Journal of Sound and Vibration 371 (2016) 132–149

Contents lists available at ScienceDirect

Journal of Sound and Vibration

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

Direct aeroacoustic simulation of acoustic feedback phenomena on a side-view mirror

Hannes M. Frank *, Claus-Dieter Munz

Institute for Aerodynamics and Gasdynamics, University of Stuttgart, Pfaffenwaldring 21, 70550 Stuttgart, Germany

ARTICLE INFO

Article history:
Received 16 October 2015
Received in revised form
1 February 2016
Accepted 5 February 2016
Handling Editor: J. Astley
Available online 22 February 2016

Keywords:
Aeroacoustics
Large Eddy Simulation
Side-view mirror
Tonal noise
Aeroacoustic feedback loop
Direct noise computation
High order method
Discontinuous Galerkin
Spectral elements
Compressible Navier-Stokes equations
Laminar separation
Global instability

ABSTRACT

The flow around a side-view mirror and its noise generation are investigated using large eddy simulation and direct acoustic simulation. To this end, we use the high order discontinuous Galerkin spectral element method on non-conforming curved elements. Tonal noise is observed, which originates at the trailing edge downstream of laminar separation, coinciding with experimental results. In order to determine the nature of the tonal noise generation mechanism, we perform a linear stability analysis and employ a global perturbation approach in combination with dynamic mode decomposition. The perturbation analysis based on the whole flow field demonstrates the existence of a global instability involving convective disturbance growth, acoustic scattering at the trailing edge and acoustic receptivity at a rounded edge slightly upstream of separation. The results clearly show the tonal noise to be caused by the so-called acoustic feedback loop known from airfoil aeroacoustics. This phenomenon has been simulated here for the first time for a complex geometry.

1. Introduction

Among other industries, automotive manufacturers are interested in the understanding of noise generation phenomena, as profound knowledge of the principle effects improves the aeroacoustic development process through potentially more purposeful design choices. As a result, fewer wind tunnel experiments may be necessary to achieve acceptable noise levels and to avoid tonal noise. One main contributor to the flow-induced noise is the flow around the side-view mirror due to its bluff-body character and its proximity to the driver. On top of broadband noise, tonal noise may originate at the side-view mirror. Tonal or narrowband noise is perceived as particularly annoying and must be eliminated or reduced to acceptable levels. Modern scale resolving simulations represent a complementary means to laboratory experiments to study flow features with aims such as the deeper understanding of noise generation. We conduct high fidelity compressible large eddy simulations (LES) of the flow around an early-development-stage side-view mirror in order to shed some light on the tonal noise generation mechanism. By solving the compressible Navier–Stokes equations, the generation and transport of acoustic waves as well as possible feedback to the hydrodynamic field are included. As this approach requires high accuracy of the

* Corresponding author.
E-mail address: frank@iag.uni-stuttgart.de (H.M. Frank).

http://dx.doi.org/10.1016/j.jsv.2016.02.014

numerical scheme, we employ the discontinuous Galerkin spectral element method (DGSEM), which combines high order accuracy with geometric flexibility and high performance computing efficiency [1].

Most of the available literature on side-view mirror aeroacoustics simulations at present is concerned with the generic side-view mirror on a flat plate first presented by Höld et al. [2] and Siegert et al. [3] in 1999. Their experimental data served as reference in subsequent studies using acoustic analogies with sources from incompressible LES or detached eddy simulation (DES), e.g. [4,5]. Published computational results on non-generic side-view mirror geometries are rare, an example using incompressible LES and the Lighthill equation with good agreement to measurements is described in Khaligi et al. [6]. However, the experimental data in neither the generic nor the non-generic case feature tonal components.

The cause for narrowband acoustic frequency content radiated from side-view mirrors often lies in the flow over notches or other devices for water management or joints. However, tonal noise may as well arise without any sharp edges in the aerodynamic shape. If the surface roughness is small enough, the convex shape of the mirror supports thin, laminar boundary layers until close to the trailing edge. This condition is the foundation for the potential occurrence of tonal noise generation mechanisms involving the instability dynamics of laminar or transitional boundary layers. Lounsberry et al. [7] recognized the similarities to tonal airfoil self-noise, which has been investigated since the early 1970s. In particular, the so-called aeroacoustic feedback loop [8,9] is hypothesized to be the reason for the side-view mirror noise in our case.

1.1. Tonal noise generation mechanism

Airfoil self-noise containing narrowband components was first investigated specifically by Paterson et al. [10] in 1973. They considered NACA 0012 and NACA 0018 airfoils in a low-turbulence, open-jet wind tunnel and documented many of the key observations of airfoil tonal noise generation which were confirmed by later authors. The general trend of the tonal frequencies with increasing free stream velocity scaled as $u_\infty^{3/2}$. While the associated semi-empirical scaling law derived by Paterson describes the general trend well, it fails to capture the so-called ladder-type structure of the tonal peaks. When plotting the tonal frequencies over the free stream velocity, the tone frequencies were organized along several ‘rungs’, each scaling with $u_\infty^{0.8}$. When increasing the velocity, at certain points in the diagram, the peak frequency jumps from one rung to another. Moreover, the simultaneous occurrence of two or more tonal components was reported. This observation is consistent with later measurements in open and closed test-section wind tunnels [9,11,12]. In contrast, while Nash et al. [13] obtained multi-peak spectra in a closed test-section wind tunnel, by use of acoustic lining only single-peak spectra remained, underlining the strong influence of the experimental configuration on the results. By tripping the boundary layer, Paterson et al. found that the narrowband peaks are associated with a laminar boundary layer on the pressure side. Nash et al. [13] and McAlpine et al. [14] highlighted that the tonal noise was dependent on the presence of a laminar separation on the late pressure side, but also reported cases that exhibited laminar separation without tonal noise emission.

Paterson et al. attributed the noise to bluff-body type vortex shedding at the trailing edge with distinct frequency. As this mechanism could not explain the ladder structure, Tam [8] proposed a self-excited feedback loop between large scale oscillating waves in the near wake and upstream running acoustic waves emitted from a noise source further downstream. A self-sustaining feedback loop implies that the phase difference over one cycle should vanish, a condition that only discrete (but possibly more than one) frequencies can fulfill. Fink [15] and Arbey and Bataille [9] proposed the noise generation to be caused by the diffraction of unstable, downstream running Tollmien–Schlichting waves at the trailing edge. In their version of the feedback loop, the upstream running acoustic wave reinforces the boundary layer instability at some point on the airfoil surface through acoustic receptivity.

Theoretical models based on this concept that estimate the overall phase difference from the phase velocity of the instability, the speed of sound and the distance between a receptivity position and the trailing edge, predict the ladder structure fairly well [9,16,17,11]. However, all of them are dependent on the prescription of the location where the receptivity process is assumed to take place. Ad hoc choices have been the point of maximum velocity [9] or the most upstream point of instability [16,17]. Using receptivity strips, Plogmann et al. [11] were able to trigger receptivity on prescribed locations experimentally. The tonal frequencies changed according to the phase criterion of the feedback model as the receptivity strips were placed at different streamwise positions, strongly supporting the notion of acoustic feedback as explanation for the frequency selection.

McAlpine et al. [14] emphasized the presence of a laminar separation region upstream of the trailing edge, over which the majority of the amplification would take place. They claimed that frequency selection occurs in a region close to the point of separation. Consequently, the dominant tone frequency would be equal to the convectively most amplified instability frequency and not selected by feedback. In the two-dimensional direct numerical simulations (DNS) of a NACA 0012 airfoil by Desquesnes et al. [18], amplified instability modes eventually rolling up to spanwise vortices were observed. The dominant tone frequency was very close to the respective most amplified frequency from linear stability theory. They observed a phase difference between the hydrodynamic pressure fluctuations on the pressure side and those on the suction side shortly upstream of the trailing edge. They explained the regular side peaks in the simulated acoustic spectrum by the resulting, very regular amplitude modulation in the near wake. However, in the recent measurements of Pröbsting et al. [12], amplitude modulation in the hydrodynamic fluctuations was present on the pressure side, even when the suction side boundary layer was tripped, thus excluding the phase modulation between suction and pressure side as the only explanation for the multiple peaks.