Effects of heaving and pitching motions on underside aerodynamics of a sedan vehicle

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Abstract
Unsteady pressure distributions around a simplified sedan automobile model were investigated by conducting dynamic wind-tunnel testing using the newly developed forced oscillating apparatus, HEXA-X3, which can produce 6-degrees-of-freedom motion. The effects of heaving and pitching oscillation were investigated as the model simulated a vehicle running on a flat road at approximately 40 m/s and 1 Hz oscillation. The effects of the ground plate on unsteady pressure distributions over the model surfaces were measured while simulating heaving and pitching motion at Strouhal-number conditions similar to those for actual vehicles. The influence of the tubing on the frequency response of the pressure sensor was evaluated to be negligible by conducting a calibration experiment first. In the static case, the overall pressure distribution was consistent with that for a typical sedan, and the influence of the local relative flow velocity changes due to the contraction effect was observed in the underside of the model. In the forced oscillation tests, the effect of heaving and pitching motions on the flow around the underside was investigated. Effects of oscillation parameters, specifically amplitude and frequency, were investigated using the gain and phase-lag normalized by data from the steady model. Results of the test indicate that there is a characteristic distribution in pressure fluctuation, and the phenomena that become dominant in the flow around the underside vary according to location. The dynamic heaving motion was shown to change the pressure distribution, possibly due to changes in the effective angle of attack in addition to the static effect. The pitching test showed that a dynamic camber effect works in addition to those effects.

Keywords: Automobile, Forced oscillation, Dynamic wind tunnel test, Ground effect, Unsteady pressure, Pitching, Heaving, Dynamic effect, HEXA

1. Introduction

The static aerodynamic force is often evaluated to determine the running performance of automobiles with an assumed condition of running on an ideally flat road. However, in actual vehicles, vertical motion is induced by irregularities in the road surface and the corresponding reaction of the suspension system and horizontal motion is induced by steering and crosswinds. Therefore, it is known that changes in those vertical and horizontal motions generate a dynamic aerodynamic force in the vehicle body. For example, Cheng et al. (2012) investigated unsteady changes in the flow structure using a simplified vehicle model that can reproduce flow structures around an actual vehicle by running and wind tunnel tests. As a result, the physical mechanism of the flow was elucidated such that the behavior of the longitudinal vortex generated from the vehicle body greatly contributes to the aerodynamic performance. Also, Tsubokura et al. (2012) investigated the flow structure around a meandering sedan and quantitatively evaluated the aerodynamic damping effect on the vehicle body slip angle. As a result, the aerodynamic response during a yawing motion was clarified to have a time lag; further, an unsteady vortex structure and its wake were demonstrated to contribute to its generation.

Especially, heaving and pitching motions greatly affect not only the running performance and ride comfort but also the steering stability. Therefore, the evaluation of unsteady aerodynamic performance is required during the initial

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stages of vehicle development (JSAE, 2017). Various studies have been conducted for comprehension of real phenomena as the first step. In general, unsteady aerodynamic forces in automobiles affect their vibration characteristics via tires and suspension, and they are treated as problems of aerodynamic elasticity. Kojima et al. (1994) examined the influence of dynamic aerodynamics from the measurement of the response behavior of a vehicle model in a wind tunnel test by the free vibration method. As a result, dynamic aerodynamic force during longitudinal motion was modeled by a quasi-steady aerodynamic model (Blevins and Iwan, 1974), which is represented by changes in the relative inflow angle, although it is limited to only gentle changes in attitude. In addition, Kawakami et al. (2010) conducted a dynamic wind tunnel test using moving belts for an Ahmed model with a built-in forced-oscillation apparatus capable of high-speed motion. An unsteady aerodynamic model with an acceleration term added to the aerodynamic model which is above-mentioned was proposed based on the results, and this model can be applied also to longitudinal combined motion. However, the fluid force acting on a model actually has a distribution over a three-dimensional object with a complicated shape, such as an automobile. Sato et al. (2010, 2011) investigated the aerodynamic force and fluctuation characteristics in the flow field for movement in the heaving and pitching directions via large-eddy simulation analyses using the arbitrary Lagrange-Eulerian method for the Ahmed model. These characteristics were shown to depend on the distribution of fluid force on the surface of the model and its oscillation frequency. Furthermore, to simulate the running state, the ground is generally moved at the flow velocity. But it was shown that the ground speed has almost no influence on the dynamic effect, even when the ground speed is zero.

Kawamura and Ogawa (2014) conducted a towing tank test using a one-degree-of-freedom oscillating apparatus with a six-component balance and numerical analysis. They quantified the unsteady lift characteristics of a simplified sedan model moving in the heaving and pitching directions. In addition, the dynamic effects were explained with a simple spring mass model with two degrees of freedom, which simulates the attenuation effect of the unsteady lift force. In addition, Kuratani et al. (2018) conducted dynamic wind-tunnel testing (DWT) in a wind tunnel equipped with a moving belt using a similar model with a built-in heaving-oscillation device. At the same time, the dynamic effect under heaving and pitching oscillation was evaluated by unsteady Reynolds-averaged Navier–Stokes simulation analyses using a realizable K-epsilon turbulence model. As a result, an unsteady but very small drag was shown to be induced by the vertical vortex generated in the wake of the model with a vertical oscillation.

The results of the previous studies mentioned above suggest that it is necessary to clarify the local phenomena for understanding the dynamic characteristics of flow around a three-dimensional object. This study focused on the local flow field in the flow around the underside of automobiles, which is strongly influenced by the ground, and investigated the influence of dynamic fluid phenomena. Here, DWT was used to experimentally elucidate the flow around objects oscillating dynamically (Asai et al., 2014). In DWT, it is possible to simulate the actual motion in the wind tunnel by moving the model using an actuator, and to directly elucidate the actual phenomenon with the wind tunnel test. In the present study, an original robot manipulator was applied as an oscillating apparatus to the DWT using a fixed ground plate simulating the ground. Unsteady pressure distributions were measured with a multipoint pressure scanner built into a simple automobile scale model, where the influence of the sensor tubing on the frequency response of the pressure sensor was evaluated by conducting initial calibration experiments. The local dynamic effect in the flow under the model was investigated based on the measured unsteady pressure distribution, they were quantitatively evaluated using gain and phase difference by comparing with the quasi-steady effect which is obtained from the static test results.
Nomenclature

\(a\) : speed of sound
\(C_p\) : pressure coefficient
\(C_p'\) : fluctuation component of \(C_p\)
\(\bar{C}_p\) : time-averaged \(C_p\) in static case
\(\hat{C}_p\) : phase-averaged \(C_p\)
\(f\) : oscillating frequency (Hz)
\(f_s\) : frequency of \(P_i\) (Hz)
\(G\) : ratio of \(C_p\) in static case and dynamic case
\(h\) : ground clearance (m)
\(h^*\) : non-dimensional ground clearance, \(h/L\)
\(L\) : total length (m)
\(n\) : polytropic constant
\(P\) : pressure fluctuation (Pa)
\(q\) : dynamic pressure of free stream (Pa)
\(Re\) : Reynolds number based on \(L, U_\infty L/\nu\)
\(St\) : Strouhal number based on \(L, fL/U_\infty\)
\(T\) : oscillating period, \(f^{-1}\) (s)
\(t\) : time (s)
\(U_\infty\) : freestream velocity (m/s)
\(V\) : volume (m\(^3\))
\(x, y, z\) : cartesian coordinates (m)
\(\Gamma\) : propagation coefficient of pressure wave passing through the tube
\(\Delta h\) : heaving amplitude (m)
\(\Delta \theta\) : pitching amplitude (deg)
\(\theta\) : pitch angle (deg)
\(\nu\) : kinematic viscosity coefficient of the free stream (m\(^2\)/s)
\(\phi\) : phase difference of \(\hat{C}_p\) with respect to motion (deg)
\(\omega\) : angular frequency, \(2\pi f_s\) (rad/s)

Subscripts

\(0\) : mean value
\(i\) : input value
\(\max\) : maximum value
\(t\) : tube value
\(u\) : output value
\(v\) : pressure transducer

2. Experimental program
2.1 Test facility

Experiments were carried out in a wind tunnel equipped with a ground plate in a test section using the forced oscillation apparatus shown in Fig. 1. This study employed the Low-Turbulence Heat-Transfer Wind Tunnel at the Institute of Fluid Science, Tohoku University. This wind tunnel has a single-path, closed-circuit design with an open-type test section. The airflow comes from the nozzle of regular octagonal cross section, which has a width of 0.81 m. The test section has a length of 1.42 m, and the mean velocity within it can be controlled with an accuracy of 0.2%. Further details of the wind tunnel and the flow characteristics in the tunnel are given in Ito et al. (1992).

The forced oscillation apparatus used in the DWT oscillates according to an amplitude command. Also, it has sufficient rigidity with a safety factor against inertial force generated by the weight and oscillation of the model. This apparatus, referred to as HEXA-X3 (hereafter HEXA), was newly developed and used for this study. It has a hexa-type parallel link mechanism and can move with six degrees of freedom. The actuators of HEXA are six servo motors...
(SHA40A51SG, Harmonic Drive Systems) mounted on a base plate. The first link of each is made of stainless steel and directly fixed to the rotating part of each motor. For controlling the manipulator, VxWorks (Wind River Systems Co., Ltd.), an operating system that has a real-time response capability, was adopted. Further details and capabilities of the oscillating apparatus in the DWT are described by Maruyama et al. (2017).

2.2 Test model and experimental setup

The orthogonal coordinate system follows a typical convention: the x-axis is aligned with the incoming flow and is positive downstream. The z-axis is normal to the ground plate and is positive downward, as shown in Fig. 1, because the model is mounted to HEXA while being inverted by a support rod attached to the center-of-gravity position. The clearance between the support device and the model is zero because it is filled with sponge. Also, the freestream is parallel to the x-axis.

This study employed an 8% scale ($L = 0.376 \text{ m}$) simplified sedan model with the same shape as the model used by Kawamura and Ogawa (2014) shown in Fig. 2. This model was made from acrylic resin by stereolithography. The model width (length in the y-direction of the model) was 0.144 m, and the wind tunnel blockage rate in the reference attitude was approximately 1.6%, including the support. There were 65 static pressure ports on the surface of the model, and they were connected to a differential pressure electronic pressure scanning module (ZOC33/64Px-1psid, hereafter ZOC) installed inside the model with a urethane tube. If the oscillating speed is too high or the amplitude is too large, the influence of the forced oscillation is a concern, but this did not appear in this experiment. Static pressure of the freestream was used as the reference pressure. Tubes, cavities, and other signal relays between the surface of taps and the sensor surface affect the frequency response characteristics. Therefore, to measure unsteady pressure, it is necessary to investigate the static frequency response characteristics in the measurement system. According to the theoretical formula presented by Bergah and Tijdeman (1965), both the gain and phase difference were less than the measurement accuracy of the ZOC module in the present study. Furthermore, it was confirmed that responsiveness to tubing was negligible as a result of calibration experiments using a fluctuating pressure generator, which are summarized in Appendix A.

For synchronization of each measurement instrument, a trigger signal was outputted when the HEXA started excitation motion. These measurement instruments started scanning when the measuring instrument received the trigger signal.

Fig. 1  Experimental setup of DWT.  
Fig. 2  8% scale simplified vehicle model. Upper panel shows shape of the model. Lower panel is a sectioned drawing. The dots represent the tap positions on the center cross section.
2.3 Experimental method

The experimental conditions for the static tests are presented in Table 1. The tests were conducted at a constant Reynolds number $Re = 5.0 \times 10^5$ while changing two parameters: ground clearance $h$ ($\theta = 0 \text{ deg}$) from the ground plate to the underside of the model and pitch angle $\theta$ ($h^* = 0.043$). $\theta$ is defined to be the angle between the ground and the centerline of the model and it was positive when the model had a nose-up attitude with respect to the ground plate as shown in Fig. 3. Although the Reynolds number is smaller than the real scale automobile running, the flow velocity is lowered and the Strouhal number of the target condition is realized because the investigation of dynamic effects is focused on in the present study. Pressure measurements were performed with the ZOC module, and the outputs were recorded and controlled by a digital service module (DSM3001, Yokogawa) with a sampling rate of 260.4 Hz. The sampling duration was 60 s, and the results shown here were obtained by averaging measured values for each condition in the static test. Apart from the pressure measurement test, the model surface flow was visualized by oil-flow for the representative case. For visualization, we used a silicone oil (viscosity, 15 cSt) to which titanium dioxide and oleic acid were added.

The model was placed parallel to the ground at a position where $h^* = 0.043$ as a reference attitude, and forced oscillation tests were conducted under the conditions shown in Table 2. In these tests, the heaving and pitching motions in the vertical direction are given to the model. The model was heaved up and down in the former and latter halves in the cycle, respectively. Also, it was pitched up and down in the former and latter halves in the cycle, respectively. The motion starts from the minimum angle $\theta_0 - \Delta \theta$ (pitching) or the minimum clearance $h_0 - \Delta h$ (heaving). Here, the mean positions are the same in all the cases, $\theta_0 = 0 \text{ deg}$ and $h_0 = 1.6 \times 10^{-2}$ m. The position as a function of time $t$ is given by

$$h(t) = h_0 - \Delta h \cos(2\pi ft),$$

$$\theta(t) = \theta_0 - \Delta \theta \cos(2\pi ft),$$

where $f$ is the oscillation frequency and $\Delta h$ and $\Delta \theta$ are the amplitudes. The forced oscillation tests were conducted based on these parameters at a constant Reynolds number of $5.0 \times 10^5$.

![Figure 3 Oscillation direction](image)

Table 1 Experimental conditions for static tests.

| $h^*$       | 3.2, 3.5, 3.7, 3.9, 4.0, 4.1, 4.3, 4.4, 4.5, 4.7, 4.8, 5.1, 5.3 ($\times 10^{-2}$) |
|-------------|-------------------------------------------------------------------------------------|
| $\theta$ (deg) | -1.00 – 1.00, incremented by 0.25                                                  |

Table 2 Experimental conditions for dynamic tests.

| Case        | $\Delta h/h_0$ | $\Delta \theta$ | $St$ |
|-------------|-----------------|-----------------|------|
| h125th0st02 | 0.125           | 0               | 0.02 |
| h125th0st06 | 0.125           | 0               | 0.06 |
| h125th0st10 | 0.125           | 0               | 0.1  |
| h250th0st02 | 0.25            | 0               | 0.02 |
| h250th0st06 | 0.25            | 0               | 0.06 |
| h250th0st10 | 0.25            | 0               | 0.1  |
| h0th1st02   | 0               | 1.0             | 0.02 |
| h0th1st06   | 0               | 1.0             | 0.06 |
| h0th1st10   | 0               | 1.0             | 0.1  |

3. Results and discussion

3.1 Static test

Figure 4 shows the time-averaged $C_p$ distribution for the 18 taps on the model center cross section in the static test with changing attitude. Figure 4(a) and (b) shows the effects of the ground clearance and the pitch angle, respectively. The dotted curve shows the roof side (hereafter the upper side), and the dashed curve shows the underside. In the reference case, the overall pressure distribution is consistent with that in a general sedan-type vehicle (Obidi, 2014). A sharp drop in the pressure distribution appears behind the upper side at $x/L = 0.4$ to 0.7 but this is considered to be the influence of the support device for the model. Not only that, it is considered that the pressure drop is caused by the flow is attached and accelerated at the roof end corner.

In Fig. 4(a), the influence of the changes in local flow velocity relative to freestream is observed on the underside...
due to the increase/decrease in the cross-sectional area of the flow path, which is a so-called ground effect. The trend in the negative pressure region of the lower leading edge ($x/L < 0.15$) is different from that in the other parts, it agrees with the report by Sato et al. (2010). Conversely, the influence of the ground clearance hardly appears on the upper side. It suggests that the relative velocity change in the flow between the ground and the underside of the model has a small influence on the overall flow fields around the vehicle except for the flow fields near the underside. In addition, the result of the visualization test is shown in Fig. 5. The separation bubbles are observed but the variation in the length of the separation bubbles due to the difference in $h^*$ could not be observed in this test.

In Fig. 4(b) as well, no influence of the attitude change is observed in the rear upper side, and a pressure drop at $x/L = 0.4$ to 0.7 appears to be caused by the supporting rod, as described above. The trend of change in $C_p$ at the rear side of the rotational center (center of gravity, $x/L = 0.5$) becomes opposite to that at the front side. These trends are consistent with the general experience that the stagnation point moves when the angle of attack changes. Changes in the pitch angle near the ground cause not only angle-of-attack effects but also cause a contraction effect. Under the pitch down condition, the flow around the front side is accelerated due to the narrow area between the ground and the underside of the model and it creates a strong low-pressure region. In contrast, the flow decelerates around the rear side because the area between the ground and the underside of the model is wider on the downstream side. The change of pressure distribution in the rear side is smaller than that in the front side because the flow area change is milder due to the diffuser area shown in Fig. 2. Thus, the ground clearance changes are different for the front and rear sides when the pitch angle varies, and the relative velocity varies locally.

(a) Effect of ground clearance

(b) Effect of pitch angle

Fig. 4 $C_p$ distribution on the center cross section for the upper side and underside.

Fig. 5 Result of visualization test on leading edge of the underside in the reference condition ($h^* = 0.043$). A is the primary separation line, B is the secondary separation, and C is reattachment.

3.2 Forced oscillation tests

3.2.1 Heaving test

The influence of relative attitude change was shown to appear clearly along the underside in Section 3.1. Therefore, this section focuses only on the underside. Figure 6 shows Lissajous curves for the phase-averaged pressure fluctuation for three representative points in the front, center, and rear. The pressure coefficients obtained by the static test are also shown in the figure for comparison. Figure 6(b) and 6(c) shows that the fluctuation trends are similar to those of the static test results. It can be said that only quasi-stationary effects appear around the central area. Also, no dynamic effect appears in the area where no fluctuation occurs during the static test. However, a counterclockwise hysteresis appears as a dynamic effect, as shown in Fig. 6(a). Drela (2014) reported that the inflow angle varies according to the moving speed of the model by the vertical gust velocity when the model oscillates in the vertical direction. This dynamic effect is considered to be remarkable at the front area owing to the movement of a stagnation point with model motion.

These results suggest that the influence of the oscillation appears in the $C_p$ distribution for the underside of the...
model. Figure 7(a) compares pressure fluctuations on the underside of the central section for the static case and the dynamic case h250th0st10. In the static case, $C_p'$ represents the difference between the maximum and minimum values in $\tilde{C}_p$ for all cases. Also, it represents the fluctuation of $\tilde{C}_p$ in the dynamic case. When discussing phenomena on a moving object, the gain and phase difference are defined for attitude change as Sato et al. (2010, 2011) in many cases. However, we consider that separation of static and dynamic effects is important because we focus on dynamic effects in pressure distribution in this research. Therefore, we consider that the evaluation method by the difference from the quasi-steady condition as described above is optimal for extraction of dynamic effects.

The figure shows that although the pressure fluctuation increases due to the oscillation, the amount is not constant throughout the surface. Figure 7(b) shows the relationship between the gain of the pressure fluctuation in each area and the oscillating frequency. Here, $G$ represents an average of the ratio of $C_p'$ in the static and dynamic cases. The figure suggests that oscillation did not have an influence for $x/L > 0.85$. In the other areas, a trend in which the amplification ratio increases as the oscillating frequency increases is observed. Figure 7(c) and (d) illustrates the phase difference $\phi$ of $\tilde{C}_p$ compared with the static case. Here, $\phi = 0$ corresponds to the no-phase-lag condition. In addition, the sign of $\phi$ is set to be positive for the phase lead of $\tilde{C}_p$. At the leading edge, $\tilde{C}_p$ is constantly delayed by approximately 90 deg irrespective of the oscillating condition. These figures indicate a trend in which the phase difference gradually increases for $0.2 < x/L < 0.85$. The trends agree with the trends indicated by Sato et al. (2010). Figure 7(c) indicates that the phase difference increases as the oscillating amplitude increases, although there is no appreciable difference. Also, Fig. 7(d) suggests that the dynamic effect is small in the case of $St = 0.02$, but there is approximately no influence due to the difference in the oscillating frequency in the other cases.

Fig. 6 Phase-averaged Lissajous curves of $\tilde{C}_p$ at representative points on the underside in forced heaving oscillation tests with Strouhal number of 0.10 and amplitude of $Ah/h_0 = 0.25$ (case h250th0st10) and $\tilde{C}_p$ of static test results at each $h^*$. (a) indicates front (around the leading edge) area, (b) is central (around the rotational center) area, and (c) is rear (around the diffuser) area.

Fig. 7 Comparison with static test results in heaving test. Panel (a) represents the effect of oscillation for case h250th0st10, (b) shows the relationship between gain of the pressure fluctuation and Strouhal number in each underside location, (c) indicates the effect of the amplitude on the phase difference, and (d) indicates the effect of the oscillating frequency on the phase difference.
### 3.2.2 Pitching test

Similarly, the results of the pitching oscillation test for case h0th1st10 are shown in Fig. 8. In the pitching oscillation test, a hysteresis caused by the dynamic effect was observed in the phase-averaged pressure coefficient in addition to the static effect of the pitch angle. The effect appears as clockwise hysteresis on the front side and counterclockwise hysteresis on the rear side, and the motions they produce act to amplify the pressure fluctuations. Although not shown here, pressure fluctuation was not observed at $x/L = 0.97$, as for the case of heaving oscillation.

Figure 8 suggests that the influence of oscillation appears in the pressure distribution on the model underside also in the pitching oscillation test. Figure 9(a) compares the pressure fluctuation on the underside of the central section for the static case and dynamic case h0th1st10. The figure shows that although the pressure fluctuation increases due to the pitching oscillation, it depends on the location on the underside. In particular, the pressure fluctuation was not observed in both the static case and dynamic test at $x/L > 0.85$. Figure 9(b) shows the relationship between the gain in pressure fluctuation in each area and the oscillating frequency. On the front side, the gain is small and constant irrespective of the oscillating frequency. In contrast, the trend is different between the fore and aft sides around the center of the oscillation motion. The gain increases linearly with respect to the oscillating frequency in front of the center of the oscillation motion, whereas it is constant behind the center. Figure 9(c) compares the effect of oscillating frequency on phase difference. The phase difference was substantially reduced in the case of $St = 0.02$. In the other cases, no influence due to the difference in oscillating frequency is observed. The difference shows a delay of 90 deg at $x/L = 0.54$, and the delay decreases in front of and behind the center of the motion.

The dynamic effect of pitching oscillation is considered to appear only at the center area. This effect is considered to be due to the change in the relative angle of attack and the dynamic camber effect, which was indicated by Ogawa et al. (2012). The flow around the underside appears to be convex about the oscillation center due to the dynamic camber effect during the downward pitching motion. This indicates that the relative velocity of the flow around the underside accelerates and decelerates according to Bernoulli’s law, and that it affects pressure fluctuation on the underside of the model near the ground. Thus, it depends on the convex shape, the influence of the oscillating frequency is considered to be less sensitive. Kuratani et al. (2018) showed a trend that lift on the front side decreases during downward pitching motion and that drag increases due to these phenomena. This suggests that the pressure fluctuation generates a lift that agrees with the trend.

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![Fig. 8](image-url)

Fig. 8 Phase-averaged Lissajous curves of $\bar{C}_p$ at representative points on the underside in forced pitching oscillation test with Strouhal number of 0.10 (Case h0th1st10) and $\bar{C}_p$ of static test results at each $\theta$. (a) indicates front (around the leading edge) area, (b) is central (around the rotational center) area, and (c) is rear (around the diffuser) area.
4. Conclusions

In this study, the DWT of an 8% scale simplified automobile model was carried out, and dynamic effects in the flow around the automobile were investigated. In the experiments, the newly developed oscillating apparatus HEXA was employed. The unsteady pressure distribution on the surface of the model was measured, and the influence of vertical oscillation near the ground plate was investigated. Also, the dynamic effects of the local pressure field were evaluated. A multipoint pressure scanner was employed for unsteady pressure measurement.

In the static test, the influence of changes in the model attitude \( h \) and \( \theta \) appeared prominently on the underside. A separation bubble was observed by the visualization test. However, the influence of \( h^* \) could not be observed in the visualization test unfortunately. In the static test with changing pitch angle, a contraction effect was also observed in addition to the effect of the change in the angle of attack on the pressure distributions.

In the forced oscillation test, the effect of heaving and pitching oscillation on the flow around the underside was investigated because the influence of the model attitude changes appeared predominantly on the underside in the static tests. The characteristics of phase-averaged pressure fluctuation were affected by the oscillating amplitude and frequency in the heaving test, and by oscillation frequency in the pitching test. Furthermore, they were quantitatively evaluated by gain and phase difference compared with those of the static test result, the dynamic effect is discussed by separating the quasi-steady and unsteady phenomenon. In the heaving oscillation test, a dynamic effect was observed in addition to the static effect due to the attitude change. The pressure fluctuation seems to be caused by the effect of a change in the apparent inflow angle effect. The dynamic motion not only amplifies the pressure fluctuation but also produces a phase delay. In the pitching oscillation test, a dynamic camber effect was observed for Strouhal numbers of 0.06 or more. Because it depends on the apparent convex shape, the influence of the oscillating frequency is considered to be less sensitive. In fact, this effect was constant irrespective of the oscillating frequency, and different trends were observed between the areas in front of and behind the center of the oscillation motion.

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Appendix A: Influence of sensor tubing on the frequency response

In this experiment, the taps on the model surface and the ports for the ZOC module were connected using urethane tubing. Therefore, it is necessary to investigate the frequency response characteristics in the measurement system beforehand and to know the influence on the unsteady pressure measurements. Bergh and Tijdeman (1965) provided the following theoretical equation for a structure with a pressure transducer:

\[
\text{Eq. (10)}
\]
\[
\frac{P_u}{P_i} = \left[ \cosh \left( \frac{a \omega \Gamma}{L} t \right) + \frac{\nu \eta_2}{\nu \eta_1} \left( \frac{a \omega \Gamma}{L} \right) \sinh \left( \frac{a \omega \Gamma}{L} t \right) \right]^{-1},
\]

where \( V \) is the volume at the end of a single tube, as shown in Fig. 11. In this study, the frequency characteristics on the ZOC measurement system for the model were evaluated experimentally. The test conditions are shown in Table 3. Also, Fig. 12(a) shows the fluctuating pressure generator used for the experiment. This device was a plate with an embedded semiconductor pressure transducer (XCL-152-5SG, Kulite; hereafter Kulite) with a tap on the upper surface of the chamber. Also, the speaker (NSWl-205-8A, AuraSound) shown in Fig. 12(b) was attached to the bottom.

The influence of tubing was investigated by measuring the \( P_i \) generated by the speaker on the plate surface with the Kulite transducer and a pressure sensor connected to the tap via tubing. However, it was shown that the gain and phase difference under this test condition were less than the measurement accuracy of the ZOC module when calculated using the catalogue value. In other words, it is suggested that accurate evaluation cannot be achieved when using an actual measurement system in this evaluation test. Therefore, a differential pressure transducer with built-in amplifier (10INCH-D2-4V-MINI, hereafter PS), shown in Fig. 12(c), was used in this evaluation test instead of the ZOC module.

The sensor output was recorded with LabVIEW via a data acquisition digitizer (PCIe-6323) along with the Kulite signal at a sampling rate of 2,000 Hz in all cases. The gain characteristics were evaluated by the amplitudes of the signals of the Kulite and PS extracted with only \( f_s \) via fast Fourier transform analysis. Furthermore, the phase characteristics were evaluated by the phase shift when the value of the cross-correlation function of both the signals became maximum.

Figure 13 shows the experimental results and the theoretical values obtained from Eq. (3). Figure 13 illustrates that the gain approximately agrees with the theoretical value and that the phase differences qualitatively agree with each other except for the high-frequency range. The tubing showed no influence in the low-frequency range similar to the oscillation frequencies used in the forced oscillation test. These results verified that it was unnecessary to make corrections for the influence of tubing in this study.

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**Table 3 Experimental conditions.**

| \( L_t \) | 0.05, 0.30, 0.80 |
| --- | --- |
| \( f_s \) | 1 – 500 |

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**Fig. 11** Conceptual diagram of tube and pressure transducer

**Fig. 12** Experimental equipment. (a) Fluctuating pressure generator; (b) Speaker; (c) Pressure sensor.

**Fig. 13** Comparison of measured value and theoretical values. Panel (a) shows the gain characteristics, and (b) shows the phase characteristics. Symbols are the measured value, and lines are theoretical values obtained from Eq. (3).
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