by subsonic jets.

6. ACKNOWLEDGEMENTS

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