

Boundary Layer Control and Flow-induced Noise Reduction in Duct Bends Using Surface Microstructures

Shunpei Nomura¹⁾ Yuta Sobue¹⁾ Sho Kosaka²⁾ Kenji Yoshida²⁾ Kaori Seki²⁾

Yasuhiko Sakai³⁾ Shuho Yamada⁴⁾ Osamu Terashima¹⁾

1) Gifu University

1-1 Yanagido, Gifu-shi, Gifu, 501-1193, Japan

2) DENSO CORPORATION

1-1 Showa-cho, Kariya, Aichi, 448-8661, Japan

3) Nagoya Industrial Science Research Institute

2-10-19 Sakae, Naka-ku, Nagoya, 460-0008, Japan

4) Toyama Prefectural University

5180 Kurokawa, Imizu-shi, Toyama, 939-0398, Japan

KEY WORDS: Vibration, Noise, and Ride Comfort, Fluid Induced Noise Analysis, Microstructure, Boundary Layer Control (B3)

The electrification of automobiles has increased the importance of flow-induced noise generated by auxiliary components such as cooling fans and duct systems. Cooling and ventilation systems must achieve both low pressure loss and low noise levels. Automotive ducts often include sharp bends due to limited installation space, where flow separation and reattachment increase pressure loss and generate unsteady flow fluctuations and acoustic responses. Therefore, controlling separated-flow behavior while suppressing pressure loss is important. Surface microstructures have attracted attention as a passive flow-control technique. Previous studies have suggested that microstructures can improve flow structures and flow-induced noise characteristics around airfoils. However, their effects on separated flow, pressure loss and acoustic energy transport in duct bends remain unclear. Therefore, this study experimentally investigates the influence of surface microstructures installed on the inner wall of a duct bend. Wall-normal active intensity, pressure loss, and flow structures near the bend were measured to evaluate their effects on flow behavior and flow-induced noise characteristics.

Experiments were conducted using an acrylic duct with a 50 mm × 50 mm square cross section and a 90° bend with a bend radius of 15 mm. Surface microstructures consisting of alternating square protrusions and recesses were installed on the inner wall of the bend. Each element had a side length of 2.5 mm, and the protrusion height and recess depth were both 0.3 mm. A mean cross-sectional velocity of 10 m/s, representative of automotive ventilation ducts, was employed. Sound pressure and wall-normal acoustic particle velocity were simultaneously measured using a sound pressure-particle velocity (p-u) probe. The end of the duct bend was defined as $x = 0$ mm, and measurements were conducted at locations $x = 30$ –270 mm downstream of the bend at intervals of 20 mm. The wall-normal active intensity, $I_n(x)$, was obtained from the real part of the cross-spectrum between sound pressure and acoustic particle velocity integrated over the frequency range from 100 to 2500 Hz. To compare streamwise distributions between conditions, the active intensity was normalized by the maximum absolute value obtained for the smooth-wall condition as follows:

$$I_n^*(x) = I_n(x) / \max |I_{n,smooth}(x)| \quad (1)$$

where I_n^* denotes the normalized wall-normal active intensity. Pressure loss was evaluated from the static pressure difference between the duct inlet and outlet. Flow visualization was conducted using DEHS tracer particles and high-speed imaging.

Figure 1 shows the streamwise distribution of the normalized wall-normal active intensity at a mean flow velocity of 10 m/s. For the smooth-wall condition, I_n^* was -1.0 at $x = 30$ mm and became positive at $x = 70$ mm. In contrast, for the microstructured surface, the value at $x = 30$ mm increased to approximately -0.54 , and the sign-reversal location shifted upstream to approximately $x = 50$ mm. Larger positive values were observed over $x = 50$ –130 mm, whereas the difference became small beyond $x = 150$ mm. These results indicate that the microstructures modified the magnitude and direction of wall-normal acoustic energy transport near the reattachment region.

Flow visualization revealed that the separated shear layer remained closer to the wall and the separated region became smaller with the microstructures. These changes are considered to be related to the modification of local acoustic energy transport.

Furthermore, the increase in pressure loss was limited to approximately 1% compared with the smooth-wall condition. A slight reduction of approximately 0.2 dB was also observed in the far-field partial overall (P.O.A.) sound pressure level below 2500 Hz at a location approximately 2 m from the duct. Although the noise reduction was small, the results suggest that changes in local acoustic energy transport caused by the microstructures may contribute to far-field noise reduction.

Overall, the present results indicate that surface microstructures reduced outward acoustic energy transport immediately downstream of the bend and shifted the sign-reversal location toward the bend. Flow visualization suggested a modification of the interaction between the separated shear layer and the reattachment surface, whereas the increase in pressure loss remained approximately 1%. These findings indicate that surface microstructures can alter local flow structures and acoustic energy transport with only a minor pressure-loss penalty.

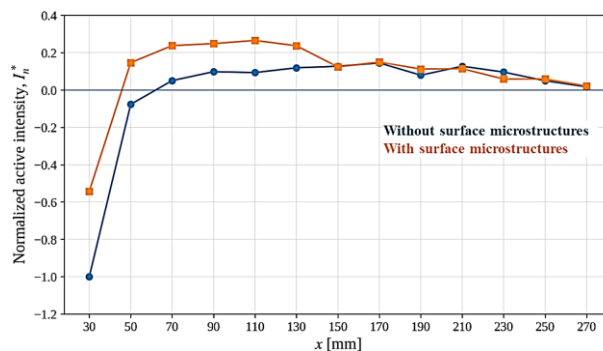


Fig. 1 Streamwise distribution of normalized wall-normal active intensity at a mean flow velocity of 10 m/s.