A new acoustic imaging method for duct spinning mode with microphone arrays

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ABSTRACT

Research of duct acoustics has practical importance in low noise turbofan engine design. [Castres and Joseph(2007)] Various analytical [Gabard and Astley(2006)] and numerical methods [Rienstra and Eversman(2001)] have been developed, particularly for spinning modes at a tonal frequency, to give insights of the particular acoustic physics of the sound transmission and radiation. It could be interesting to visualize acoustic images of spinning modes in a duct cross section in real-time. Advanced signal processing theory was considered in this work to achieve the objective. A new testing method was developed and proposed that constitutes the main contribution of this paper.

The fundamental idea behind the proposed method shares the same theoretical background of previous works in real-time acoustic beamforming of coherent noise sources. [Bai and Huang(2011)] However, the noise sources discussed in this work are spinning modes, having a relatively more complex propagation model. The model was formulated in a modern control form and a so-called observer was designed to infer acoustic velocities and pressures from the in-duct circular array measurements.

The perturbations of acoustic pressure, density and velocities, (p', ρ', u', v', w') are generally small compared with the background mean flow variables ($p_0, \rho_0, u_0, v_0, w_0$). Sound wave propagation can thus be simply modeled by linearized Euler equations. The acoustic disturbances can be represented by Fourier series in terms of azimuthal modes m. For example, the acoustic pressure has the form of $p' = \sum_{m=-\infty}^{\infty} p'_m(x,r,t)e^{-im\theta}$. For a uniform mean flow $(u_0, 0, 0)$ in the engine duct, the three-dimensional LEE are

$$\frac{\partial \rho'_m}{\partial t} + u_0\frac{\partial \rho'_m}{\partial x} + \rho_0\left(\frac{\partial u'_m}{\partial x} + \frac{\partial v'_m}{\partial r} + \frac{v'_m}{r} + \frac{\partial w'_m}{r\partial \theta}\right) = 0, \quad (1)$$

$$\frac{\partial u'_m}{\partial t} + u_0\frac{\partial u'_m}{\partial x} + \frac{\partial p'_m}{\rho_0 \partial x} = 0, \quad (2)$$

$$\frac{\partial v'_m}{\partial t} + u_0\frac{\partial v'_m}{\partial x} + \frac{\partial p'_m}{\rho_0 \partial r} = 0, \quad (3)$$

$$\frac{\partial w'_m}{\partial t} + u_0\frac{\partial w'_m}{\partial x} + \frac{\partial p'_m}{\rho_0 r \partial \theta} = 0, \quad (4)$$

where all variables are nondimensionalized using a reference length, a reference speed, and a reference density.

A so-called observer-based method can be conduced as follows to visualize the acoustic images.
Step 1: Measurements of the sound pressure are generated by the circular sensor array installed on the outer wall.

Step 2: The observer is conducted to extract the approximation of sound parameters, such as ρ', u' etc.

Step 3: Step 2 is instantaneously conducted for each samples. The observation error $(\mathbf{y} - \hat{\mathbf{y}})$ is examined.

Numerical simulations are conducted for a tonal sound of a single spinning mode to validate the proposed method. Figure 1 shows the good reconstruction. Practical systems generally include various spinning modes at broadband frequencies, which can be decomposed to a tonal single spinning mode by Fourier transform and mode detection. After that the proposed method can be applied to each component to reconstruct the related acoustic field. More details of the proposed method and computational validations will be presented in the conference.

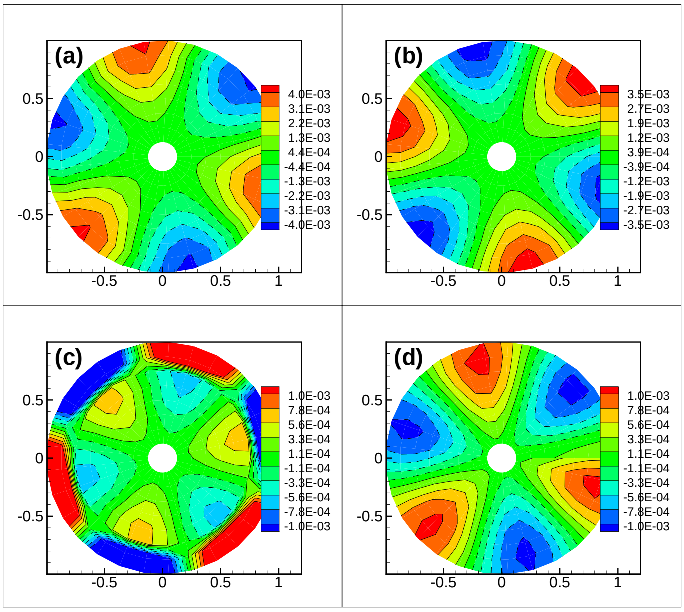

Figure 1: Observer solutions of the cross section at $x = 0.1$ from the spinning mode sound source, where $t = 10$, $(m, n) = (3, 1)$, $k = 400$, (a) $\hat{\rho}'$, (b) $\hat{u}'$, (c) $\hat{v}'$ and (d) $\hat{w}'$.

Keywords: low-noise engine, spinning mode, acoustic imaging, linearised Euler equations.

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