Experimental Study on Aerodynamic Noise Radiated from Delta Wing

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Abstract: Aerodynamic noise has been impairing the comfort of passengers in automobiles. Studies have shown that the aerodynamic noise is generated by the separation of the flow and the generation of the longitudinal vortex at the front pillar (A-pillar) and the door mirror. To remove the effects of the door mirror and extract the longitudinal vortex from A-pillar, studies employ the delta wing model. This research also employed the model and observed relations between the generated sound from the vortex at the A-pillar and the surface pressure fluctuation of the wing. The experiment was carried out in a wind tunnel of the Japan Aerospace Exploration Agency (JAXA) wind tunnel using the delta wing model. The radiated sound was measured using a far-field microphone to characterize the sound, and microphone array to conduct sound source exploration. Distribution of surface pressure fluctuation was measured using electret condenser microphones. Results showed that the radiated sound has a characteristic of dipole sound, and broadband sound from 1 kHz is radiated from the apex of the wing. Those indicate that sound generated from the apex of the delta wing was scattered at the surface of the delta wing, which follows the Lighthill-Curle theory. Surface pressure fluctuation with high fluctuation was distributed following the cone-like shape of the longitudinal vortex. Their peaks moved to the apex with the frequency increase. Coherence between far-field sound and surface pressure fluctuation was calculated. The point which is 70 mm inward from the apex showed higher value than those at the apex. As the diameter of the longitudinal vortex grows at the downstream, it is considered that a certain vortex scale radiates the most noise.

Key words: Aerodynamic noise, longitudinal vortex, delta wing, experiment.

Nomenclature

\[ f_s \] Sampling time
\[ SPL_i \] Sound pressure level in each point/frequency
\[ c_0 \] Sound velocity in stationary fluid
\[ x, y \] Observation point coordinates
\[ r \] Distance between observation point and object center
\[ n_i \] Inward unit normal vector on the body surface
\[ p_s \] Pressure on object surface
\[ t \] Time at the observation point
\[ S \] Surface area

1. Introduction

Aerodynamic noise generated while the automobiles cruise at high speed is impairing the comfort inside the vehicle, and the elucidation of its generation mechanism and its reduction are important issues. Previous studies have shown that the generation of the aerodynamic noise is due to the separation of the flow between the front pillar and the door mirror and the vertical vortex generated there [1]. Ogawa created a delta wing model (Fig. 1) that eliminates the influence of door mirrors and extracts the vertical vortex of the A-pillar [2]. By placing the model in the flow at an angle of attack of 15°, a flow field that closely resembles the flow around a longitudinal vortex of an automobile can be generated. The hypotenuse of the wing corresponds to the A-pillar and the outer plate corresponds to the side panel. By observing only the longitudinal vortex of the A-pillar using this, the aerodynamic noise of the body involving the generation of the vertical vortex in the low Mach number airflow has a dipole characteristic, and the quadrupole sounds radiated...
from the vertical vortex can be ignored. Yano et al. [3] performed numerical fluid analysis and wind tunnel experiments using the model and calculated the FFT of the time differential pressure fluctuation on the wing surface. As for the sound pressure in the far-field, the area equivalent to the time differential pressure fluctuation on the wing surface behaves as a sound source from the Lighthill-Curle equation. As a result of the study by Yano et al. [3], low-frequency sounds are generated near the rear end of the vertical vortex (the rear end of the delta wing), and the high-frequency sounds are generated near the front end of the vertical vortex (the delta wing tip).

The purpose of this study is to observe the noise generated by the longitudinal vortex from the A-pillar and the vibration applied to the panel using the delta wing model. The high-frequency sound at the tip of the wing, shown in the research by Yano et al. [3] and the research by Okada et al. [4], is observed using the far-field microphone and microphone array. The characteristics of the radiated sound and the sound source exploration are performed. An electric condenser microphone (ECM) is embedded on the wing surface, and the vibration applied to its surface is measured as pressure fluctuation. From these results, we consider the relationship between aerodynamic noise radiated from the wing and surface pressure fluctuation.

2. Experiment

The wind tunnel experiment was conducted in the Low-Speed Wind Tunnel (LW2) at Chofu Airfield of Japan Aerospace Exploration Agency (JAXA). The wind tunnel is a circulation-type wind tunnel with the measuring part of 2.0 m × 2.0 m square cross-section and the measuring part is 4.0 m long. One of the
measurement walls is made of Kepler to propagate the generated sound to the adjacent anechoic chamber through the wall. The delta wing model was held by the model support device under the floor of the measurement unit. At the velocity of 40 m/s, the non-uniformity of the airflow is within ±1.0% and the turbulence is within 0.1%. Fig. 2 shows a schematic diagram. The main flow velocity during the experiment was 10 m/s, 20 m/s, 30 m/s, and 40 m/s, and the wing was installed at an angle of attack of 15° in uniform flow [2].

2.1 Delta Wing

The delta wing is composed of a wing, a strut, and a base, and the wing and part of the strut are in the measurement section. The windbreak blade was attached to the columns in the measurement section to reduce background noise. Fig. 3 shows the configuration of the wing. The wing is 800 mm × 800 mm, a total thickness of 20 mm, and the apex angle is 90°. Beams and flames (12 mm × 20 mm square, steel) are in between the outer plate (thickness of aluminum 4 mm). The outer plate where the longitudinal vortex is generated has a diameter of 2 mm hole penetrated for measuring surface pressure fluctuation. The inside has a 4 mm medium density fiberboard (MDF) with a 10 mm diameter hole penetrated for fixing an electric condenser microphone (ECM). In this experiment, a wide-area MDF shown in Fig. 3 and a tip MDF as shown in Fig. 4 were employed to measure the pressure distribution at the apex of the delta wing.

2.2 Attachment of a Sphere

Howe [5] shows the acoustic radiation efficiency becomes larger by a sharp edge or a shape. The wing has a sharp apex without any chamfering or R. Therefore, the authors expected that the blunt apex shape could suppress the radiated sound by suppressing the generation of longitudinal vortices and the acoustic radiation efficiency. Therefore, a sphere with a diameter of 4 mm was attached to the apex of the wing in the experiment, and its effect was evaluated from the results of sound source search. The mounting state is shown in Fig. 5.
2.3 Far-Field Sound Measurement

A Brüel & Kjær (B&K) Type 4939 microphone was employed to measure the far-field sound. The measurable range is 4 Hz to 100 kHz. The microphone was installed in the anechoic chamber at approximately 1.8 m away from the center of the delta wing. The results are recorded through the B&K NEXUS Type 2690 amplifier and the data logger and recorded on the personal computer.

2.4 Surface Pressure Fluctuation Measurement

Two types of ECM were employed to measure surface pressure fluctuation. A diameter of 9.7 mm ECM, manufactured by DB Products Limited, was for the wide area shown in area B in Fig. 6. ECM with a diameter of 5 mm, manufactured by Four-Leaf, was for apex-area shown in area A in the same figure. These ECMs were attached to the wide-area MDF and the apex MDF shown in Figs. 3 and 4, respectively. The measurable ranges of wide-area ECM and apex ECM are 50 Hz-16 kHz and 50 Hz-20 kHz, respectively. The spacing between ECMs of the same type was 20 mm. The measurement was performed separately for the wide area and the apex. The measurement holes that were not measured were closed, and the measurement was performed for every 16 channels with the original amplifier with an amplification rate of 10 times. Fig. 7 shows the circuit diagram.

The analysis upper limit frequency $f_c$ in this experiment was 20 kHz. Sampling frequency $f_s$ and sampling time $\Delta t$ are calculated by Eqs. (1) and (2).

$$f_s \geq 2.56f_c$$

$$\Delta t = \frac{1}{f_s}$$

Fig. 6  Sampling points at the wing surface.

Fig. 7  Circuit diagram of an amplifier.
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Therefore, the sampling frequency $f_s$ is 51.2 kHz. However, four points are recorded for each wavelength to perform the more detailed measurement in this experiment. Therefore, $f_s$ was set as 81.92 kHz, the sampling time as 12 μs, and the measurement time was 26 s.

2.5 Sound Source Exploration

A sound source exploration was carried out by the Conventional Beamforming method. Each microphone on the array records sound pressure, arrival time difference, and phase difference. The results are put into the analysis grid of the Conventional Beamforming method to calculate the sound pressure distribution $S(x', y')$. Since the calculated sound pressure distribution is a point sound source, the point spread function (PSF), which considers their spatial spread, is employed as convolution integration (Eq. (3)), and the sound source distribution $A(x, y)$ can be determined [6].

$$A(x, y) = \int \int S(x', y')PSF(x - x', y - y')dxdy'$$  \hspace{1cm} (3)

The frequency and measurement distance affect the spatial resolution of the beamforming analysis result. When the target frequency is low, the sound source in the analysis result becomes large and blurry. Beamwidth is the size of the sound source (radius of a point sound source) in the analysis result. It is where the sound pressure is 3 dB below the peak value of the point sound source. Fig. 8 shows the beamwidth of the microphone array employed in this experiment. Beamwidth increases as the observed frequency decreases, and the distance required to separate the two sound sources increases. In this experiment, the maximum width of the delta wing was set to 0.80 m to measure the aerodynamic noise above 1 kHz.

The microphone array deployed has a diameter of 1.5 m and 96 microphones. They are B&K Type 4954 with a measurable range of 4 Hz-100 kHz. The microphone array was installed in the anechoic chamber at a position about 1.6 m horizontally from the center of the delta wing. It is about 0.85 m away from the far-field microphone. Sound source exploration and surface pressure fluctuation measurements were carried out at the same time.

3. Results of Experiment

3.1 Far-Field Sound

Fig. 9 shows the measured far-field sound results. A narrowband sound was confirmed between 80 and 700 Hz (left frame in the figure). A broadband sound was confirmed between 1 and 11 kHz (right frame in the figure). The narrowband sound is mostly due to wingtip vortices generated at the trailing edge of the delta wing [7]. The overall value of the sound pressure level ($SPL_{O,A}$) and its square of the sound pressure was calculated from $P_{0,A}^2$ to study the characteristics of narrowband sounds and broadband sounds from their respective speed dependences. Eqs. (4) and (5) determine $SPL_{O,A}$ and $P_{0,A}^2$. The reference sound pressure $P_0$ was 20 μPa.

$$SPL_{O,A} = 10log_{10}\left(\sum_i 10^{(SPL_i/10)}\right)$$  \hspace{1cm} (4)

$$P_{0,A}^2 = P_0^2 * 10^{(SPL_{0,A}/10)}$$  \hspace{1cm} (5)

Fig. 10 shows the calculation results. The velocity dependences of narrowband and broadband sounds were proportional to about 5.8th power and about 6.3th
characteristics of dipole sound. In the study by Ogawa [5], the velocity dependence of the broadband sound was 6.4th power, which is close to the present result. This experiment partially reproduced Ogawa’s experiment [5] as a result.

3.2 Sound Source Exploration

Fig. 11 shows the results of sound source exploration at a flow velocity of 40 m/s. The sound source was concentrated at the rear and apex of the delta wing at 1 kHz. The wingtip vortex is the cause of the rear sound source, as described above. The rear sound source contracted with the frequency increase, but the apex sound source kept on existing at 4 kHz.

Howe [2] found the sound radiation efficiency from an object in the flow increase by the presence of a solid wall in the sound field generated by the unsteady motion of a vortex and a sharp edge. In this experiment, the wing surface acted as a solid wall in the sound field, and the sharp edge was the apex of the wing. That led to the increase of the acoustic radiation efficiency at the apex of the wing, which actualized the sound field by the longitudinal vortex generated at the apex.

Fig. 12 shows the results of sound source exploration when a sphere was attached at a flow velocity of 40 m/s. No noticeable change in the sound source distribution by sphere was confirmed, compared to Fig. 11. Fig. 13 is a spectrum comparison of the surface integral of each microphone on the microphone array. The spectra matched well in all bands, and the effect of sphere attachment was not confirmed. Therefore, the change of the tip shape of the delta wing has little effect on the radiated sound, and the solid wall that contributes greatly to the increase of the acoustic radiation efficiency is considered.

3.3 Surface Pressure Fluctuations

Eq. (6) expresses the sound pressure $p$ in the far-field as the solution of the Lighthill-Curle equation where it is obtained as the surface integral of the power of flow velocity, respectively. The flow field in this experiment is a low Mach number flow similar to the flow field of an automobile. In low Mach number flow, the dipole sound caused by the pressure fluctuation on the surface of the body acts more dominantly than the quadrupole sound generated by the unsteady motion of the vortices. In particular, squared sound pressure $p^2$ of the dipole sound is proportional to the 6th power of velocity $U$ [2]. Since the sound pressure $P_{O,A}^2$ of the narrowband sound and the wideband sound is proportional to the 5th-6th power, it is considered that they have the
Fig. 11  Sound source of delta wind at 40 m/s.

Fig. 12  Sound source of delta wind at 40 m/s with sphere attached.

Fig. 13  Spectrum obtained from microphone array at 40 m/s.
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Fig. 14  Time derivative of surface pressure fluctuation.

Fig. 15  Coherence of far-field sound and surface pressure fluctuation at 40 m/s. Point which is 70 mm inner from the apex showed higher value than the apex point.

The time derivative pressure fluctuation $P_s$ on the wing surface [2].

$$p(x, t) = \frac{1}{4\pi c_0 x^2} \int n_i \frac{\partial p_s}{\partial t} dS$$  \hspace{1cm} (6)

Fig. 14 is a contour plot of the time derivative surface pressure fluctuation at a flow velocity of 40 m/s. Here, mainstream direction as $x$, the height direction of the wing as $y$, and the origin $x = y = 0$ as the apex of the wing are set. For broadband sound, the fluctuation peak was at $(x, y) = (175, 110)$ [mm], 1 kHz. At 4 kHz, the fluctuation peak occurred at $(x, y) = (135, 90)$ [mm]. From this, it was found that the peak position of the fluctuation moved to the apex of the wing as the frequency increased. The positions of large fluctuations are distributed in a triangular shape starting from the apex, which corresponds well to the conical longitudinal vortex generated at the delta wing apex.

Fig. 15 shows the coherence of broadband sound and surface pressure fluctuation at 40 m/s. The coherence $\gamma_{xy}^2$ represents the association between the two signals. It is calculated from the power spectra.
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$P_{xx}$ and $P_{yy}$ of the two signals and the cross-spectrum $P_{xy}$ as shown in Eq. (7).

$$y^2_{xy}(f) = \frac{|P_{xy}(f)|^2}{P_{xx}(f)P_{yy}(f)} \quad (7)$$

The coherence was higher at the point (70, 20) than the point (10, 0), which was slightly inside from the apex. The maximum was about 0.17. The coherence was less than 0.01 at 255 mm and 415 mm from the apex. Coherence increased significantly at 2-4 kHz and 6-10 kHz.

4. Conclusions

This study investigated the generation mechanism of aerodynamic noise emitted from the delta wing. As a result, the following was found.

(1) The radiated aerodynamic noise is roughly classified into a narrowband sound of 80-700 Hz and a broadband sound of 1-11 kHz, which have the characteristics of dipole sound.

(2) The broadband sound source concentrated on the tip of the wing. This is due to the actualization of the sound field by the longitudinal vortex caused by the increase of the acoustic radiation efficiency.

(3) The time derivative of the surface pressure fluctuation on broadband sound occurred near the wing apex and moved to the tip with the frequency increase. The maximum coherence with the far-field sound was at 70 mm inside from the tip of the wing.

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References


