TRANSIENT DRAG FORCE ON 2-D BLUFF BODIES UNDER GUSTY WIND CONDITION

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ABSTRACT

Sudden increase of wind velocity like a step function produces transient time history of aerodynamic forces on a 2-D bluff body. Some 2-D cylindrical models indicate overshoot in drag force, that is, large drag force in a moment which exceeds its steady state level. In this study, transient drag force under sudden increase of wind velocity was measured in wind tunnel for 2-D rectangular cylinders with the side ratio B/D (B: chord length, D: depth) of 0.5, 1, 2, 5 and for a circular cylinder. Surface pressure measurement was also carried out in each cylinder in order to discuss the generation mechanism of the overshoot. It is found that the contribution of inertia force cannot be ignorable for rectangular cylinders especially for more slender cross sections such as B/D=2 and 5. The overshoot is not so clearly recognized, on the contrary, for more bluff cross sections such as B/D=0.5, 1 and a circular cylinder. The drag force reaches to the maxima when the wind velocity is still increasing for B/D=2 and 5, while those for more bluff cross sections show their peaks in later. It is also known that the time delay exists in the surface pressure to the static pressure in wind tunnel. This time delay differs depending on the surface. The time difference to approach to the quasi-steady level in the windward and leeward surface should play significant role on the generation of the drag force overshoot.

KEYWORDS: DRAG FORCE, 2-D BLUFF BODY, GUSTY WINDS

Introduction

Transient aerodynamic forces due to gusty winds caused by tornadoes or downbursts can induce severe damage on structures, overturn of vehicles. Those may also cause flying debris which is harmful to human being, cattle, crops, vehicles, roofs and walls of structures. For high hazard facilities which handle radioactive or other hazardous materials including nuclear reactors or large capacity of liquefied natural gas, enough safety level should be guaranteed to these severe wind action. [Stevenson and Zhao (1996)] For example, 10⁻⁷ of annual exceedance of the design basis tornado should be considered to nuclear power plants. [NRC Guide 1.76 (2007)] Wind loads due to the design basis tornado yields almost 15 times larger than those in conventional building codes. By taking tornado statistics into account, the expected value of strong wind velocity is enhanced about 1.1 times for 500 years return period, and about 1.7 times for 1000 years. [Wen and Chu (1973)] The chance of a given point being hit by tornado was evaluated in several studies. Risk of tornado encounter, that is an annual probability of a certain point in a particular prefecture enters a tornado damage path, was calculated based on the tornado database which includes 677 tornadoes in Japan from 1961 to 1993. [Niino et al. (1997)] Most of tornadoes in Japan occur near the coastal line. According to their evaluation, the annual number of tornado occurrence per unit area of
$10^4 \text{km}^2$ along coastal region in Japan was evaluated as 1.4. It is almost comparable number with those in Alabama and Missouri (the 13th and the 14th largest in US). Therefore, a particular care on the safety for nuclear power plants and liquefied natural gas storage tanks and other hazardous facilities should be required in Japan as well. Tamura et al. evaluated that about 8 tornadoes per year must cross railway in any place in Japan. [Tamura et al. (2008)] This implies the safety evaluation is important also for transportation facilities and power transmission lines, similarly to the adequate supply of prediction system for gusty winds.

Wind speed changes very rapidly during a tornado passage. For example, the design-basis tornado for the region III provided in the NRC Guide can induce more than 40m/s of wind speed change during 3 seconds interval in the worst case. This intensity corresponds almost to the upper limit of a F2 class tornado with respect to the maximum wind speed, $U_{max}=72$ m/s. F2 class tornadoes are experienced also in Japan.

It is known that aerodynamic forces on a bluff body indicate overshoot when approaching wind velocity sudden increases in a short period. Saripkaya reported the overshoot of drag force on a circular cylinder which suddenly starts in a still water tank. The formation of a pair of recirculation flow in a wake like pair vortices plays the most important role in the overshoot mechanism. [Sarpkaya (1966)] Taneda found the overshoot of lift force on an elliptic cylinder with 20 degree angle of attack and that the instance of the formation of a vortex in a wake corresponds well to the peak of lift force. [Taneda (1972)] Shiraishi and Matsumoto discussed the mechanism of a train overturning due to tornado hitting. They reported that when approaching wind velocity increases in very short time period ($t=0.05$ sec), the large peak was observed in a lift force on a square cylinder with a slight positive (nose-up) angle of attack. While the direction of the lift force is downward in quasi-steady state, the peak indicates upward for short time duration but with large magnitude. This is the main reason of the overturning. [Shiraishi and Matsumoto (1982)] The overshoot of drag force on a square prism was simulated by the CFD technique. Contribution of the inertia force component, which is proportional to the increasing rate of wind velocity with time $dU/dt$, was pointed out. [Nomura (2000)] Matsumoto focused on the drag force overshoot. Its relationship to the Karman vortex was discussed on rectangular cylinders with variety of side ratio and a circular cylinder. [Matsumoto et al. (2007)] From the practical point of view, the ratio of the drag force peak in the overshoot to the quasi-steady level will be important. Takeuchi et al. evaluated the ratio termed as “overshoot coefficient” for a railway wagon. The coefficient decreases sensitively with increase of the time duration of wind speed from still-air condition to the steady state. [Takeuchi et al. (2008)]

In this study, the transient characteristics of drag forces on 2-D rectangular cylinders with side ratio $B/D=0.5, 1, 2, 5$ ($B$: width, $D$: depth of cross section) and a circular cylinder were focused under the situation of sudden increase of wind velocity. Drag force was directly measured by load cells to evaluate the magnitude of overshoot and the instance when the drag force reaches to its maxima. Surface pressure measurements and flow visualization were also conducted for each cylinder in order to discuss the mechanism of the overshoot of drag force.

**Wind Tunnel Experiments**

The wind tunnel used in this study has a 200mm square working section. Sudden increase of wind velocity can be reproduced in the wind tunnel in which the shutter B (see Fig.1) is installed in downstream of a model. The shutter is closed initially and then suddenly opened to have rapid increase of wind velocity. Each 2-D model has a 180mm span length and 30mm in depth. No correction of blockage effect was made. To make the time duration to reach the steady-state level as short as possible ($t=0.08$ sec in minimum), wind velocity in steady state was adjusted to from $U=3.0$ m/s to 7.0 m/s for entire cases, while the initial wind velocity was not kept zero but 30 to 50 % of the steady state level. The Reynolds number was
between 6 x 10^3 to 14 x 10^3 with respect to \( U \) in steady state and depth of a model \( D \). Drag force can be measured by load cells (LMC3501-20N, Nissho Electric Works Co., Ltd.) being connected with a model at both ends. Surface pressure at each pressure tap is simultaneously led to the multiple channel pressure measurement system (ZOC17, Scanivalve) through tubes installed inside of models. Wind velocity is measured by the hot wire anemometer (Model 1011, 1013, Kanomax) with X-type probe (Model 0252, Kanomax). By the measurement of wind velocity in the empty working section, it was thought that the sudden open of the shutter B can make the entire air in the working section move downstream simultaneously. Therefore the X-type probe was installed at 400mm upstream from the model. All signals were converted to digital quantities simultaneously by 1kHz sampling rate.

![Fig. 1 Wind tunnel for generating gusty winds](image)

**Results and Discussions**

**Transient Drag Force due to Sudden Increase Wind Velocity**

The transient drag force normalized by its steady-state value \( D/D_\infty \) on the 2-D rectangular cylinder model with \( B/D=5.0 \) is shown in Fig 2(a) together with wind velocity \( U/U_\infty \). Both curves in the figure are the output through digital low-pass filters with 40Hz cutting frequency. Some fluctuation remains in the drag force in steady-state. A part of this reason is a noise caused by a mechanical shock of the sudden open of the shutter. The vertical broken line in the figure indicates the instance when the drag force reaches to the maxima. It is known that the drag force gets to the maximum value when the wind velocity is still increasing, namely \( dU/dt \) is still positive. The same tendency can be observed also for \( B/D=2.0 \) as shown in Fig.2(b). On the contrary, for more bluff cross sections, a circular and a

(a) rectangular \( B/D=5.0, \ U_0=4.08\text{m/s} \)  
(b) rectangular \( B/D=2.0, \ U_0=3.99\text{m/s} \)

![Fig. 2 Transient drag force by sudden increase of wind velocity](image)
rectangular with $B/D=0.5$, the drag force gets to the maximum value when the wind velocity reaches almost to the steady-state level, namely $dU/dt$ becomes relatively small or almost zero, as shown in Fig.3(a) and (b). As for the height of the drag force peak seems to be lower than those for $B/D=2.0$ and 5.0 in Fig.2.

**Transient Surface Pressures due to Sudden Increase Wind Velocity**

Fig.4 shows the transient drag force $D/D_\infty$ on $B/D=5.0$. Longitudinal wind velocity $U/U_\infty$, the pressure at the windward (“front” in the figure) and the leeward (“rear” in the figure) surface, the static pressure on the wind tunnel floor (“tunnel floor” in the figure) and opening ratio of the shutter B ($A/A_\infty$) are plotted in the figure altogether. Drag force in this figure is obtained by integrating pressures on the windward and the leeward surfaces. The overshoot is recognized in the drag force, and its peak occurs with a short time delay of $\tau \approx 2$ ($\tau = U_\infty t/b$, $b=B/2$) after when pressures on both surfaces reach their maxima. All pressures are the difference between those in each pressure tap and static pressure in the working section. The front pressure increases immediately at first after the wind velocity starts to increase. Then, it decreases before the drag force reaches to the peak.
and indicates even negative sign, which means the surface pressure on the windward surface becomes suction although in a quite short moment. As for the leeward surface pressure, it seems to increase a little bit in the initial stage. And, it decreases similarly to the windward surface pressure. Pressures on both surfaces take negative peak simultaneously after the drag force peak took place. Then, both are gradually approaching to each steady-state level. This transient behavior of the surface pressure seems to be correlated neither to the drag force peak nor the static pressure. Fig.5 reproduces the net pressure signals in each pressure tap together with the net static pressure using the same data for those in Fig.4. In the initial stage when the wind velocity starts to increase, the pressures in the windward surface starts to decrease, but its difference with the static pressure seems to be gradually more significant as the wind velocity increases. This corresponds to the initial increase of the windward surface pressure in Fig.4. On the contrary, the leeward surface pressure decreases similarly to the static pressure. Therefore, the difference to the static pressure does not change so much apparently as shown in Fig.4.

Fig. 6 shows the transient drag force $D/D_{∞}$ on a more bluff cross section $B/D=0.5$. Similarly to Fig.4, $U/U_{∞}$, the pressure on the windward and the leeward surface, the static pressure on the wind tunnel floor and $A/A_{∞}$ are also plotted in the figure. The surface pressures behave in quite similar way to those in Fig.4. The only different observation is the leeward surface pressure also indicates positive value in the initial stage. This is because the decreasing rate of the static pressure is more rapid than that of the leeward pressure which can produce the higher leeward pressure level than the static pressure for a short moment. Furthermore, since the separating shear layer cannot reattach on the side surface of the cross section, the sudden pressure change occurring at the windward surface may be transferred instantaneously to the pressure near the leeward surface. The time delay between the drag force peak and the surface pressure peak is also almost the same as $B/D=5.0$. Fig. 7 indicates the net pressures for $B/D=0.5$ using the same data in Fig.6. The drag force occurs when the windward and leeward pressures increase on the way to each steady-state level. In this stage, the increasing rate of the leeward pressure may be slightly slower than that of the windward pressure for a moment, which produces the drag force overshoot. The drag force overshoot does not have direct relation apparently to the time variation of the static pressure, but the pressures on both surfaces must be significantly affected by the static pressure level. If a structure would encounter a tornado hit directly, the instance of the maximum wind velocity...
does not coincide with the instance of the minimum static pressure, because the maximum tangential velocity appears at a certain distance from the center of a tornado. Therefore, the drag force overshoot phenomenon should be investigated under the different static pressure condition.

Static Pressure Characteristics and its Influence on Transient Drag Force

Fig. 8 shows pressures on the wind tunnel floor during sudden increase of wind velocity. Pressure taps are installed in the center of the floor and 180mm interval along wind direction. It is known that there is no time lag in the negative pressure peaks which supports the entire air in the working section moves suddenly and there is no propagation like a gust front. It is also known that there is some difference in peak value and larger absolute value is observed for more downstream pressure tap. This fact may produce longitudinal force on a model due to static pressure difference along wind tunnel. If the model width $B$ would be relatively large, the force may be significant. Some calculation proved that the above static
pressure difference for a $B/D=5$ model yields about 30% of drag peak value when $U_\infty = 4.06\text{m/s}$. Therefore, the overshoot of drag force should be due to other reasons. Since the static pressure is automatically cancelled, these static pressure properties do not give any influence to the drag force on a 2-D bluff body such as focused in this study. On the contrary, the aerodynamic force on a structure standing on the ground should have significant influence of the static pressure. The atmospheric pressure near the structure is usually used as the static pressure. In case of a tornado passing close to a structure, the atmospheric pressure must be changing with time to large extent. Therefore, dynamic pressures on a structure and the atmospheric pressure should be taken into account but independently.

![Fig.8 Transient static pressure under sudden increase of wind velocity. ($U_\infty = 8.77\text{m/s}$)](image)

**Contribution of Inertia Force**

The inertia force due to added mass and longitudinal pressure gradient is normally taken into account in the marine structures. [Clauss, et al. (1994)] It is proportional to the time derivatives of approaching flow velocity. Total along wind force is therefore expressed by the following equation:

$$F_D = \rho V_o C_m \frac{dU}{dt} + \frac{1}{2} \rho U^2 C_D A \tag{1}$$

Where, $\rho$ : air density $[\text{kg/m}^3]$, $V_o$ : volume of a model $[\text{m}^3]$ ($V_o = BD\ell$, $\ell$ : span length of a model $[\text{m}]$), $C_m$ : inertia force coefficient, $C_D$ : drag force coefficient, $A$ : projected area of a model $[\text{m}^2]$ ($A = D\ell$).

Fig.9 compares the total along-wind force between measured and calculated values. The calculated value of along wind force is obtained using the time derivatives of measured wind velocity and inertia force coefficient. The inertia force coefficient $C_m$ is derived assuming potential flow and depends on the geometry of cross section. For $B/D=5.0$ rectangular cylinder, $C_m$ is equal to 3.0. From the figure, the measured and calculated along wind force agree with each other. On the contrary, as for more bluff cross section in Fig.5, for example, the overshoot is not so clearly observed as those for $B/D=5.0$. $C_m$ is equal to 2.3 for $B/D=0.5$ and 2.5 for $B/D=1.0$. The agreement between observed and calculated values still exists. Therefore, the inertia force component contributes significantly to the transient drag force (along wind force) properties.

The possibility still remains in the generation mechanism of the overshoot due to unsteady (not quasi-steady) characteristics of drag force and the effect of initial circulatory flow in wake just after sudden increase of wind velocity.
Conclusions

1. The drag force reaches to the maxima when the wind velocity is still increasing for $B/D=2.0$ and 5.0, while those for more bluff cross sections show their peaks in later.
2. There is a time delay in the surface pressure to the static pressure in wind tunnel. This time delay differs depending on the surface. The time difference to approach to the quasi-steady level in the windward and leeward surface plays significant role on the generation of the drag force overshoot.
3. The inertia force component contributes significantly to the transient drag force (along wind force) properties for rectangular cylinders especially for more slender cross sections such as $B/D=2.0$ and 5.0. While the overshoot is not so clearly recognized, on the contrary, for more bluff cross sections such as $B/D=0.5$, 1.0 and a circular cylinder.

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