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PREDICTION OF SOUND PROPAGATION EFFECTS OF INSTALLED JET CONFIGURATIONS AT SUBSONIC OPERATING CONDITIONS

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Abstract. *Aircraft noise is associated to noise pollution and various adverse effects on human health, thus representing an important barrier to the growth of aviation transport system. In this regard, developing numerical tools with improved predictive capabilities is crucial for noise reduction solutions. In this regard, the present work accounts for the development and evaluation of a sound propagation numerical model based on two-dimensional Ray-tracing method, which is able to predict major installation effects. These effects are inherent to under-wing-mounted engine configurations, originating from interaction between sound sources of exhausting jet and solid surfaces, such as wing and flap. This is accomplished by combining the fundamental Ray-Tracing equations with a sound reflection algorithm. The flow domain properties required to the numerical model, are previously calculated via Computational Fluid Dynamics (CFD) based on Reynolds Averaged Navier-Stokes (RANS). Acoustic rays, representing the sound energy of the flow sources, are launched from point sources, distributed throughout the jet, and their propagation paths are obtained by solving the Eikonal equation. The numerical tool was evaluated through qualitative analyses of the ray paths considering different flow conditions and wing-flap configurations. Based on the results, it was observed that the implementation of the new predictive capabilities substantially modified the behavior of the acoustic rays, resulting in more realistic propagation paths.*

Keywords: *jet noise, installation effects, ray-tracing, computational fluid dynamics, Eikonal equation.*

1. INTRODUCTION

The close proximity between jet engine and aircraft structures (wing, flap, etc.) in most recent aircraft designs can dramatically modify the aerodynamic pattern and affect the performance of noise suppression mechanisms, such as chevrons (Thomas and Kinzie, 2004; Bastos, et al., 2017). In this regard, being able to accurately predict the resultant sound field of different installed jet configurations at varied operating conditions is of great importance for aerospace industry (Casalino, et al., 2008; Ilário, 2011). This requires the development of fast prediction tools, which can account for complex phenomena occurring near the exhaust nozzle of a typical under-wing-mounted engine configuration.

An example of such numerical tool is the LRT method (Ilário, 2011), which combines an acoustic analogy based on Lighthill's formulation (Lighthill, 1952; Lighthill, 1954) and the ray-tracing method to predict refraction effects on the Sound Pressure Level (SPL) reaching an observer at the acoustic far field. This method, however, is used to evaluate isolated jets, not being able to account for jet-wing or jet-flap interactions.

In this paper, a sound propagation tool is proposed, which can be applied to evaluate the sound propagation of jets under isolated and installed condition. This is achieved by combining ray-tracing equations and a sound reflection algorithm. The numerical tool is here described and evaluated for different jet flow conditions.

2. COMPUTATIONAL PROCEDURE

2.1 Ray-tracing equations

The numerical tool proposed adopts a ray acoustics model described by Pierce (1989), which accounts for sound propagation discontinuities in an inhomogeneous fluid flow. The ray-tracing equations can be written in its indicial notation as follows:

$$\frac{dx_i}{dt} = \frac{c_0^2 s_i}{\Omega} + U_i \tag{1}$$

$$\frac{ds_i}{dt} = -\frac{\Omega}{c_0}\frac{\partial c_0}{\partial x_i} - \sum_{j=1}^{2} s_j \frac{\partial}{\partial x_i} U_j \tag{2}$$

where *x* is the Cartesian coordinate, *t* is the time variable, c_0 is the sound speed, and *U* is the velocity component. The other variables are the slowness vector *s*, and the omega Ω given by

$$s_i = \frac{n_i}{c_0 + \sum_{j=1}^{2} U_j n_j} \tag{3}$$

$$\Omega = 1 - \sum_{j=1}^{2} U_j s_j \tag{4}$$

where *n* is the normal vector of the ray emission point. Note here that the index of the summation operator represents the 2-dimensional case. Therefore, to simulate a 3-dimensional problem a *z* or third-dimension is needed.

Equations (1) and (2) are numerically solved by a standard 4th order Runge-Kutta method to obtain the coordinates of each ray launched from different locations in the flow field for any desired time.

2.2 Reflection algorithm

The reflection algorithm is the tool by which the rays will be able to have their trajectories modified when a ray intersects a surface. Differently from a code that would compute the ray paths for isolated jets, the installed condition requires the time marching to be breakdown into a loop. This loop enables the rays to be evaluated at each time step to check whether the intersection condition (Glassner, 1989) is satisfied for a specific step duration, and once a ray intersects a surface, its path is corrected following the Snell's Law principle by changing the direction of the slowness vector of the ray. When dealing with vector direction changes, the following rotation matrix is adopted:

$$R(\theta) = \begin{bmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{bmatrix} \tag{5}$$

Figure 1 shows an example of ray being reflected when it encounters a surface (flap), where θ represents the angle formed between the ray and the flap surface.

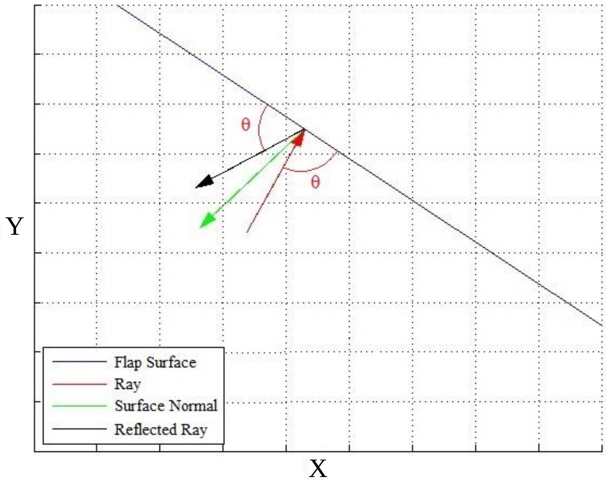

Figure 1. Specular reflection of a ray onto a flap surface.

2.3 Code structure

Figure 2 shows how the code was structured. It is worth mentioning that the flow properties required to solve the ray-tracing equations are obtained previously from a CFD RANS-based solver, which is discussed in the following section, and then used to feed the ray-tracing code by projecting/interpolating the CFD data onto a different grid. The code was implemented in MATLAB Release 2016b (2016).

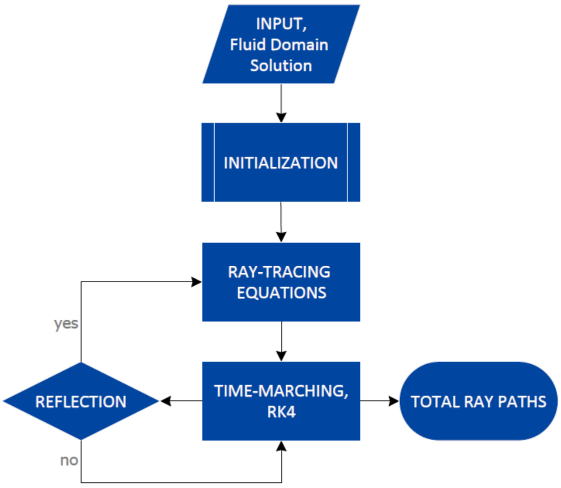

Figure 2. Code flowchart.

3. FLUID DOMAIN

This section presents the fluid domain used to evaluate the ray-tracing code. It is important to notice, however, that it is not the focus of this paper to enter in detail about the CFD solution procedures. For that matter, readers are encouraged to read the work done by Ilário (2011), Da Rosa (2013), and Souza (2015), to acquire more information.

The fluid domain presented here is a 2D representation of a simplified installed jet configuration, whereas the jet Mach number was setup as 0.9. The geometry of the wing and flap were defined as flat plates, where the flap presents a deflection of 25º with respect to the wing horizontal axis. The software FLUENT version 6.3.26 was used to run the flow simulation and the Standard k-ε model was applied for modelling the turbulence. Figure 3 depicts the *U* velocity (m/s) contour obtained for the fluid domain and in Fig. 4 is possible to observe the mesh used in the simulation.

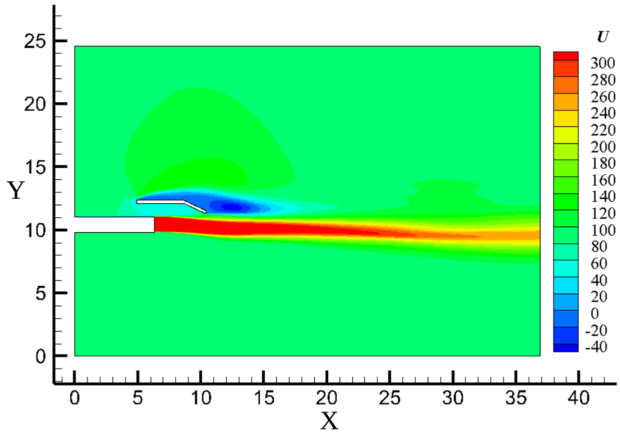

Figure 3. Fluid domain, *U* velocity contour.

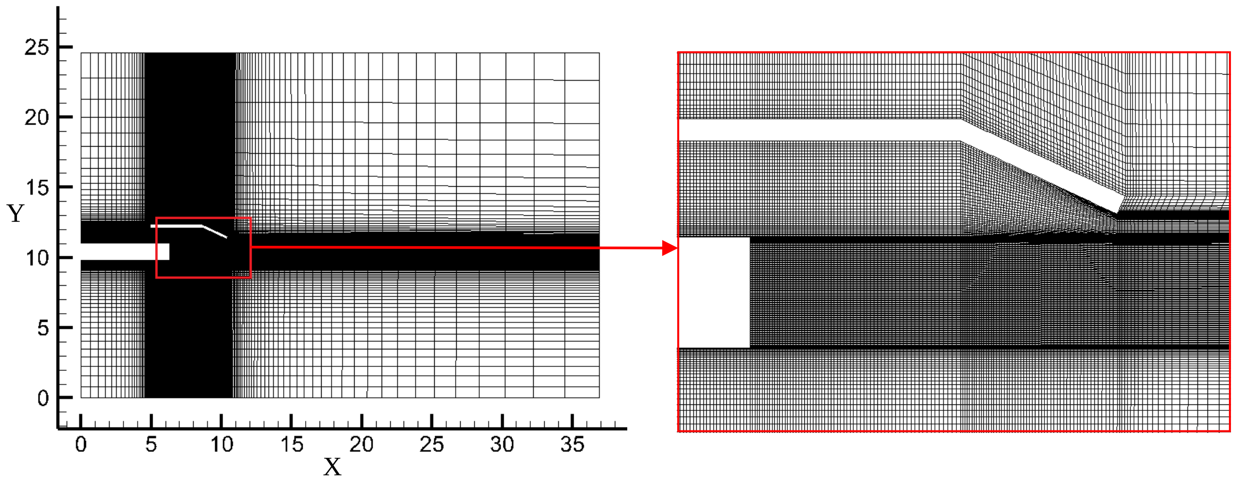

Figure 4. Structured mesh for the fluid domain.

4. RESULTS

The results obtained with the numerical model described herein show that ray paths are substantially modified by the presence of solid bodies (reflection effects) and by the temperature and velocity gradients (refraction effects). The first evaluation consisted of checking if the ray-tracing equations employed can generate the same results as a standard ray-tracing code, i.e., the rays should not suffer diffraction and convection effects when considering an isotropic and quiescent media. For that matter, the grid was set up with velocities components close to zero, and constant temperature. The results are shown in Fig. 5 and 6 for both, with and without the presence of solid surfaces, respectively; one can be observed in Fig. 5 that ray paths are not refracted throughout their trajectories, respecting the omnidirectionally expansion of the monopole source pattern that was implemented for the ray's emission. On the other hand, it is possible to see in Fig. 6 that the rays have their paths modified accordingly to the reflection algorithm (see section 2.2) when a surface is added inside the computational domain. Thereby, the acoustic rays maintain the straight-line pattern for the sound propagation.

The second evaluation regard the most complex case, the jet domain in the presence of a solid surface (see Fig. 3). For that, two ray sources were inserted in different regions of the jet shear layer. Figure 7 shows the resulting ray field being refracted due to the presence of velocity and temperature gradients throughout the fluid domain and the reflection effects of rays intercepting the solid surface. It is worth mentioning that for some jet flow conditions, acoustic rays can assume a pattern where they might reflect two or more times in the solid surface (high-order reflections). The code showed robustness to deal with such conditions. In addition, the effect of rays that are trapped inside the jet region was also observed as well as the refraction pattern, resembling the behavior of rays for isolated jet conditions. This behavior is consistent with the pattern noticed by other authors (Freund and Fleischman, 2002; Mclaughlin, 2010). The pattern formed by the rays seem to agree to what is observed in terms of noise perception between isolated and installed jet conditions, since it is known that higher noise levels are experienced in the latter case (Mead and Strange, 1998;

Mclaughlin, 2010; Ilário, 2011). Therefore, the higher density of rays at the lower section of the vertical axis in Fig. 7 indicates a promising future in relation to the noise predictions using this tool.

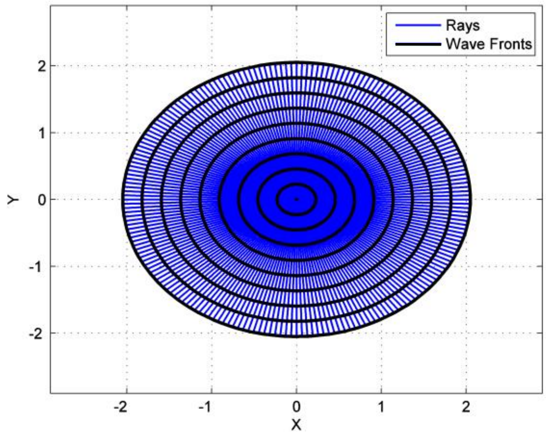

Figure 5. Ray paths and wave fronts in an isotropic and quiescent media without solid surfaces.

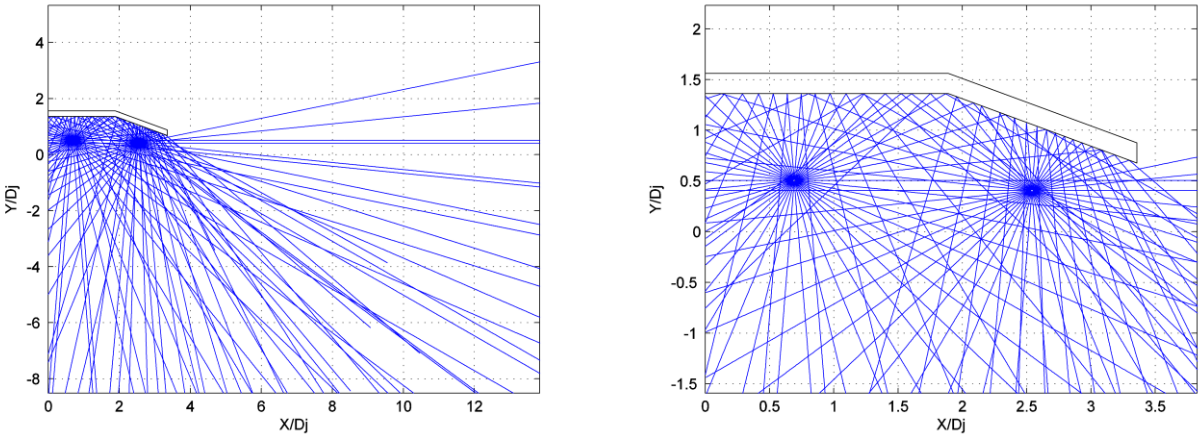

Figure 6. Ray paths in an isotropic and quiescent media with solid surfaces (wing and flap).

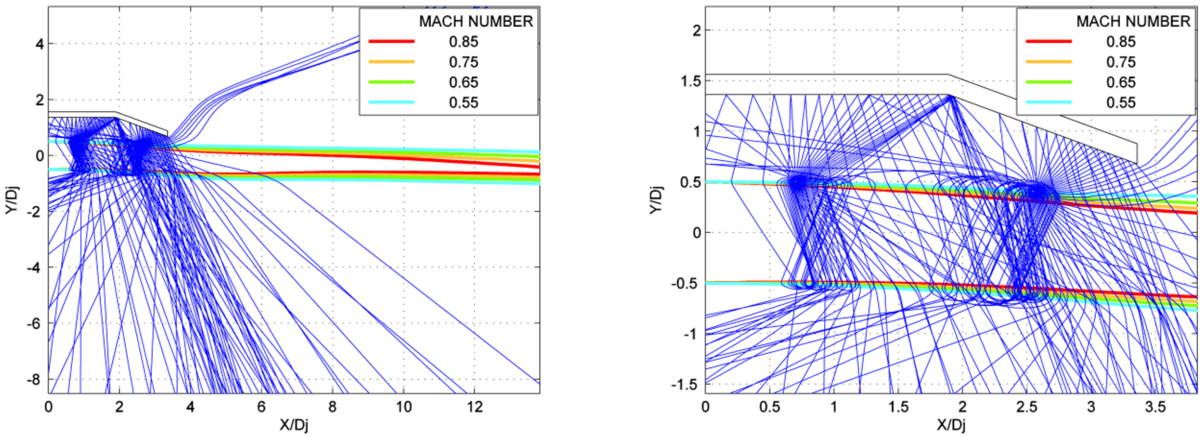

Figure 7. Ray paths in a moving inhomogeneous media with solid surfaces (Dj : jet diameter).

5. CONCLUSION

A ray-tracing code able to account for sound propagation effects on installed jet configurations has been developed. The approach was tested considering different jet operating conditions, from isotropic and quiescent media (linear acoustics) to moving inhomogeneous media with solid surfaces (installed jet configuration). The predictive capabilities of the newly developed numerical tool showed that the medium characteristics and the presence of solid surfaces can greatly change the ray paths, modifying the resulting sound field. This is clearly observed by comparing Figures 5 and 7, which represents the simpler and the more complex case, respectively. For all cases, the rays described trajectories that comply to what was expected from a geometry point of view for the physics of the reflection. Finally, it was found that the rays behave in a similar fashion as reported in the literature for the cases of isolated jet configurations. This represents an important improvement towards a ray tracing model that can accurately predict the far field noise of under-wing-mounted engine configurations.

6. REFERENCES

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7. RESPONSIBILITY NOTICE