Journal of Sound and Vibration 411 (2017) 60–74

Contents lists available at ScienceDirect

Journal of Sound and Vibration

journal homepage: www.elsevier.com/locate/jsvi

Aerofoil broadband and tonal noise modelling using stochastic sound sources and incorporated large scale fluctuations

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ARTICLE INFO

Article history:
Received 7 March 2017
Received in revised form 30 June 2017
Accepted 16 August 2017

Keywords:
Broadband and tonal noise
Aerofoil noise
Synthetic turbulence
FRPM
Blunt trailing edge
Vortex shedding

ABSTRACT

The present work discusses modifications to the stochastic Fast Random Particle Mesh (FRPM) method featuring both tonal and broadband noise sources. The technique relies on the combination of incorporated vortex-shedding resolved flow available from Unsteady Reynolds-Averaged Navier-Stokes (URANS) simulation with the fine-scale turbulence FRPM solution generated via the stochastic velocity fluctuations in the context of vortex sound theory. In contrast to the existing literature, our method encompasses a unified treatment for broadband and tonal acoustic noise sources at the source level, thus, accounting for linear source interference as well as possible non-linear source interaction effects. When sound sources are determined, for the sound propagation, Acoustic Perturbation Equations (APE-4) are solved in the time-domain. Results of the method's application for two aerofoil benchmark cases, with both sharp and blunt trailing edges are presented. In each case, the importance of individual linear and non-linear noise sources was investigated. Several new key features related to the unsteady implementation of the method were tested and brought into the equation. Encouraging results have been obtained for benchmark test cases using the new technique which is believed to be potentially applicable to other airframe noise problems where both tonal and broadband parts are important.

1. Introduction

Aerofoil noise, or the noise generated by scattering of hydrodynamic field in the turbulent boundary layer close to the wing trailing edge, has been a subject of investigation since 1970s [1,2]. In recent years, this classical problem has kept attracting attention [3–6] and despite the availability of several experimental databases [7–9], an understanding of trailing edge noise mechanisms leading to robust scaling laws is still lacking.

Numerical modelling of aerofoil noise based on unsteady computational fluid dynamics approaches such as Large Eddy Simulation (LES) or Direct Numerical Simulation (DNS) came into practice in 2000 [10,11]. Since then, there have been approaches of various validity and complexity used for modelling the unresolved near-wall turbulence or directly resolving this for low Reynolds number flows [4,12–16]. For acoustic modelling, there has also been a range of formulations of various

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http://dx.doi.org/10.1016/j.jsv.2017.08.036

complexity used starting from Ffowcs Williams-Hawkings (1969) [17] and Amiet's theory (1976) [18] to solving the Acoustic Perturbation Equations (APE) [19] and performing direct noise computations [20,21].

A serious limitation of using LES for trailing edge noise modelling is their restriction to relatively low Reynolds numbers due to prohibitively high computational cost of resolving the boundary layer turbulence. This limitation has resulted in a very little use of LES in support of existing experimental aerofoil noise campaigns or industrial design processes where the computational cost is further increased due to the geometrical complexity. Therefore, attention turned to methods with a fast turnaround time, such as Reynolds-Averaged Navier-Stokes (RANS) simulations that evolved through 1990s and by the end of the decade were extensively used to obtain a time-averaged flow prediction for a wide variety of industrial problems with varying degrees of success. Despite its drawbacks in transition modelling and inability to accurately model the separation, RANS methods can provide a quick prediction for high Reynolds number flows typical to many industrial problems and therefore, these tools remain commonly used to the present day. Compared to LES the validity of acoustic prediction schemes based on RANS strongly depends on the model calibration. This also applies to hybrid RANS/LES methods [22] where a calibrated transition from one scheme to another needs to be performed.

In the context of trailing edge noise modelling, URANS simulations have been used to predict the tonal noise generated by a bluff body vortex generator attached to an aerofoil boundary close to the trailing edge [23]. Pure tonal noise prediction schemes based on URANS were applied for multi-blade configurations in turbo-machinery, for example, in application to fan noise [24] and turbine noise [25] modelling with a reasonable computational efficiency. However, the ability of such schemes to provide reliable tonal noise predictions through estimating an isolated vortex shedding characteristic is rather questionable.

For broadband noise predictions, the stochastic Fast Random Particle Mesh (FRPM) method was developed [26–29] which can predict sound generated by turbulent flows over a wide range of Reynolds numbers. The approach is based on using RANS flow solution to generate synthetic turbulence whose statistics that matches the RANS calculation. The synthetic turbulence fluctuations obtained are then, typically, substituted into the right-hand-side sources of some acoustic formulation, the same way as the LES fluctuations would be, to propagate the acoustic solution to the far field.

More recently, the FRPM method together with APE for sound propagation was used [30] for fast-turn-around time acoustic calculations in the framework of Altus solver that is a proprietary code of BAE Systems. The solver applies the FRPM method on a Cartesian grid with the flow field interpolated from the RANS calculation to generate the sound sources. The sources are then interpolated onto an unstructured grid of general complexity around a scattering body to solve a set of Acoustic Perturbation Equations (APE-4 formulation) [19] using a high-order Quadrature-Free Discontinuous Galerkin method and the ADER scheme for time integration [31]. This solver is further developed to be used in the current work for broadband and tonal noise predictions.

Importantly, unlike the LES-based noise prediction schemes [32], which automatically account for all types of noise sources in the flow solution, the original FRPM model can only simulate broadband fluctuations which are generated by the stochastic particles moving with the time-averaged RANS flow field. For example, the original FRPM model cannot include any unsteady flow features such as vortex shedding or pairing which would produce tones in the noise spectra. However, under the scale separation assumption between the high-frequency turbulence fluctuations and the low frequency tones typical of the URANS solution methods, the tones should also be possible to incorporate in the corresponding acoustic prediction scheme.

Recently, an attempt to combine the FRPM method with a URANS solution for improved broadband noise predictions called U-FRPM method was developed for a centrifugal fan noise problem [33]. However, the underlining acoustic formulation used in that work remains unclear. For example, the U-FRPM model appears to be based on simply adding up squares of two far-field pressure amplitudes, one being the broadband signal from FRPM and the other is the tonal signal from a separate steady-state model, to obtain the final power spectral density amplitude at the far-field observer location. Thus, first of all, this approach requires two acoustic calculations of the sound propagation to the far field for a single flow case that may be expensive. Moreover, such simplified treatment does not only ignore any possible nonlinear source interaction but also neglects any acoustic interference of the different source components that are assumed to be uncorrelated at the far field despite sound propagation effects, which assumption needs to be verified.

The current work is devoted to developing a consistent modelling framework for combining the flow scales responsible for the broadband and tonal noise generation at the source level in the FRPM scheme and implementing it in an engineering code such as ALTUS. The article is organised as follows:

- In Section 2, the governing acoustic formulation based on the APE is presented. The FRPM method and the numerical setup based on the RANS $k-\omega$ *SST* [34] model and the finite-element solution of Acoustic Perturbation Equations are briefly reviewed.
- In Section 3, basic numerical model verification results are presented. First, the RANS flow solutions for two benchmark trailing edge noise configurations with a sharp and a blunt trailing edge are demonstrated. Then, for verifying the numerical propagation solution, an analytical sound propagation test is considered where the current numerical solution is compared with theory.