Unsteady wind force on an elliptic cylinder subjected to a short-rise-time gust from steady flow

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ABSTRACT: The properties of unsteady wind force on an elliptic cylinder under a rapid change from steady flow were investigated using a gust wind tunnel. As a result, we confirmed that the overshoot phenomenon of wind force occurred under a short-rise-time gust from steady flow as well as from calm. And it was found that the overshoot coefficient, defined by the ratio of maximum to a steady-state value of wind force, decreased with an increase in the ratio of the initial wind velocity to the target wind velocity. For each ratio of the initial wind velocity to the target wind velocity, the overshoot coefficient was determined by an expanded non-dimensional rise time composed of rise time, body size, and initial and target wind velocities.

KEYWORDS: Overshoot of wind force, Non-dimensional rise time, Gust wind tunnel test.

1 INTRODUCTION

A wind force acting on a structure under a gust with a very short rise time, which occurs in high winds associated with typhoons and tornadoes, differs from a quasi-steady aerodynamic force in consideration of a small turbulent flow, and occasionally reaches a large value not seen in a steady wind flow. Several reports have shown that an overshoot phenomenon bringing a much bigger wind force than in a steady flow occurs on a structure subjected to a short-rise-time gust. Taneda1 investigated unsteady lift acting on an elliptic cylinder rapidly started at an angle of attack using a water tank test and reported that a remarkably big lift appeared just after starting. Sarpkaya2 showed that the drag of a body increased by approximately 25 percent during the growth of the first pair of vortices as compared to a steady flow, using an impulsive flow test over circular cylinders in a vertical water tunnel, adding some results of potential flow analyses around the circular cylinders. Morison et al.3 evaluated the force acting on a small cylinder in a flow with acceleration using a semi-empirical equation added to an inertia term proportional to flow acceleration. Nomura et al.4 computed unsteady drag acting on a square cylinder under a sudden change of flow speed and reported that the drag component proportional to flow acceleration played quite an important role in the total unsteady drag when the flow speed was relatively low. Matsumoto et al.5 measured transient drag on a two-dimensional cylindrical model under a suddenly-changing wind speed using a wind tunnel test with a working section of 200mm by 200mm square and reported an overshoot phenomenon in which the drag increased by approximately 20% compared to the force in a steady flow.

We have investigated the unsteady wind force on a body under a short-rise-time gust from calm using a specially-equipped wind tunnel, which could generate gusts with a rise time of 0.2 to 5 seconds from a flat calm by controlling the rotation speed of the blade rows. Takeuchi et al.6 investigated the effects of the rise time of a step-function-like gust on the overshoot phenomenon of wind forces acting on a railcar-like body, and reported that the overshoot phenomenon was
more remarkable in the case of gusts with a shorter rise time. Takeuchi et al.\textsuperscript{7} confirmed some overshoot phenomena of wind forces acting on an elliptic cylinder with some angles of attack, and reported that a non-dimensional rise time composed of rise time, body size, and target wind velocities considerably influenced the occurrence of the overshoot phenomenon. Takeuchi et al.\textsuperscript{8} investigated the effect of the inertia force proportional to wind acceleration on the overshoot of wind force on an elliptic cylinder subjected to step-function-like gusts, and reported that the inertia force strongly influenced occurrence of the overshoot phenomenon in the case that the non-dimensional rise time was relatively small, but the overshoot phenomenon was due to other factors in the case of relatively large non-dimensional rise times.

Many of these reports have studied unsteady wind force acting on a body under a short-rise-time gust from calm. The unsteady wind force under a short-rise-time gust from steady flow has not been well studied. However, Tomokiyo et al.\textsuperscript{9} investigated the features of the short-rise time wind gusts picked up from observation data of NeWMeK (Network for Wind Measurement in Kyushu, presented by Maeda & Ishida\textsuperscript{10}), and reported that many of them were short-rise-time gusts from steady flow. Therefore, it is necessary to clarify the unsteady wind force on a body subjected to a short-rise-time gust from steady flow.

In this study, the properties of unsteady wind force on an elliptic cylinder under a short-rise-time gust from steady flow were investigated using wind tunnel tests. Short-rise-time gusts from steady flow were generated by the control of blade rows which were installed for generating a pulsation flow. We measured the unsteady drag and lateral forces on an elliptic cylinder under such gusts and organized the measured data by the non-dimensional rise time expanded to a short-rise-time gust from steady flow.

2 GENERAL SPECIFICATIONS OF THE WIND TUNNEL TEST

We used a wind tunnel of the Eiffel type at Kyushu University. The site plan of our testing system is illustrated in Figure 1a. The section area of the working space was 1.5m by 1.5m and the available length was 3m. The wind tunnel can generate a step-function-like gust to rise from a calm state by controlling the rotation of flat blade-rows. In this study, a short-rise-time gust from steady flow was generated by the following procedures. Firstly, we generated a steady flow with a constant wind velocity controlled by opening the blade rows partially. Secondly, we opened the blade rows quickly and fully, to generate a short-rise-time gust. An example of the time evolution of the wind velocity generated by control of the blade rows is shown in Figure 1b. The rise time of a gust, $t_r$, is defined as the time required for an approaching wind to reach a target wind, and the initial wind velocity, $U_s$, and the target wind velocity, $U_t$, are referred to as the initial and reached winds, respectively.

![Site plan of wind tunnel and time evolution of wind velocity.](image-url)
In our earlier study, in which we generated step-function-like gusts from a calm state, we set the time required to open the blade rows as the rise time, because the rise time of a gust was almost equal to the time required to open the blade rows (Takeuchi et al. 7). In this study, the rise time was decided by the following equation:

\[ t_r = 2.348 \left( t_{80} - t_{20} \right) \]  

(1)

where \( t_{80} \) = the time for wind velocity to increase by 80% of the difference between \( U_s \) and \( U_t \); and \( t_{20} \) = the time for wind velocity to increase by 20% of the difference.

The rise time, \( t_r \), in Equation 1 was determined from the cubic function shown in Figure 1b which fits the time evolution of wind velocity. It should be noted that regarding the rise time of a short-rise-time gust from calm, \( t_r \) in this paper is different from that in our earlier study for the above reason. The wind velocity in the working space was confirmed by a hot-wire anemometer and an ultrasonic anemometer. The wind velocity was scanned at a frequency of 1000Hz.

We investigated some features of short-rise-time gusts generated by the above-mentioned
procedures. Figure 2 shows the distribution of the averaged values of wind velocity measured under steady flow controlled by opening the blade rows. We generated steady flows with 20%, 50%, 80% and 100% of wind velocity reached when the blade rows were opened fully, and measured wind velocity at 4 points over the aerodynamic balance, as shown in Figure 2a. Figure 2b indicates that the steady flow controlled by opening the blade rows was uniform. Figures 3 and 4 show the comparisons of the time evolutions of wind velocity measured at two points in the wind tunnel together under a short-rise-time gust. Figure 3 shows the comparisons of the time evolutions of wind velocity measured at points A and B over the aerodynamic balance, and indicates that they rose simultaneously under short-rise-time gusts from steady flow and calm. Figure 4 shows the comparisons of the time evolutions of wind velocity measured at point A and point C located 1000mm windward of point A, and indicates the same result as Figure 3. Thus, it was found that the wind velocity in the wind tunnel on the whole rose simultaneously under a short-rise-time gust from steady flow as well as under a short-rise-time gust from calm.

The specimens were two elliptic cylinders of axial ratio 2:1, both 500mm high, one 70mm and the other 140mm in major axis, as shown in Figure 5, and referred to as “Small-cylinder” and “Large-cylinder”, respectively. They were fixed to the aerodynamic balance with a 45-degree angle of attack, and the drag and lateral forces acting on them were scanned at a frequency of 1000Hz. They were subjected to step-function-like gusts with a target wind velocity, \( U_t \), between 2.0m/s and 7.0m/s, with the ratio of the initial wind velocity to the target wind velocity, \( U_s/U_t \), between 0.0 and 0.9 and rise time, \( t_r \), between 0.1sec and 1.4sec.

3 PROPERTIES OF UNSTEADY WIND FORCE ON ELLIPTIC CYLINDER UNDER SHORT-RISE-TIME GUST FROM STEADY FLOW

3.1 Overshoot of wind forces

Figures 6-9 show the time evolutions of the wind velocity, drag and lateral force on Large-cylinder, when the wind velocity reached 2.0m/s from 0.0m/s, 0.4m/s, 1.0m/s and 1.6m/s in a rise time of approximately 0.15sec. We confirmed that the overshoot phenomena of drag and lateral forces occurred under a rapid change from steady flow as well as from calm. But the peak of wind force changed with the initial wind velocity. The drag in the case of \( U_s = 0.0m/s \) had two peaks at approximately 0.1sec and 0.3sec. The first peak of drag in the case of \( U_s = 0.4m/s \) was smaller than that in the case of \( U_s = 0.0m/s \). The drag in the cases of \( U_s = 1.0m/s \) and 1.6m/s had just one peak. Referring to Takeuchi et al.\(^8\), it would appear that the first peaks of drag in the cases of \( U_s = 0.0m/s \) and 0.4m/s were caused by the inertia force proportional to wind acceleration. The inertia force and the wind acceleration decreased with an increase in the initial wind velocity, and the first peak of drag decreased with an increase in the initial wind velocity. In con-

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**Figure 5. Specimens.**

- Small-cylinder: \( D = 70 \text{ mm} \)
- Large-cylinder: \( D = 140 \text{ mm} \)

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Contrast, it is believed that the second peak of drag was due to unsteady vortex shedding. The value of the second peak of drag in the case of \( U_s = 0.0 \text{m/s} \) was hardly different from that in the case of \( U_s = 0.4 \text{m/s} \). In cases where initial wind velocity was larger than 0.4m/s, the peak value decreased with an increase in the initial wind velocity.

The lateral force was little affected by the inertia force proportional to the wind acceleration,
and had just one peak due to unsteady vortex shedding. The peak value of lateral force decreased with an increase in the initial wind velocity as well as that of drag.

3.2 Effects of parameters of short-rise-time gust on overshoot phenomenon

Figure 10 shows the relationship between the overshoot coefficient and the rise time for Large-cylinder in the case of \( U_t = 3.0 \text{m/s} \) and \( U_s / U_t = 0.0, 0.3 \) and 0.6. The overshoot coefficient is defined as the ratio of the peak value to the steady value, as shown in the following equation:

\[
\text{Overshoot coefficient} = \frac{\text{Peak wind force}}{\text{Steady wind force}}
\]

where the peak wind force is defined as the actual maximum force, and the steady wind force is defined as the mean over 20 seconds in a steady flow.

For each ratio of the initial wind velocity to the target wind velocity, both overshoot coefficients of drag and lateral force increased with a decrease in the rise time. Figure 11 shows the relationship between the overshoot coefficient and the target wind velocity for Large-cylinder in the case of \( t_r \approx 0.15 \text{sec} \) and \( U_s / U_t = 0.0, 0.3 \) and 0.6. Both overshoot coefficients of drag and lateral force increased with a decrease in the target wind velocity for each ratio of the initial wind velocity to the target wind velocity.

Figure 12 shows the relationship between the overshoot coefficient and the ratio of the initial wind velocity to the target wind velocity for Large-cylinder and Small-cylinder in the case of \( U_t = 3.0 \text{m/s} \) and \( t_r \approx 0.15 \text{sec} \). It was found that both overshoot coefficients of drag and lateral force decreased with an increase in the ratio of the initial wind velocity to the target wind velocity for each elliptic cylinder. And the overshoot coefficient of Large-cylinder was lar-
ger than that of Small-cylinder for all ratios of the initial wind velocity to the target wind velocity.

Figure 13 shows the overshoot coefficient for Large-cylinder and Small-cylinder in the case of $t_r = \text{approximately } 0.15\text{sec}$ and the increase of wind velocity of 1.8 m/s ($U_i = 0.2\text{m/s}$ and $U_t = 2.0\text{m/s}; \ U_i = 1.2\text{m/s}$ and $U_t = 3.0\text{m/s}; \ U_i = 4.2\text{m/s}$ and $U_t = 6.0\text{m/s}$). Even when the increase of wind velocity was the same, the overshoot coefficient decreased with an increase in the initial wind velocity or the target wind velocity.

### 3.3 Relationship between overshoot coefficient and non-dimensional rise time

In our earlier study, we reported that the overshoot coefficient of wind force on a body subjected to a short-rise-time gust from calm was determined by a non-dimensional rise time, which was composed of a rise time, a gust speed and the body size, as shown in the following equation (Takeuchi et al.):

$$t' = \frac{U_i \cdot t_r}{d}$$

where $U_t = \text{the target wind velocity; } t_r = \text{the rise time; and } d = \text{a reference length (here, the length of the flow direction of the elliptic cylinder).}$

However, in this study, the overshoot phenomenon of wind force on a body subjected to a short-rise-time gust from steady flow was affected by the initial wind velocity, as previously mentioned. Thus, we need to consider the initial wind velocity to organize the overshoot coefficient of wind force on a body subjected to a short-rise-time gust from steady flow. In this study,
Figure 14. Relationship between overshoot coefficient and non-dimensional rise time ($U_s / U_t = 0.0$).

Figure 15. Relationship between overshoot coefficient and non-dimensional rise time ($U_s / U_t = 0.2$).

Figure 16. Relationship between overshoot coefficient and non-dimensional rise time ($U_s / U_t = 0.4$).

Figure 17. Relationship between overshoot coefficient and non-dimensional rise time ($U_s / U_t = 0.6$).
the non-dimensional rise time was expanded in consideration of the initial wind velocity as follows:

$$t' = \frac{(U_s - U_t) \cdot t_s}{d}$$

(4)

where $U_s$ = the initial wind velocity. When $U_s = 0$, Equation 4 is the same as Equation 3.

Figures 14-17 show the relationships between the overshoot coefficients of drag and lateral force and the non-dimensional rise time obtained by Equation 4 in cases of $U_s / U_t = 0.0, 0.2, 0.4$ and 0.6, respectively. For each figure, the overshoot coefficients for Large-cylinder are plotted on one line regardless of the target wind velocity, and the overshoot coefficients for Small-cylinder are plotted on the line for Large-cylinder. Thus, for each ratio of the initial wind velocity to the target wind velocity, the overshoot phenomenon may be strongly affected by the non-dimensional rise time. And these figures show that the overshoot phenomenon was more remarkable in the case of a gust with the smaller ratio of the initial wind velocity to the target wind velocity. However, the variation in the overshoot coefficient increased with the ratio of the initial wind velocity to the target wind velocity. In future studies we will investigate the presence of a non-dimensional parameter associated with the overshoot phenomenon, additional to the non-dimensional rise time.

4 CONCLUSIONS

The properties of unsteady wind force on an elliptic cylinder under a rapid change from steady flow were investigated using wind tunnel tests. We introduced a procedure for generating short-rise-time gusts from steady flow by the control of blade rows which were installed for generating a pulsation flow. The following features of unsteady drag and lateral forces on an elliptic cylinder under such gusts were found:

1. It was confirmed that the overshoot phenomenon of wind force occurred under a short-rise-time gust from steady flow as well as from calm.
2. The overshoot coefficient, defined by the ratio of maximum to a steady-state value of wind force, decreased with an increase in the ratio of the initial wind velocity to the target wind velocity.
3. For each ratio of the initial wind velocity to the target wind velocity, the overshoot coefficient was determined by an expanded non-dimensional rise time composed of rise time, body size, and initial and target wind velocities. And it was shown that the overshoot phenomenon was more remarkable in the case of a gust with the smaller ratio of the initial wind velocity to the target wind velocity.

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6 REFERENCES