

Effects of Notches on Surface Pressure Fluctuations Downstream of a Leading Edge Spoiler

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ABSTRACT

Notched spoilers have been observed to be more effective than uniform spoilers to suppress the flow-induced cavity resonance of vehicles with open sunroofs. In this study, a few mechanisms possibly involved in buffeting suppression from notched spoilers were investigated experimentally and numerically. One objective was to investigate the spatial coherence and phase of the wall pressure fluctuations downstream of notched spoilers in comparison with the same quantities for uniform spoilers. Another objective was to gather detailed measured data to allow the verification of computer simulations of the flow over the notched spoiler. Experiments were performed to measure the velocity and wall pressure fields downstream of spoilers mounted on the rigid floor of a closed test section wind tunnel for different spoiler heights. Efforts were made to reproduce the spoiler and wind tunnel geometry and boundary conditions of the experimental set-up in the numerical simulations. The numerical investigation used the Lattice Boltzmann Method (LBM), with the so-called Very Large Eddy Simulation (VLES) viscosity turbulence model. The results of the numerical investigation were in satisfactory agreement with measured data at low frequencies, where buffeting is expected to occur. The results clearly showed that the notches act as streamwise vortex generators. They reduced spoiler drag, resulting in an upstream shift of the flow reattachment region. The results confirmed that the

streamwise vortices break down the homogeneity of the leading edge cross-stream vortices predominantly responsible for the cavity excitation. This decreased the cross-stream coherence of the surface pressure field, thereby reducing the magnitude of the net equivalent excitation force acting over the surface downstream.

1. INTRODUCTION

Flow grazing over open cavities causes vortices to be shed, which may induce large amplitude self-sustained, tonal pressure oscillations inside the cavity. This phenomenon is a species of flow-induced cavity resonance which typically occurs at acoustic resonance frequencies of the cavities, which depend on the geometry and dimensions of the cavity. The high level and character of these pressure fluctuations may cause structural fatigue, and excessive radiated noise. Previous studies in this field, specifically in the automotive industry, have been directed mainly towards understanding excitation phenomena and the mechanisms involved in the suppression of the flow-induced oscillations. Applications in the aircraft industry include flows over wheel wells during landing.

Geometric modifications to leading and trailing edges have been attempted to move the separation location or the flow reattachment region further downstream of the trailing edge of the cavity. Rockwell and Naudascher[1] reviewed various investigations using ramped edges,

spoilers, cowl, and rounded edges. They reported that ramped leading and trailing edges were effective at reducing cavity sound pressure levels by 20 dB. Uniform leading edge spoilers were investigated by Rossiter[2], who reported an increase of the upstream boundary layer thickness leading to reductions of the cavity SPL by 25 dB. The flow over a uniform spoiler or spoiler mounted at a certain angle of attack over a rigid surface is characterized by a separation region followed by a free shear or vortex formation zone. Further downstream, a flow reattachment zone and a re-attached boundary layer flow were observed. It has been argued that the effectiveness of uniform spoilers to suppress buffeting is due to a shift of the reattachment zone downstream of the sunroof trailing edge[3]. It has also been argued that high-level tones can be reduced by inhibiting shear layer oscillations in and out of the cavity at the trailing edge location. Disruption of mass exchange and motion of the upstream separation location away from the cavity are other suppression concepts[4]. Research has shown that uniform spoilers deflect the shed vortices over the spoiler into a region of greater flow velocity. The organized flow structures formed at the spoiler are prohibited from impinging on the trailing edge of the cavity, disrupting the feedback loop necessary to maintain large amplitude oscillations. This feedback loop involves the coupling of the vortex shedding frequency at the leading edge of the cavity with the natural frequency of the cavity. Kook et al.[5] used an oscillated uniform spoiler to control the phase of the discrete vortex shedding in a side-branch Helmholtz resonator. They reported a reduction of the SPL up to 20 dB over a range of flow velocities.

Many aspects of the excitation pressure in the orifice region of flow-excited cavities are postulated to be analogous (at least qualitatively) to the blocked pressure on the surface underneath similar outer flows. The wall pressure fluctuations produced by the impingement of turbulent flows on structures generate noise and cause structural vibrations. Many efforts have been made to better understand the interactions between convective turbulent flows and panels or other types of extended vibrating structures. Turbulent boundary layer wall pressure fluctuations have been frequently investigated to reduce vibration and noise from flow-excited vehicle cabins and other applications. The characterization of fluctuating wall pressure fields on plates with surface irregularities was investigated for example by Farabee and Casarella[6], who measured the wall pressure field upstream and downstream of a backward-facing and forward-facing step. They found that the recirculation region is dominated by low frequency fluctuations close to the step, and higher frequency fluctuations further downstream. Park[7] investigated the vibration response and sound radiation of a visco-elastically supported, aluminum plate excited by turbulent flow. Other investigators focused on the study of smooth-wall

boundary layers such as Blake[8], Willmarth and Wooldridge [9] and Bull[10], among others. Skudryzk and Haddle[11] and Blake[8] performed measurements on smooth and rough surfaces. However, most of the early results on wall pressure fluctuations under smooth and rough surfaces were limited by spatial averaging due to the finite size of the microphones, and the lack of low-noise wind tunnel facilities. Blake measured wall pressure fluctuations on smooth and rough surfaces using a reduced microphone sensing area of 0.08 cm (1/32 in.) diameter holes, varying the wall roughness height and separation distance. He concluded that roughness separation affected the large scale structures while the roughness height affected the medium and small scale turbulence. Farabee and Casarella [6] measured the wall pressure spectra and velocity profiles of various heights of backward-facing and forward-facing steps, observing that highly energized velocity fluctuations are convected downstream near the wall, decaying gradually and finally diffusing. Experiments aimed at separating aerodynamic and acoustic excitation loads for structures excited by turbulent flows were performed by Arguillat and Ricot[12]. Their spectral analysis showed that the broadband acoustic pressure field component accounts for approximately 5% of the aerodynamic excitation pressure field. But subsequent study showed that this may be due to background noise in the test facility.

Modeling of the surface pressure fluctuations behind complex bodies using numerical methods is a very challenging task. Efforts have been made in recent years to perform simulations of the turbulent pressure field using large Eddy simulations. But these methods are only possible for rather simple channel flow configurations and simplified boundary conditions. Their cost precludes the simulations of fluctuating pressures at high frequencies. For low Mach number flows, an approach which has been investigated in recent years for automotive applications is the use of the lattice Boltzmann Method (LBM). LBM was developed from the foundations of the lattice Gas Cellular Automaton (LGCA) in the mid 80's which incorporates lattices with particles residing on the nodes. A discrete number of displacement directions and velocity distributions require a set of Boolean variables describing the particle occupation in the lattice. The increased noise levels in the LGCA can be suppressed by coarse graining over large domains and/or time intervals. The need to further reduce the noise generated by the LGCA models led McNamara and Zanetti[13] to introduce the use of the lattice Boltzmann models to simulate lattice-gas automata in 1988. They replaced the Boolean fields with continuous distribution functions. Further, Higuera and Jiménez[14] introduced the linearized collision operator based on the LGCA. Later, the collision operator was replaced by the single time relaxation in the Bhatnagar-Gross-Krook (BGK) approximation by

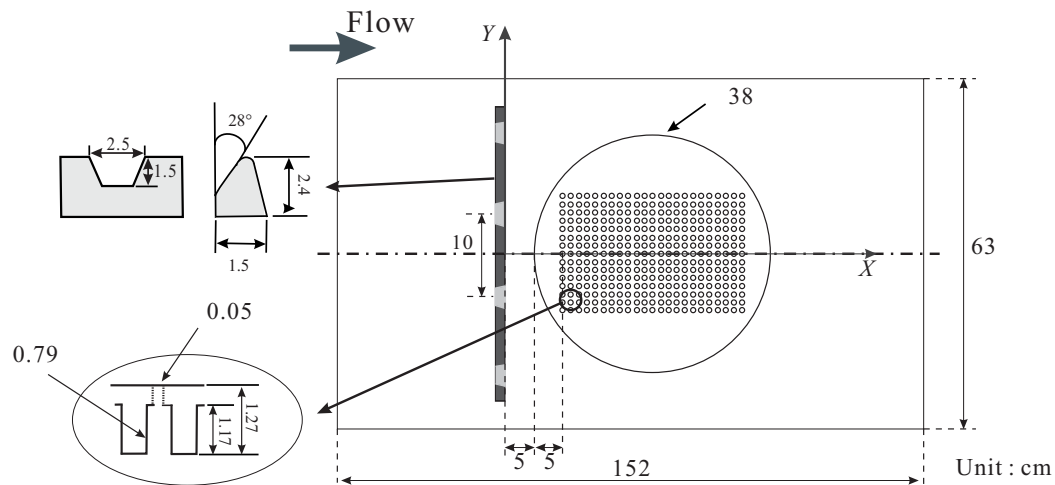


Figure 1. Schematic of the experimental setup and its dimensions. Circular pressure tap plate with a rectangular array of pinholes is placed downstream of the spoiler to measure the surface static and dynamic pressures.

various researchers [15-16]. Simulations that specifically make use of the LBM have led to the development of improved models that correlate well with experiments. Ricot et al.[17] developed a two-dimensional nine velocity model of the lattice Boltzmann equation for aero-acoustic investigations. Crouse et al.[18,19] used the LBM combined with a ReNormalization Group (RNG) turbulence model to obtain the acoustic response and flow field of a passenger cabin subjected to self-sustained oscillations. Yakhot et al.[20] also used the lattice Boltzmann kinetic equation with the RNG turbulence model in two and three dimensions to simulate a controlled experiment by Nelson et al.[21] on acoustic resonance excitation by a grazing flow. Maillard and Vaillant[22] used the LBM to test a simple two-dimensional Helmholtz-like cavity under grazing flow aiming to simulate the aerodynamic feedback loop found in sunroof buffeting mechanisms. Although the computational grids used do not resolve all scales in the near wall region, it has been observed that LBM methods yield acceptable estimates of the wall pressure spectra over a wide frequency range[23-25].

Uniform sunroof spoilers have been shown to reduce interior sound pressure levels (SPL) in cars by as much as 25 dB[2,4]. Experimental investigations have shown that notched spoilers may further reduce the SPL by 20 dB over uniform spoilers. The fundamental physical mechanisms involved in the improved effectiveness of the notched spoiler are of interest for the development of better suppression devices. There is no detailed study of flows over notched spoilers in the literature. The common explanation for the enhanced suppression mechanism is that the notches break the lateral coherence of the flow over the sunroof. But no objective measurements or detailed computations have been done to verify the validity of this hypothesis. The present investigation utilizes pressure and velocity profile measurements to shed some light on the effects of the

notches, on the size of the recirculation region, and on the spatial and temporal coherence of the dynamic wall pressure field downstream the spoiler, where the cavity would normally be located. It is hypothesized in this investigation that the notches may alter the hydrodynamic pressure fluctuations over the region downstream of the spoiler in a way that reduces the net excitation. Thus, the present experimental and numerical investigations aims to: 1) validate the main hypothesis of the investigation, 2) investigate the spatial coherence and phase of the wall pressure fluctuations downstream of notched spoilers in comparison with the same quantities for uniform spoilers, 3) simulate the flow and resulting wall pressure fluctuations numerically using the LBM scheme, and 4) compare results from experimental and numerical approaches.

2. EXPERIMENTAL AND NUMERICAL METHODS

The experimental apparatus under investigation consisted of spoilers with and without notches, mounted into the test section of a low-speed, quiet wind tunnel. The notched spoiler was similar to that was used on a Fiat Lancia Y. Experimental instrumentation and procedures are described in subsequent sections.

2.1 INSTRUMENTATION

A circular aluminum pressure tap plate was placed in the middle of the wind tunnel test section, as shown in Figure 1. A spoiler of 2.5 cm height was installed 5 cm upstream of the pressure tap plate. Two spoilers, with and without 2.5 cm wide notches, were used. The pressure tap plate included a rectangular array of 15 x 22 pressure-measuring points with a spacing of 2.5 cm in both the streamwise, x, and the lateral, y, directions. To minimize spatial average effects in pressure measurements[26], pinholes with a diameter of 0.79 mm

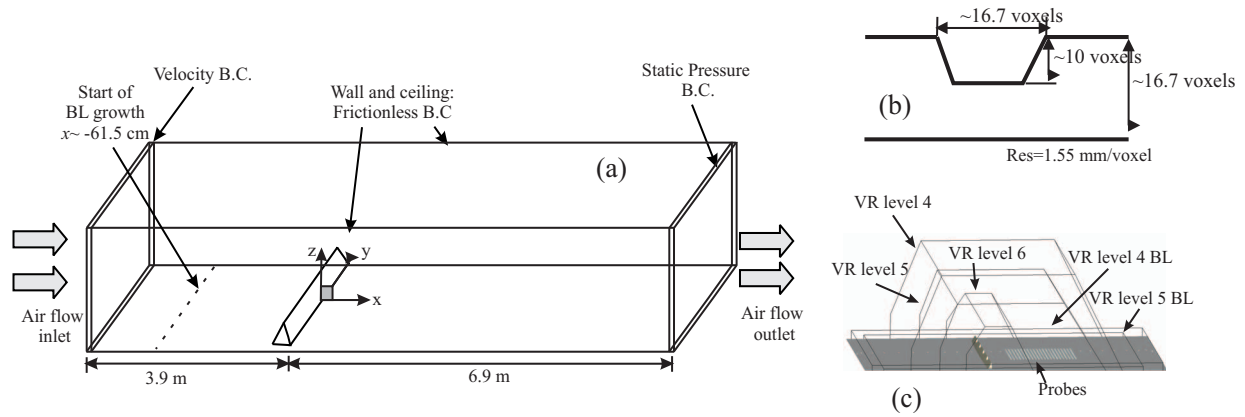


Figure 2. Configurations for numerical simulation: (a) digital wind tunnel setup and boundary conditions, (b) spatial resolutions for spoiler and notch, and (c) variable resolution (VR) regions used for simulation.

were drilled at each location on the measuring grid. The pinholes were then counter-sunk from below at a depth of 1.17 cm for insertion of the measuring devices. The static surface pressure field was measured using a MKS pressure gauge, Baratron 220D, connected by a plastic hose to each pressure tap. Three 6 mm diameter B&K microphones, type 4939, were installed in adjacent holes to measure the instantaneous dynamic pressure. Measurements were repeated with one fixed microphone and two roaming microphones over the measuring grid to map the dynamic pressure field. The free stream velocity was 50 km/h (~ 14 m/s). Unused transducer holes were blocked while pressure measurements were conducted at each measuring points. A dual sensor hot-wire probe was employed to measure streamwise and vertical flow velocity components. The hot-wire measurements encompassed two x - z planes located at $\{(x, y, z) : 1.5 < x/h < 18, y/h = 0 \text{ and } -2, 0.3 < z/h < 2.5\}$, with the notched spoiler configuration.

2.2 EXPERIMENTAL PROCEDURES

General properties of the flow field were firstly obtained from the static surface pressure values. The pressure loss coefficient,

$$C_P = \frac{\Delta p}{1/2 \rho u_\infty^2}, \quad (1)$$

where u_∞ and Δp are free stream velocity and pressure difference with respect to ambient pressure, was calculated. The surface pressure distribution was used to determine the approximate location of the flow reattachment zone.

Auto-power spectra of the dynamic pressure at each measuring points were measured for both spoiler configurations to evaluate the influence of the notches on the streamwise variation of the fluctuating pressure. Frequency-spectral scaling was used in computing the auto-power spectrum to compare with experimental

results from other studies [27,28]. Because velocity fluctuations of various scales in the boundary layer contribute to the wall pressure fluctuations, different scaling laws lead to a collapse of experimental data over different spectral ranges.[10] In the present study, because low frequency range is of the primary interest, low frequency scaling was used, which is based on the free stream dynamic pressure, $q = 1/2 \rho U_\infty^2$, and the displacement thickness frequency scale, U_∞/δ^* , and yields spectral data in the form of $\Phi_{xx}(\omega) U_\infty/q^2 \delta^*$ as a function of $\omega \delta^*/U_\infty$.

Cross-power spectrum, coherence and phase distribution between lateral measurement locations were calculated from the dynamic surface pressure data and analyzed to investigate the influence of the notches on the lateral flow structure. The spectral analysis is based on Corcos' empirical model where cross-power spectrum is expressed by

$$S_{xy}(\xi_x, \xi_y, \omega) = \Phi_{xx}(\omega) e^{-\alpha_x \left| \frac{\omega \xi_x}{U_c} \right|} \cdot e^{-\alpha_y \left| \frac{\omega \xi_y}{U_c} \right|} \cdot e^{i \frac{\omega \xi_x}{U_c}} \quad (2)$$

where Φ is auto-power spectrum, ξ is the displacement between two locations, and α is the decay coefficient. The coherence between two locations is therefore obtained as

$$\gamma^2 = \frac{\Phi_{xx}^2(\omega)}{\Phi_{xx}(\omega) \cdot \Phi_{yy}(\omega)} \cdot e^{-2\alpha_y \left| \frac{\omega/U_c \cdot \xi_y}{U_c} \right|} \cdot e^{-2\alpha_x \left| \frac{\omega/U_c \cdot \xi_x}{U_c} \right|} \quad (3)$$

For the computation of the spectral densities of the fluctuating pressure, it was necessary to compensate the measured power spectrum to account for the effects of microphone installation on its frequency response. The acoustic response function of the microphone insertion pinhole was measured independently before the wind tunnel experiments. While the plate was insonified by a random acoustic source from a loudspeaker, the pressure inside the pinhole, H_{ir} , and the external pressure above the pinhole, H_e , were simultaneously measured with respect to a reference