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Broadband noise prediction using large eddy simulation and a frequency domain method

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ABSTRACT

A new LES-acoustic analogy method for accurate flow and broadband noise prediction is proposed. A frequency domain method for the generalized Lighthill acoustic analogy theory is derived in detail and the final equations for code is provided which can help to bridge the gap between the flow field prediction and the acoustic field prediction for those who are interested in acoustic results but lack of acoustic prediction ability. The hybrid method (LES and acoustic analogy method) for broadband noise prediction is validated using the rod-airfoil interaction problem. Both flow field results and acoustic field results are compared with experimental results and other numerical results in detail. The flow field results agree very well with the experimental results and other numerical results. The predicted acoustic results and experimental results also reach good agreement both in far field acoustic pressure Power Spectral Density (PSD) and noise directivity. The method developed in the paper proves to be an effective tool for broadband noise prediction. In addition, the different span correction methods for the acoustic pressure spectrum are also discussed.

1. Introduction

The strong market demand for quieter aircraft encourages airplane and turbo engine manufacturers to provide more environmentally friendly and quieter aircraft and turbo engines. Noise prediction capability is of great importance for the design of future aircraft and turbo engines to make sure that the increasingly more rigorous regulations can be met.

Turbo engine noise involves tonal noise and broadband noise. For modern ultra-high by-pass ratio engines, fan noise is becoming more and more significant. The tonal part of the fan noise and the broadband part of the fan noise both carry about half of the sound power. The underlying generation mechanism of fan tonal noise is relatively well understood. However, the fan broadband noise generation mechanism is much more complicated and only partly understood. And for military aircraft, the broadband noise from the exhaust jet often dominates all other sources. Therefore, broadband noise is of great academic and technical importance.

There are several methods to predict broadband noise: empirical prediction models [1–3], analytical prediction models [4,5], fully numerical prediction methods [6] and hybrid prediction methods [7–10]. Empirical prediction models are generally simple and fast but they cannot assess the acoustic performance between different detailed designs of engine components since they can only associate a few parameters. The analytical prediction models can provide satisfactory results fast. Nevertheless, they cannot guide the detailed designs due to the many simplifications. Fully numerical prediction methods can provide flow-to-far field simulations with little simplification of the geometry. However, they require huge computational resources. The hybrid prediction methods, which use CFD (like LES, DES, URANS) to obtain noise sources information and use acoustic analogy [11–14] to obtain far field acoustic information, can take detailed design parameters into consideration and require much less computational resources compared with fully numerical prediction methods. For these reasons, the hybrid prediction methods are very promising methods to predict aircraft/engine broadband noise.

In order to predict noise sources, especially broadband noise sources, highly accurate unsteady CFD solutions must be obtained. LES numerical method is adopted in this study. The rod-airfoil configuration is particularly suitable for the assessment of CFD codes in modeling broadband noise sources. Its relevance has been thoroughly discussed by Jacob et al. [15]. The rod-airfoil configuration combines the periodic vortex shedding with a random

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perturbation due to the wake's transition into turbulence. The airfoil undergoes a broadband perturbation which is dominated by a preferred shedding frequency, somewhat like that observed in turbomachinery applications. The ability of a combined CFD/acoustic approach to predict the spectral broadening around the shedding frequency and its harmonics is a relevant measure of its ability to model broadband sources [15]. Due to these reasons, the rod-airfoil configuration is widely used for assessing the different CFD/acoustic approaches. Casalina et al. [16] used 2D unsteady RANS combined with FW-H equation to predict rod-airfoil interaction noise. The vortex shedding frequency is significantly over predicted. Magagnato [17] and Boudet et al. [8,18] performed the first 3D LES on rod-airfoil interaction noise. Boudet's LES was performed with the Turb'Flow code and the near field is in good agreement with experiment. However the far field acoustic results are poorly converged. Peth et al. [19] used LES and the Linearized Perturbed Compressible Equations (LPCE) to predict rod-airfoil interaction noise. The shedding frequency is slightly under-predicted and the far field pressure Power Spectral Density (PSD) peak is under predicted by 5–7 dB. More recently, Jacob et al. [20], Giret et al. [7] and Greschner [9] also carried out detailed analysis of rod-airfoil interaction noise prediction.

Many researchers have validated their in-house codes using this benchmark case and most of their acoustic analogy methods are based on time domain method [7–9,10,20]. At the same time, although many of the CFD solvers have demonstrated impressive ability in flow field prediction, the accurate prediction of aeroacoustic noise, especially broadband noise, is a more challenging work compared to steady or unsteady flow field predictions. Because of this, only a few CFD solvers have integrated the basic noise prediction ability, for example the familiar Fluent solver. Whereas there are also many CFD solvers whose noise prediction ability is limited and not mature (e.g. CFX). Obviously, developing the broadband noise prediction tools will help to extend CFD solvers' functionality and add our option and freedom. Epikhin [21] presented a Dynamic Library for computational aeroacoustics applications using the OpenFOAM source package, however, the details of the method are not available which may hinder its further application and development by others. Moreover, the Dynamic Library is specific for OpenFOAM source package. For other codes the Dynamic Library does not work. Therefore, there is a need to develop a broadband noise prediction tool for various CFD codes which are not ready for direct broadband noise prediction.

The current study proposed a new LES-acoustic analogy method for accurate flow and broadband noise prediction. A frequency domain method for generalized Lighthill acoustic analogy theory is derived in detail. Compared with time domain method, the frequency domain method has several advantages. For time domain methods, the determination of the retarded time is computationally intensive. In addition, the variables and their time derivatives must be interpolated to the retarded time for every grid point, retarded time and observer position, which also leads to intensive calculation. In contrast, frequency domain methods are more computationally efficient. The frequency domain methods can be carried out further faster when harmonic noise is of interest where only several selected frequencies need to be calculated. In this paper, the final equations of the frequency domain method for code are also provided which can help to bridge the gap between the flow field prediction and the acoustic prediction for those who are interested in acoustic results but lack of acoustic prediction ability. The code of the frequency domain method is then successfully validated through the comparison with experimental results and other numerical results.

2. Methodology

2.1. Numerical method for flow field

LES is used to compute the broadband noise sources with the commercial code CFX [22]. In LES, the large three-dimensional unsteady turbulent motions are directly represented, whereas the effects of the smaller-scale motions are modelled. The rationale behind LES technique is a separation between large and small scales. Large scales of the flow contain the main part of the total fluctuating kinetic energy and characterize the flow. The driving physical mechanisms are carried by the large scales. The large scales of the flow are sensitive to the boundary conditions and so are anisotropic [23]. In contrast, small scales of the flow contain only a few percent of the total kinetic energy and have weak influence on the mean movement. Their main function is viscous dissipation, however, they can also have an effect on higher scales. In LES, the unresolved small scales of the flow may be isotropic or anisotropic which depends on the user and how they decided to model the unresolved scales. A filtering operation is defined to decompose the flow variable Φ into the sum of a filtered (or resolved) component $\bar{\Phi}$ and a residual (or subgrid-scale, SGS) component Φ'. The equations for the filtered field can be derived from the Navier-Stokes equations, however a closure problem arises because of the SGS stress tensor. The closure can be obtained by modeling the SGS stress tensor.

There are several methods to model the SGS stress. Smagorinsky proposed the original Smagorinsky model [24], Nicoud and Ducros proposed the WALE model [25] (wall-adapted local eddy-viscosity model), Germano and Lilly presented the Dynamic Smagorinsky-Lilly model [26,27]. The Smagorinsky model and WALE model are algebraic models and the model coefficient is constant. In contrast, the Dynamic Smagorinsky-Lilly model uses information contained in the resolved turbulent velocity field to evaluate the model coefficient. Thus, the model coefficient is no longer a constant value and adjusts automatically to the flow type. In this paper, the Dynamic Smagorinsky-Lilly model and the Second Order Backward Euler transient scheme are adopted.

2.2. Numerical method for acoustic field

The acoustic prediction method is based on Goldstein's generalized Lighthill equation [14]. Goldstein extended Lighthill's acoustic analogy to include the effects of solid boundaries and moving medium. The fundamental equation governing the generation of sound in the presence of solid boundaries is presented below with slight changes to its original form for the current application.

$$c_0^2\rho'(\vec{x},t) = \int_{-T}^{T}\int_{A(\tau)}\rho_0 V'_N \frac{DG}{D\tau}dA(\vec{y})d\tau + \int_{-T}^{T}\int_{A(\tau)} f_i\frac{\partial G}{\partial y_i}dA(\vec{y})d\tau + \int_{-T}^{T}\int_{v(\tau)} T'_{ij}\frac{\partial^2 G}{\partial y_i \partial y_j}d\vec{y}\,d\tau \quad (1)$$

where c_0 is the ambient speed of sound and ρ' is the acoustic density disturbance. At sufficient distance from the source, $c_0^2\rho'$ is equal to the acoustic pressure p'. $\vec{x} = (x_1, x_2, x_3)$ is the observation coordinate and $\vec{y} = (y_1, y_2, y_3)$ is the source coordinate. τ is the source time (retarded time). V'_N is the velocity of the surface normal to itself relative to the fluid. The first term in Eq. (1) represents the sound generated due to volume displacement effects of the surface, the second term represents the sound generated due to the exertion of unsteady forces by the boundaries on the fluid, and the last term represents the generation of the sound by volume sources. In each