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NUMERICAL PREDICTION METHODS FOR THE ASSESSMENT OF AERODYNAMIC SOUND GENERATION ON HIGH SPEED TRAINS

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ABSTRACT
Numerical models are developed to predict the sound generated by various aeroacoustic sources encountered on high-speed trains. These models use statistical information about the flow field obtained from a k-ε code (STAR-CD) and are validated by experimental data. Classical aeroacoustic analogies are applied to free stream turbulence whereas specific models are adapted to geometrical singularities such as steps or blunt trailing edges. Measurements of the acoustic far field and sources localizations compare favorably with the computations.

1 - INTRODUCTION

Aerodynamic sound generation becomes a major concern in ground transportation when speeds reach 250 km/h. On high speeds trains, aeroacoustic sources are due to the flow perturbations induced by geometrical singularities on one hand and to the turbulent boundary layers on the other hand. In order to predict aerodynamic sound the flow has to be known very accurately: it is the flow unsteadiness, which is responsible for the sound generation. Therefore it is important to get an insight into the unsteady flow field if the sound is to be computed. Unfortunately, unsteady CFD (computational fluid dynamics) is still in its infancy, and is not yet ready to handle with enough accuracy complex geometries at high Reynolds numbers such as those encountered on trains. As a result, computational approaches based on Random Averaged Navier-Stokes (RANS) equations are still much used in the industry. These methods provide only statistical information about the turbulent flow and thus some modeling efforts are required in order to recover the flow unsteadiness. However, so-called unsteady RANS computations are now possible: these approaches capture low frequency variations which are not turbulent. They are helpful whenever there is a coherent mechanism in the flow such as vortex shedding by a pantograph or a blunt trailing edge.
In the present paper, aeroacoustic models for different types of sources are shown: broadband random sources due to the turbulent flow including geometrical singularities and coherent tonal source due to vortex shedding.

2 - SOUND AND FLOW COMPUTATIONS

2.1 - Sound generated by turbulence

The instantaneous sound generated by a subsonic isentropic non-viscous flow is obtained by a space-time convolution of Lighthill's quadrupole source [1] with an appropriate Green function. This formulation requires an exact space-time representation of the flow, since the source term involves the fluctuating velocity. When only statistical parameters of the flow are known, the mean sound intensity and its spectrum can be obtained by computing the density autocorrelation. Ribner [2] wrote a simplified expression of the acoustic far field for free parallel shear flows. He modeled space-time correlations according to turbulence theory and to experimental evidence. As a result, the flow dependence of the radiated sound comes down to a few parameters: the mean velocity components and mean turbulence parameters (mean square velocity fluctuations $u'^{\,2}$, integral length scale L and eddy turn-over time) can be computed from a k- ε code. Although it is extremely simplified, this model applies successfully to free jets [2], [3]. In this formulation a plane wall can be taken into account by using the half space Green function. The contribution of a unit flow volume located at a distance y_s from the wall to the far field at an angular frequency ω is then:

$$I(\omega) = K\left(A_\omega L^3 u'^4 + L^5 u'^2 P_\omega(\cos\theta, \sin\theta) \times \left(1 + \cos\left(\frac{2\omega y_s \sin\theta}{c_0}\right)\right)/R^2\right) \quad (1)$$

where R and θ are the observation distance and the angle relative to the mean flow direction, c_0 is the speed of sound, A_ω and the coefficients of P_ω are known functions of the geometry and mean flow parameters, K is an adjustable constant. This expression is the product of a free field term and a frequency dependent term due to wall reflections [4]. The intensity spectrum is obtained by integrating this function over the whole flow. The total intensity is obtained by integrating over all frequencies.

2.2 - Effect of geometrical singularities on broad band noise

Singularities such as steps amplify the sound radiation of nearby turbulent eddies and modify their directivity. Howe [5] developed a model based on the plane wall pressure spectrum given by Chase [6]. By applying a conformal mapping Howe found an expression for the intensity spectrum in the case of a turbulent boundary layer flow over a forward facing step. If the step of height h is acoustically compact, the related sound intensity comes down to:

$$I = \mathrm{Kh}\frac{\mathrm{U}^2\mathrm{u}'^4}{\mathrm{R}^2}\cos^2\theta \quad (2)$$

where U is the mean free stream velocity of the incoming flow and u' the local rms value of turbulent velocity fluctuations. R and θ are the observation distance and angle relative to the singularity and the mean flow direction. The constant K depends on physical constants and on the relation between the free flow and near wall flow. Since u' scales on U, I scales on U^6.

2.3 - Pure tone radiation

Some flows give rise to pure tone radiation. It is often due to flow instabilities which occur at discrete frequencies and generate organized flow patterns. This is typically the case of vortex shedding by blunt trailing edges such as the rear end of trains which radiate sound at preferred Strouhal numbers. Corresponding source models require a description of the slow mean flow fluctuations. According to Blake [7], for a 2-D configuration the sound intensity of a flat plate compact trailing edge is related to the mean streamwise velocity U and the vortex circulation Γ by the following relation:

$$I = KM\Gamma^2\sin^2(\theta/2)\frac{L}{hR^2}U^2 \quad (3)$$

M is the Mach number, h the plate thickness, L its spanwise extent, R and θ the observation distance and angle relative to the edge and the mean flow direction. K is a constant that depends on the vortex convection speed, the excess speed induced by the vortices and the transverse distance between vortices shed from opposite sides of the plate. Since M and Γ scale on U, the intensity varies as U^5.

3 - VALIDATION

Validation experiments are carried out for the various source types in 2-D flow in the large anechoic room of the Ecole Centrale de Lyon. Source models for turbulence noise (eq. (1)) were validated for free jets [3] and for wall jets [4].

3.1 - Backward facing steps

The step is a test case for the source model (eq. (2)). On a TGV it is useful for the study of singularities like the pantograph cavity which can be modeled as a forward facing step in the far wake of a backward facing one [8]. The computation of turbulence noise alone explains only part of the sound radiated by a step because of the edge diffraction [9]. If the source model (eq. (2)) is applied together with Ribner's model (eq. (1)) to a backward-facing step under a wall jet, a good estimate of the sound level and directivity is obtained. This is illustrated on Figure 1 which was obtained for an h=4 cm step 1 m downstream of the nozzle of a wall jet (cross-stream extent e= 5 cm). For all flow speeds the directivity and the U^6 power law of the source model feature quite well the real behavior. Figure 2 shows the source locations for various frequencies obtained with acoustic near field measurements: the step source is located about $3h$ downstream of the edge (x=0) where highest turbulence levels are observed. It radiates between 0.5 and 3 kHz. The upstream sources are due to the wall jet.

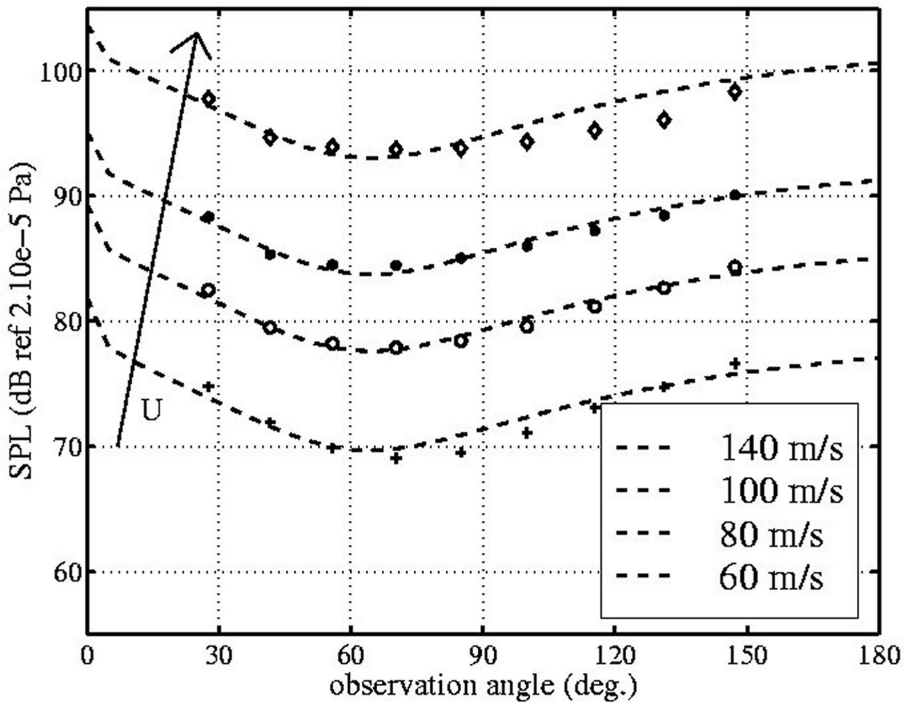

Figure 1: Directivity of a backward facing step under a wall jet (—: num., symbols: exp.).

3.2 - Blunt trailing edge

The source model of § 2.3 is validated for an h=5 cm thick plate with a squared-off blunt trailing edge placed in a channel: the edge is in a test section with acoustically transparent walls to allow acoustic far field measurements. Vortex shedding is computed with unsteady RANS. Computed and measured Strouhal numbers associated to the shedding frequency are in excellent agreement (0.22 and 0.23 respectively). Figure 3 shows the vorticity contours in the near wake for a 100 m/s incoming flow. The circulation of the first shed vortex is taken for the sound computations (the contour is the broken line on the plot). Experimental and numerical directivities are compared on Figure 4. A good agreement is found at high angles where levels are highest. At small angles significant discrepancies appear: they are due to low frequency spurious sources in the experiment that are not modeled in the computations. However the U^5 power law predicted by the source model is confirmed experimentally.

4 - CONCLUSION

Aeroacoustic prediction methods based on RANS computations can be applied to complex geometries encountered on high-speed trains. The information loss between the real flow and the one computed with RANS is recovered by only a few adjustable constants which can be tuned independently for each type of source. They do not depend on the particular configurations (step height, flow velocity ...). Thus they can be applied to the acoustic design of trains and give a good estimate of the way particular elements of the train contribute to the overall sound radiated by the train. This study is not exhaustive: further models have to be included to account for resonant cavities, pantographs and bogies.

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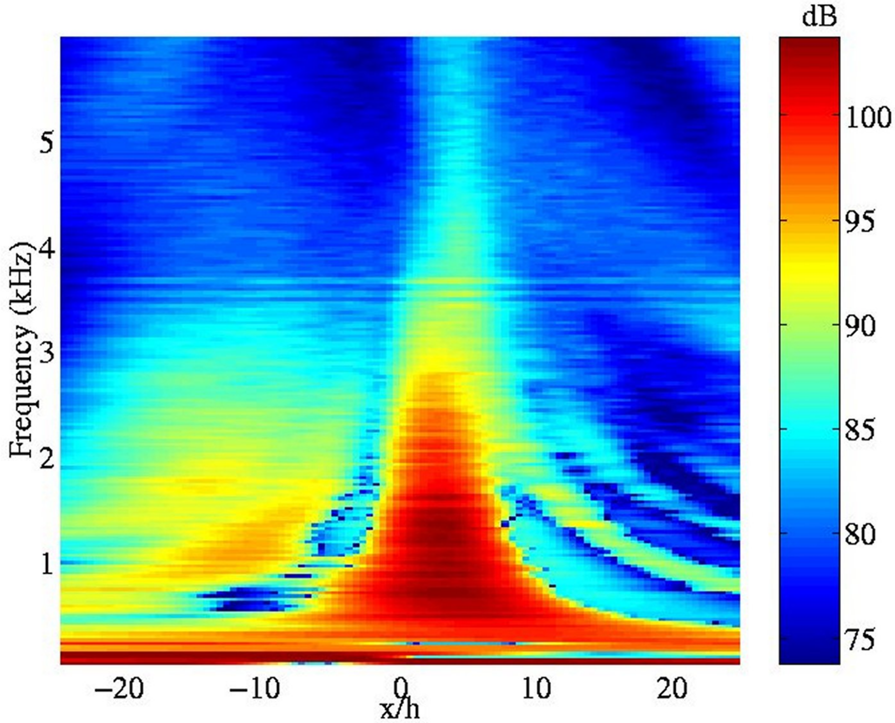

Figure 2: Source locations for the step (step edge at x=0; h=4 cm; speed: 140 m/s).

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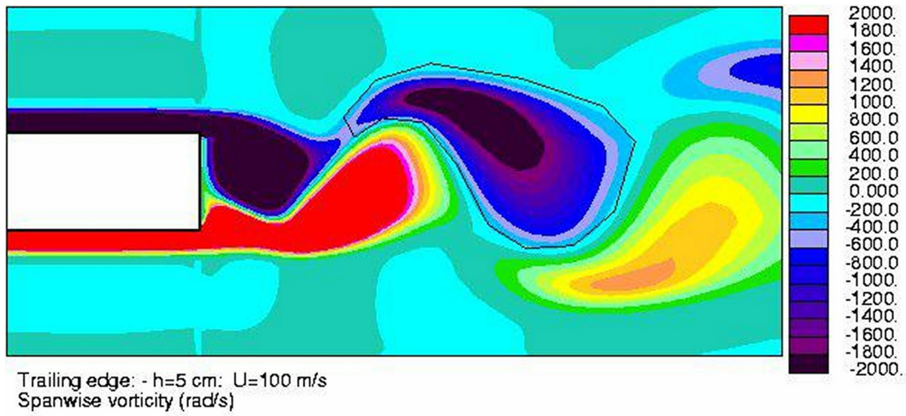

Figure 3: Vorticity contours in the near wake of an h=5 cm trailing edge at 100 m/s.

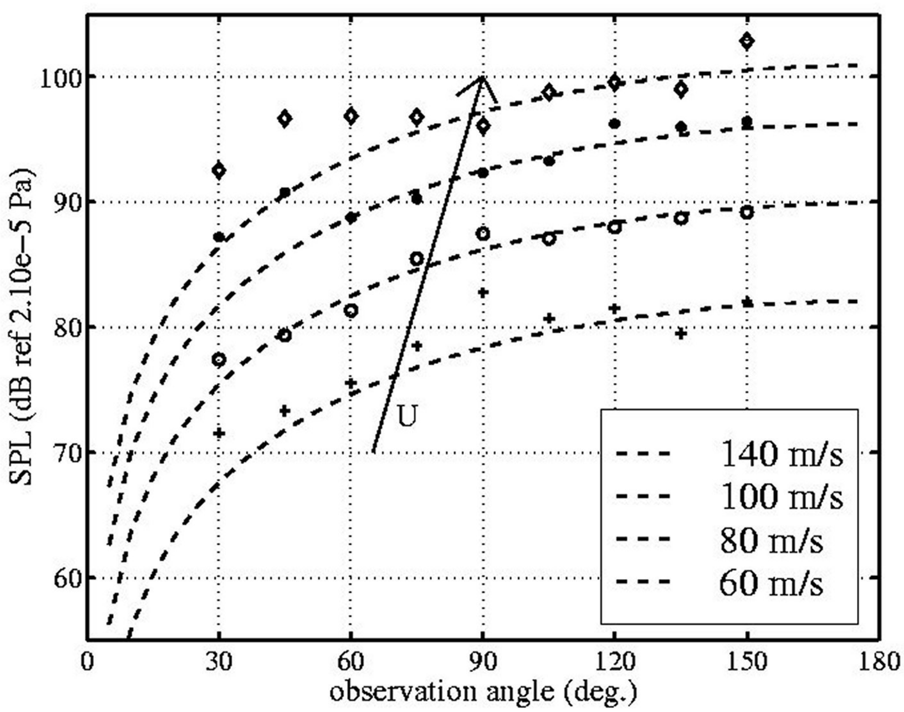

Figure 4: Directivity of an h=5 cm trailing edge (—: num.; symbols: exp.).