

Experimental Investigation of Aeroacoustic Cabin Noise in Unsteady Flow by Means of a New Turbulence Generating Device

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ABSTRACT

With advancement of aeroacoustic wind tunnels and CAE technology, aeroacoustic cabin noise in steady flow has been improved. On the other hand, passenger comfort is also impacted by aeroacoustic noise in unsteady flow. There have been comparatively few studies into this area, and the mechanism remains unclear. Considering the future proliferation of autonomous driving, drivers will pay more attention to cabin noise than previously, and aeroacoustic noise is expected to become more prominent. Thus, the reduction of fluctuating aeroacoustic noise is important. Most of the previous research relied on road tests, which don't provide reproducible conditions due to changing atmospheric and traffic conditions. To solve these problems, research using devices that generate turbulence are being conducted. However, the fluctuations of flow generated in previous studies were small, failing to simulate on-road conditions sufficiently. In this report, the development of a new turbulence generating device for 1/1 scale wind tunnel is described. This device consists of dampers and airfoils at the nozzle, producing turbulence intensity up to 13%. Then the analysis of the fluctuating aeroacoustic noise generated using this device is presented. When the fluctuation frequency of the incoming flow is as high as 5Hz, aeroacoustic noise shows time delay and peak value declines in comparison to simulated cabin noise predicted by quasi-steady technique using the cabin noise and flow velocity measured in steady flow. It is also shown that the change of modulation of aeroacoustic noise due to the modification of vehicle shape could be evaluated quantitatively using this device.

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INTRODUCTION

Reduction of aeroacoustic cabin noise improves the comfort of the passengers and increases a vehicle product's appeal, therefore much research has been done. With advancement in aeroacoustic wind tunnels and CAE technology in recent years, aeroacoustic cabin noise in steady flow has been studied and reduced, and cabin comfort greatly improved. However a vehicle on road encounters unsteady flow due to atmospheric winds and wakes of other vehicles ahead, resulting in fluctuating aeroacoustic cabin noise. This time-varying cabin noise affects passengers' comfort significantly. Considering the proliferation of autonomous driving in highways, drivers will potentially become more aware of cabin noise, and fluctuating aeroacoustic cabin noise in high speed may become prominent among other noises. For these reasons, reducing this unsteady fluctuating aeroacoustic noise is an important issue. Blommer [1] and Ito [2] proposed the metric and index that have correlation with subjective impressions of wind gusting or transient fluctuating noise. The cause that makes aeroacoustic noise modulate is thought to be the fluctuation of incoming flow. The relationship between cabin noise

levels, turbulence intensity and turbulence length scale was investigated by Lindener[3], and Oettle simulated the unsteady cabin noise response by quasi-steady technique [4]. All these surveys show the importance of input flow conditions. Most of the previous research on aeroacoustic noise in unsteady flow has been investigated with road tests, which have low reproducibility of flow conditions. The results of these on-road studies have proven difficult to conduct detailed transient analysis or extract clear vehicle response for various conditions. To ensure accuracy and repeatability of test conditions, investigations are being conducted to produce turbulent flow in a wind tunnel. The point is how the turbulent flow in the natural environment should be reproduced. Cooper and Watkins [5] investigated the turbulent flow that vehicles encounter on road. The factors of the fluctuation of aeroacoustic noise around a vehicle are thought to be crosswise directional changes in wind [6] and the changes of flow speed [7], and these two factors need to be reproduced in a wind tunnel. According to Iida [8], who summarized research in small-scale wind tunnels, it was confirmed that turbulent flow field could be reproduced by methods such as cabin model test of rectangular wings mounted on turbulence grids [9], multiple

independently controlled fans [10], and damper plates and airfoils arranged vertically at the nozzle exit [11]. None of these had been applied to 1/1 scale wind tunnel for vehicles. For 1/1 scale wind tunnel, a method has been attempted of using spires affixed to the wind tunnel nozzle to disrupt the wind [12], that produced turbulence intensity up to 8%. However, it's difficult to control fluctuation of flow speed and cross wise direction at will. In 2015 FKFS has developed a device (SWING) which consists of an airfoil cascade at nozzle [13]. It can produce turbulent flow with maximum frequency 10Hz and angle of flow deflection ± 2.5 degrees, that is enough performance to reproduce the turbulence of natural wind in the crosswise direction. Research on 1/1 scale vehicles with fluctuations of flow at higher frequencies is getting underway, albeit in the crosswise direction only. Still, no devices exist yet for controlling changes in flow speed and direction at the same time in 1/1 scale wind tunnels. To solve this issue, a new device named Natural Wind Generator (NWG) was developed for Toyota's wind tunnel [14], that produces fluctuations in flow speed and direction at the same time. It can reproduce natural wind measured in road tests. This work also presents the results of an analysis of the fluctuating aeroacoustic cabin noise using the NWG. When the fluctuation frequency of the incoming flow is set at as high as 5Hz, time delay occurs and the peak value of aeroacoustic cabin noise declines in comparison to the simulated aeroacoustic cabin noise predicted by quasi-steady technique based on the relationship between cabin noise and flow velocity measured in steady flow. And also it is shown that the change of modulation of aeroacoustic cabin noise due to the modification of vehicle shape could be evaluated quantitatively using this device.

All of the sound pressure data analyzed in this paper were measured at the outward driver's ear with an artificial head. A sampling frequency is 48kHz and the duration is 60 seconds. All post processing of sound data was done using 65536 samples with an overlap of 50% for the Discrete Fourier Transform.

OUTLINE OF NATURAL WIND GENERATOR (NWG)

Mechanism of Producing Unsteady Flow

NWG was developed to reproduce the natural wind which is measured during occurrence of notable fluctuating aeroacoustic cabin noise in on-road tests. The flow speed and flow direction with respect to the vehicle was measured during test runs on a windy day on a proving ground by an X probe hot wire anemometer mounted on the hood of a vehicle (Fig.1). The location of the anemometer was chosen by wind tunnel testing as where measured flow speed is close to the value of a pitot tube installed on the nozzle exit and measured flow direction is close to vehicle yaw angle. The natural wind measured in track test was set as a target the device should achieve. Histograms and spectrum of this natural wind are shown in Fig.2 and Fig.3. The spectrum in Fig.3 was calculated with a block length of 128 samples, a sampling frequency is 100Hz and the duration is 10 seconds. The longitudinal turbulence intensity of this natural wind is 10% and turbulence length scale is 1.8m. These properties of this natural wind are comparable to the strong traffic condition reported by Lindener[3]. Turbulence length scale was calculated using Taylor's hypothesis and integral time scale derived from autocorrelation [3].



Figure 1. Hot wire anemometer mounted on hood

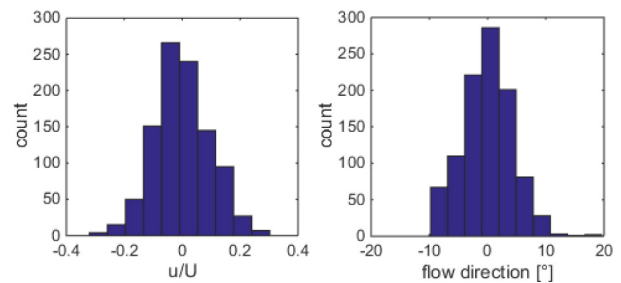


Figure 2. Histogram of flow speed and flow direction of the natural wind measured in track test

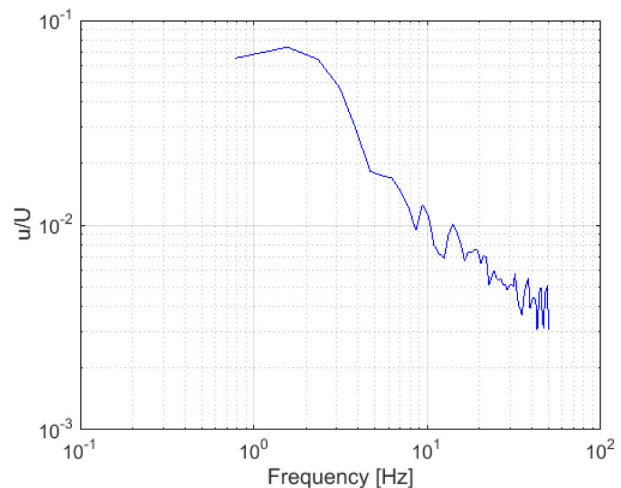


Figure 3. Flow speed spectrum of the measured natural wind in track test

As shown in the previous research [3,5,6], there are some metrics which describe turbulence such as turbulence intensity and turbulence length scale. Considering the factors of fluctuating cabin noise [6,7], turbulence intensity and flow direction are focused on for this study. Based on Fujimoto's work [11], the system consists of damper plates and airfoils. The dampers positioned on the upper portion of the nozzle outlet in the wind tunnel generate flow speed changes, while the airfoils on the lower portion generate flow direction changes (Fig.4). The dampers consist of 20 plates with a rhomboid-shaped cross section symmetrical in the back-to-front direction and its chord length is 318mm (Fig.5). By operating two adjoining plates at a time in opposite phases, the effective cross section of the nozzle outlet can be altered and the flow speed changes. The airfoils below them consist of 24 airfoils with a symmetrical NACA0012 airfoil shape and chord length is 300mm. Flow direction is changed by altering the attack angle of the airfoils. The dampers can operate at 0° and 75°, with the front-back direction as 0° and the airfoils can operate

over $-15^\circ \leq \Phi \leq 15^\circ$. The maximum frequency of the oscillation of both dampers and airfoils is 5Hz. This is based on the research by Oettle et al. [4] that shows unsteadiness of the aeroacoustic cabin noise appears when the flow fluctuates at as high as 5Hz, and also Cooper's research [5] that the turbulent intensity of the natural wind has its peak at up to 2Hz.



Figure 4. NWG

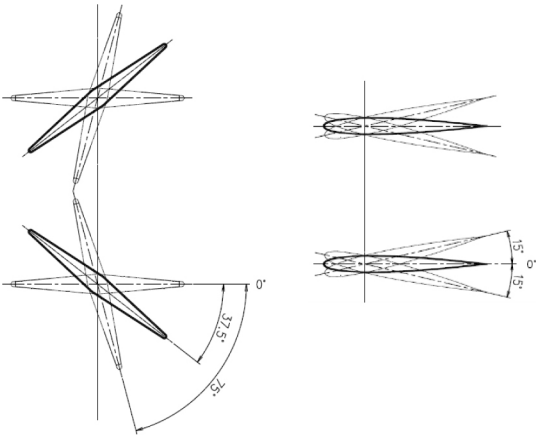


Figure 5. Cross section of the dampers (left) and the airfoils (right)

In the case of pure dipole sources, a change in the sound power level (SPL) is proportional to the flow speed ratio raised to the sixth power. Using this relationship, the effect of the flow speed fluctuation of the natural wind at above 5Hz is estimated as follows. From the natural wind speed spectrum shown in Fig.3 of which frequency resolution is about 1Hz, the oscillation amplitude of turbulence intensity at 5Hz is 2% or less than. The effect of this oscillation is estimated smaller than 0.5dB. Therefore, 5Hz maximum oscillation frequency of dampers and airfoils is considered sufficient to investigate unsteady aeroacoustic cabin noise.

Fig.6, Fig7 and Fig.8 show comparison of the target natural wind and the flow reproduced by the NWG. Both flow data were measured by hot wire anemometer on hood for 10seconds. Post-processing was done using a block length of 2048 samples and a sampling frequency is 300Hz. One can see good agreement found for fluctuations of both

flow speed and flow direction. This was accomplished by making the transfer function from the position of dampers and airfoils to flow speed and flow direction at the test vehicle.

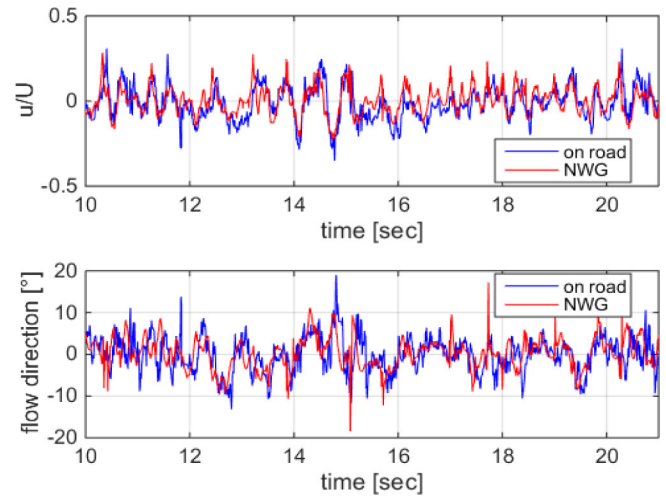


Figure 6. Flow speed and flow direction of the natural wind measured in track test and the natural flow reproduced by NWG

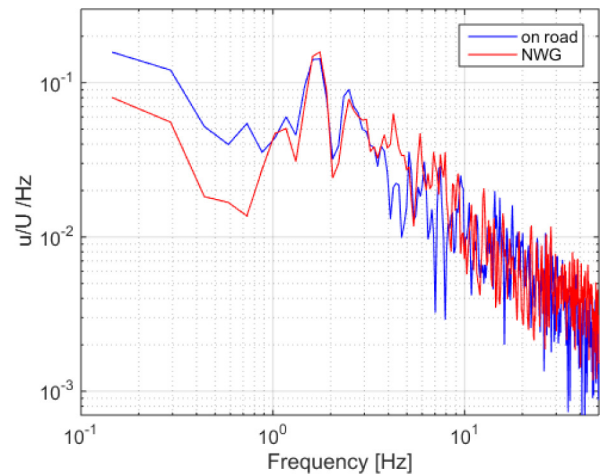


Figure 7. The spectra of flow speed for the measured natural wind in track test and the reproduced flow measured in wind tunnel with NWG

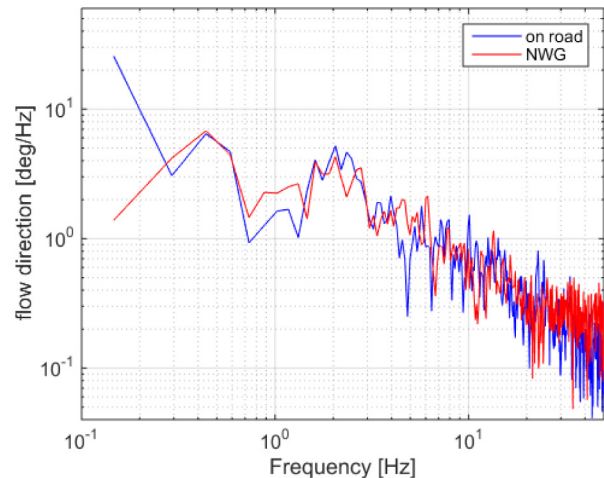


Figure 8. The spectra of flow direction for the measured natural wind in track test and the reproduced flow measured in wind tunnel with NWG