Computers and Fluids 140 (2016) 308–319

Contents lists available at ScienceDirect

Computers and Fluids

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

Parameterization and optimization of broadband noise for high-lift devices

A. Fosso Pouangué, C. Mnasri, S. Moreau*

Mechanical Engineering Department, Université de Sherbrooke, 2500 Bd Université, Sherbrooke J1K2R1, Canada

ARTICLE INFO

Article history:
Received 11 February 2016
Revised 6 June 2016
Accepted 29 September 2016
Available online 14 October 2016

Keywords:
High-order parametrisation
Optimisation
Genetic algorithm
Self-organizing maps
Multi-element high-lift device

ABSTRACT

The multi-objective optimization of both aerodynamic and broadband noise characteristics of a high-lift device is studied. The optimization is based on combining a recently developed parameterized Navier-Stokes approach as a surrogate model for solution reconstructions to a genetic algorithm for Pareto front construction. The parameterized Navier–Stokes solver Turb'Opty is a high-order sensitivity method around a reference Reynolds-Averaged Navier–Stokes (RANS) flow field. The present implementation takes into account up to the second-order partial derivatives including cross-derivatives of the RANS solver with respect to the optimization parameters. Acoustic predictions are based on Amiet's airfoil models and their extensions for turbulence interaction noise and self-noise respectively. The needed temporal data are reconstructed from wall-resolved RANS simulations or estimate through the surrogate model. The use of the parameterized Navier–Stokes approach and the self-noise model are validated with both experimental and detailed simulation data on a NACA0012 configuration. The whole optimization process is then applied to the L1T2 high-lift device. The application of these noise models seems to qualitatively capture the broadband noise generated in gaps between the elements. The study of the Pareto front exhibits optimal solutions with the expected trends: for instance decreasing the Mach number and the camber reduces the noise and yields a lift reduction. Details of two optimal solutions are finally provided.

1. Introduction

Airfoil noise is a significant part of airframe noise, and is a dominant contributor with the landing gear for mid- and long-range aircrafts at approach [1]. For High-Lift Devices (HLD), noise is mainly generated in the coves between the slat and the main wing, and if relevant, between the main wing and the flap [2]. This slat cove noise has both a broadband part and a tonal part. The broadband noise is caused by the interaction between the turbulent shear layers from slat trailing edges and the main wing leading edge. The tonal noise is found in the slat cove and can possibly be related to ”cavity” noise, boundary layer instability or vortex shedding (see Fig. 1 in Choudhari et al. [3]). Other possible noise sources are the trailing edges of all elements and the vortex shedding if the trailing edges are blunt. The most efficient way to numerically study all these noise sources is to perform an unsteady simulation of the flow around the HLD using Direct Numerical Simulation (DNS) or Large Eddy Simulation (LES) methodology. Yet, even the latter appears to be currently prohibitive considering the required computational resources at the high Reynolds number based on the chord length of the clean configuration of these devices (greater than 10^6): for instance the wall-resolved LES of Terracol and Manoha requires 2.6 billion nodes and several million CPU hours [4]. To circumvent this, different studies are based on Unsteady Reynolds-Averaged Navier–Stokes (U-RANS) computations [5,6], hybrid methodologies combining LES and Linearized equations [7] or RANS and Linearized Euler Equations (LEE) equations [8], RANS/LES methodologies [9] or more recently Lattice-Boltzmann methods [10]. However, all these methods remain expensive to be applied in an industrial context and cannot be included in an optimization loop. A first objective of this study is to assess the use of Amiet-like models with RANS computations to predict the noise generated, and a second one is to perform an optimization of the configuration to reduce HLD noise based on these low-order models.

Amiet's analytical models for leading [11] and trailing [12] edges noise have been extensively used to predict noise generated by profiles (airfoil [13–15], fan or propeller [16–21]). Molin et al. successfully used both Amiet's [22] and Howe's [23] analytical models to predict noise radiated by HLD with experimental measurements as inputs. Since then, Roger and Moreau [13,24] further improved Amiet's models by accounting for some geometrical

---

* Corresponding author.
E-mail addresses: arnaud.fosso@usherbrooke.ca (A. Fosso Pouangué), cmnasri@kfu.edu.sa (C. Mnasri), stephane.moreau@usherbrooke.ca (S. Moreau).

http://dx.doi.org/10.1016/j.compfluid.2016.09.024

airfoil parameters as camber and thickness, and by also integrating the backscattering effect of the leading edge on trailing-edge noise. Recently, Rozenberg et al. [18] applied these modified Amiet's models to compute noise generated by single airfoils using RANS computations. To achieve this, they tested and extended different semi-empirical models for recovering Power Spectrum Density (PSD) of fluctuating velocities describing incoming turbulence, and wall-pressure fluctuations from boundary-layer statistics obtained through RANS computations. The efficiency of such models in terms of computational resources is obvious and makes them interesting candidates for the noise prediction of such complex configurations as HLD. The present noise models also go significantly beyond the compact models proposed by Hosder et al. [25] or Jouhaud et al. [26] for instance.

Knowing that reducing noise of HLD could sometimes decrease the aerodynamic performances, engineers need a way to find configurations that allow the best compromise between aerodynamic performance and noise reduction. Therefore, a multi-objective multi-disciplinary optimization (MOO-MDO) process is required. To achieve an efficient automatic optimization process, it is necessary to have an efficient way to compute the aerodynamic field around the HLD and then the noise generated. To compute the aerodynamic field for each set of parameters, the recently developed method based on parameterized Navier–Stokes solver is used [27,28]. It is based on high order Taylor series expansion in the parameter space. The methodology only needs one RANS simulation with a set of reference parameters. The RANS simulation is performed using the finite-volume block-structured solver Turb'Flow. The derivatives needed in the Taylor series expansions are precomputed using a differentiated code of the solver Turb'Flow, named Turb'Opty. This methodology has been successfully used to aerodynamically optimize airfoils, blade cascades, casing treatment in low speed turbomachinery [29], and more recently HLD aerodynamic performances [28]. The present work extends the latter to aerodynamic and acoustic performances of a typical 3-element HLD called L1T2 in an optimization methodology based on the same parameterized approach. To be consistent with the two-dimensional flow simulations around the L1T2 HLD, only the 2D noise sources as defined by Molin et al. are considered and important 3D noise sources as the slat-cove noise or the flap side-edge noise are discarded here [22,23]. Molin et al. also showed that these 2D sources were dominant in the mid-frequency range (typically between 100 Hz and 2 kHz) by successfully comparing with acoustic flight data on the A320 and A340 aircrafts. The analytical broadband noise models of these 2D sources are first presented. The following section describes the optimization process. The validation of the latter on the trailing-edge noise of the NACA0012 airfoil is then shown, before moving to the aeroacoustic optimization of the L1T2 HLD. Finally some conclusions are drawn.

2. Noise prediction models

2.1. Leading-edge model: turbulent interaction noise

The noise radiated from an airfoil leading edge is based on the method proposed by Amiet [11]. It computes the noise radiated in free-field by a turbulent flow impinging on the leading edge of an infinitely thin airfoil without incidence at a mean Mach number M_0 in a fluid of density ρ_0 and kinematic viscosity ν. As was shown by Moreau et al. [13], the model could be modified to account for the airfoil thickness and the camber. Spectra and directivities that compare very well with measurements in the Ecole Centrale de Lyon (ECL) anechoic wind tunnels could then be retrieved for the NACA0012 airfoil used below. The influence of the angle of attack on this noise mechanism was also shown to be limited as also recently verified by Devenport et al. [30]. The PSD of the acoustic far-field pressure at a position $\mathbf{x}$ of the observer and an angular frequency ω is given by:

$$S_{pp}^{LE}(\mathbf{x},\omega) = \left(\frac{\rho_0 k c x_3}{2S_0^2}\right)^2 \pi U_x \frac{L}{2} \int_{-\infty}^{+\infty} \Phi_{ww}\left(\frac{\omega - K_y U_y}{U_x}, K_y\right) \tag{1}$$

$$\times \left|\mathcal{L}^{LE}\left(x_1, \frac{\omega - K_y U_y}{U_x}, K_y\right)\right|^2 \tag{2}$$

$$\times \frac{\sin^2\left[\left\{\left(k(1-M_x^2)x_2/S_0 - M_y\right)/\beta_0^2 - K_y\right\}L/2\right]}{\pi\frac{L}{2}\left[\left(k(1-M_x^2)x_2/S_0 - M_y\right)/\beta_0^2 - K_y\right]^2},$$

where $\mathbf{x} = (x_1, x_2, x_3)$ are the coordinates of the observer, x_1 being the streamwise direction, x_2 the spanwise direction, and x_3 the direction orthogonal to the two previous directions. L and c are the span and the chord length of the airfoil respectively. S_0 is the corrected distance to account for convection effects ($\beta_0^2 = 1 - M_0^2$). U_x and U_y are the mean velocity components yielding the Mach numbers M_x and M_y respectively. K_x and K_y are the wavenumber components following the streamwise and spanwise directions respectively. k is the acoustic wavenumber. Φ_{ww} is the normal turbulent velocity spectrum. $\mathcal{L}^{LE}$ is the aeroacoustic transfer function including the main leading-edge term $\mathcal{L}_1^{LE}$ and the trailing-edge backscattering correction $\mathcal{L}_1^{TE}$ defined by Amiet [11]. More details can be found in Roger and Moreau [31].

For an infinite span (the large aspect-ratio approximation), Eq. (3) simplifies to:

$$S_{pp}^{LE}(\mathbf{x},\omega) = \left(\frac{\rho_0 k c x_3}{2S_0^2}\right)^2 \pi U_x \frac{L}{2} \Phi_{ww}\left(\frac{\omega}{U_x}, \frac{k x_2}{S_0}\right) \left|\mathcal{L}^{LE}\left(x_1, \frac{\omega}{U_x}, \frac{k x_2}{S_0}\right)\right|^2. \tag{3}$$

If only 2D parallel gusts (without a spanwise component) are considered, Eq. (3) further reduces to:

$$S_{pp}^{LE}(\mathbf{x},\omega) = \left(\frac{\rho_0 k c x_3}{2S_0^2}\right)^2 \pi U_x \frac{L}{2} \Phi_{ww}\left(\frac{\omega}{U_x}, 0\right) \left|\mathcal{L}^{LE}\left(x_1, \frac{\omega}{U_x}, 0\right)\right|^2. \tag{4}$$

The Von-Karman spectrum is used to reconstruct the turbulent velocity spectrum Φ_{ww} from statistics obtained through RANS computations as originally proposed by Lysak and Brungart [32].

2.2. Trailing-edge model: self-noise

The noise radiated from an airfoil trailing edge is again based on a method proposed by Amiet [12]. It computes the noise radiated in free-field by the diffraction of the pressure fluctuations born in the boundary layer at the trailing edge of an infinitely thin airfoil without incidence. It has been extended by Roger and Moreau [24] to account for the airfoil finite chord length. By comparing with several anechoic wind tunnel data, they then showed that the noise spectra and the directivities could be well predicted on several airfoils including the NACA0012 airfoil used below. The model gives the following expression for the PSD of the far-field acoustic pressure at a position $\mathbf{x}$ of the observer and an angular frequency ω:

$$S_{pp}^{TE}(\mathbf{x},\omega) = \left(\frac{\omega c x_3}{2\pi c_0 S_0^2}\right)^2 \frac{L}{2} \left|\mathcal{L}^{TE}\left(\frac{\omega}{U_c}, \frac{k x_2}{S_0}\right)\right|^2 \Phi_{pp}(\omega) l_y(\omega), \tag{5}$$

where Φ_{pp} is the PSD of the wall-pressure fluctuations and $l_y(\omega)$ the spanwise coherence length of these pressure fluctuations near the trailing edge. c_0 is the fluid speed of sound. $\mathcal{L}^{TE} = \mathcal{L}_1^{TE} + \mathcal{L}_2^{TE}$ is the aeroacoustic transfer function where $\mathcal{L}_1$ is the main trailing-edge term defined by Amiet [12] and $\mathcal{L}_2$ is the leading-edge backscattering correction obtained by Roger and Moreau [24]. More