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Effects of aerodynamic interferences between heaving and torsional vibration of bridge decks: the case of Tacoma Narrows Bridge

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Abstract

There are still some unknown facts on the failure of old Tacoma Narrows Bridge in 1940, especially on the mystery of onset velocity of torsional flutter. In this study, the aerodynamic interferences between heaving vibration and torsional vibration on this bridge deck were investigated to explain the mystery. It became clear that there are aerodynamic interferences between vortex-induced heaving vibrations and torsional vibrations. These interferences have not only the stabilizing but also unstabilizing effects. Then, the mystery of Tacoma Narrows Bridge failure might be able to explain by the aerodynamic interference, that is, the vortex-induced heaving vibration might suppress the torsional flutter.

Keywords: Tacoma Narrows Bridge; Aerodynamic interference; Vortex-induced vibration; Torsional flutter

1. Introduction

It is well known that the old Tacoma Narrows Bridge failed on November 7th, 1940, due to torsional flutter induced by wind velocity of about 19 m/s. Farquharson [1] reported the bridge behavior at the time of failure as follows. At 5 min before the occurrence of torsional vibration, there was a heaving vortex-induced vibration of

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the fifth symmetrical mode ($f_{\eta 0} = 0.6$ Hz, where $f_{\eta 0}$ denotes natural frequency of heaving mode) under the wind velocity of 18.7 m/s. Next, the vibration mode suddenly switched to the first asymmetrical torsional mode ($f_{\phi 0} = 0.23$ Hz, where $f_{\phi 0}$ denotes natural frequency of torsional mode), and then the bridge was destroyed. After the failure, Farquharson [1] conducted a series of wind tunnel tests and reported that this flutter was confirmed in the wind tunnel at the site wind velocity 6 m/s assuming the structural damping as $\delta = 0.034$. Then, the question is why the old Tacoma Narrows Bridge could survive till the wind velocity of 19 m/s. Farquharson [1] tried to explain this fact by center diagonal stays, which might be possible to stabilize the torsional flutter of the bridge. However, this explanation has not been proved yet and the effects of center diagonal stays may be questionable. Considering the situation just before the occurrence of torsional flutter, a hypothesis can be formulated, that is, the vortex-induced heaving vibration might stabilize the torsional flutter. Therefore, an aerodynamic interference between heaving and torsional vibration might exist on this bridge.

The aerodynamic interferences between different kinds of vibrations, such as vortex-induced vibration, galloping and torsional flutter, have been reported. Some for example, Scruton [2] reported the relation of Karman vortex-induced vibration and galloping of a square prim using a parameter of Scruton number. Also, Farquharson [1] mentioned a possibility of the aerodynamic interference of vortex-induced heaving vibration and torsional flutter of Tacoma Narrows Bridge deck in his report.

In this study, details of this historical bridge failure are reconsidered based on interferences between two different aerodynamic phenomena. To investigate the aerodynamic interferences, some free vibration tests in the wind tunnel were conducted, using a spring supported two-dimensional model of the old Tacoma Narrows Bridge deck. Then, the aerodynamic interferences between heaving vibration and torsional vibration, including their stabilizing and unstabilizing effects, are discussed.

2. Wind tunnel tests

The wind tunnel used in this study is a room-circuit Eiffel-type located in Kyoto University. The working section of the wind tunnel is 1.8 m height and 1.0 m width, and the maximum wind velocity is 30 m/s. The deck model used in this study is $\frac{1}{40}$ scale of the old Tacoma Narrows Bridge deck as shown in Fig. 1, where B is the deck width and D is its height. The model was supported by springs in the wind tunnel as two-degrees-of-freedom system, which consist of heaving and torsional motions, and

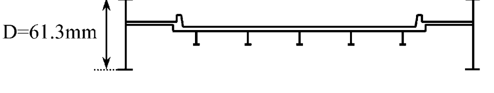

Fig. 1. Model of Tacoma Narrows Bridge.

then these vibration amplitudes were measured at each wind velocity. The ratio of natural frequencies was set as about $f_{\eta 0}/f_{\phi 0} = 2.5$. This ratio was chosen to simulate the situation of the bridge failure, which is to investigate the aerodynamic interferences between heaving vibrations of the fifth symmetrical mode and torsional vibrations of the first asymmetrical mode. Also, Scruton number Sc of the system was varied in these wind tunnel experiments, and Sc is defined as follows:

$$Sc_\eta = \frac{2m\delta_\eta}{\rho D^2} \text{ for heaving motion,} \quad Sc_\phi = \frac{2I\delta_\phi}{\rho D^4} \text{ for torsional motion,} \tag{1}$$

where m is the mass per unit span length, I the moment of inertia per unit span length, δ_η the logarithmic decrement for heaving system, δ_ϕ the logarithmic decrement for torsional system, ρ the air density and D the height of bridge deck. In this study, combinations of m, δ_η and I, δ_ϕ were varied using additional masses and a electromagnetic damper, and then the heaving and torsional responses were measured with various Scruton numbers to clarify the effects of Scruton number on the aerodynamic interferences.

3. Aerodynamic interferences between heaving vibration and torsional vibration

Roughly speaking, two kinds of aerodynamic phenomena can be expected in this 2DOF system. One is heaving vortex-induced vibration, and the other is torsional flutter. The occurrence of wind velocity regions and the amplitudes of these vibrations can be controlled by Scruton numbers. Therefore, it seems that the aerodynamic interferences between these vibrations depend on the combination of Scruton numbers for heaving motion and torsional motion. A few examples of the aerodynamic interferences will be explained as follows.

3.1. Interference between vortex-induced heaving vibration and torsional flutter

To investigate the aerodynamic interaction between the vortex-induced vibration of heaving motion and the torsional flutter, structural parameters were set to realize these phenomena in the same wind velocity region. As the first case of the aerodynamic interferences, velocity–amplitude diagrams are plotted in Fig. 2. In Fig. 2, experimental results for heaving 1DOF, torsional 1DOF and 2DOF are shown. In 1DOF tests, one of the degrees of freedom was constrained at the 2DOF situation. Also, in Fig. 2, 2η and 2ϕ denote the double amplitude of heaving and torsional motion, and $2\eta_p$ denotes the full-scale amplitude of heaving motion. In horizontal axes, V is the wind velocity in the wind tunnel, $V/f_\eta B$ and $V/f_\phi B$ are reduced wind velocities, and V_p is the full-scale wind velocity.

From heaving 1DOF result shown in Fig. 2(a), there are two vortex-induced vibrations, which occur around at reduced wind velocity $V/f_\eta B = 0.75$ and 1.7. Especially, the latter vortex-induced vibration has rather large amplitude and its maximum amplitude can be seen at $V/f_\eta B = 2.6$. On the other hand, from torsional 1DOF results shown in Fig. 2(b), the torsional flutter occurs at around $V/f_\phi B = 2.3$.

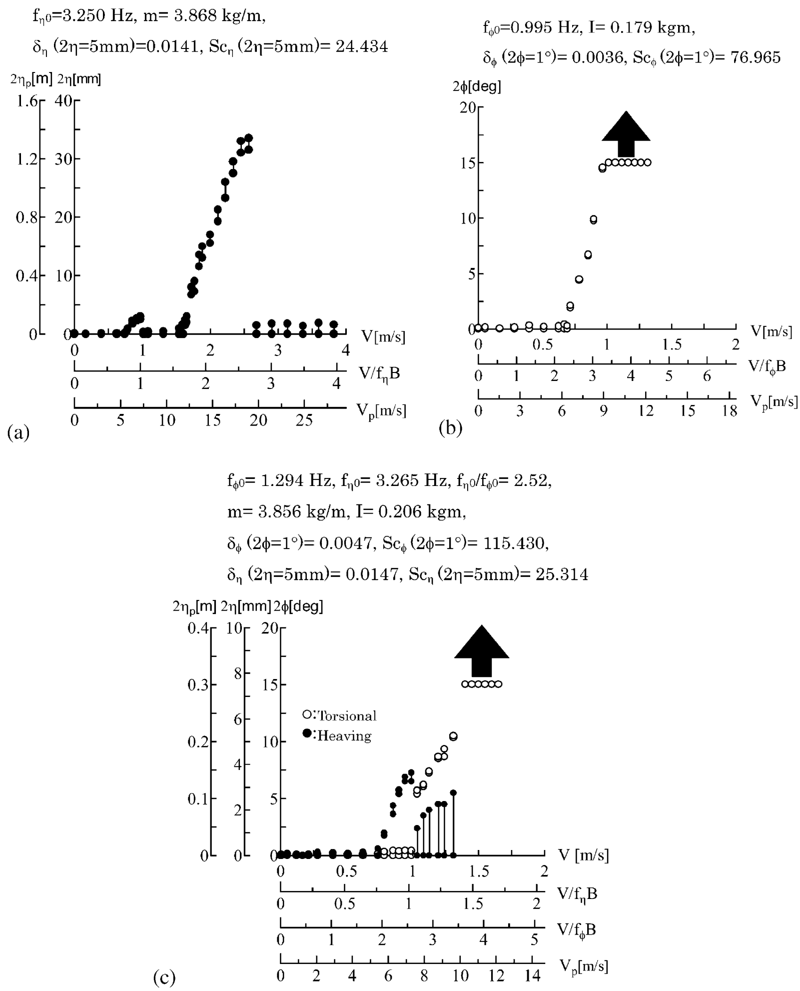

Fig. 2. Velocity–amplitude diagrams: (a) heaving 1DOF, (b) torsional 1DOF and (c) 2DOF.

Therefore, these two phenomena are expected to occur in the same wind velocity region of the wind tunnel. 2DOF responses are shown in Fig. 2(c), and it becomes clear that the amplitude of second vortex-induced heaving vibration is extremely reduced and the torsional flutter remains almost the same. Therefore, it can be explained that the torsional flutter suppressed the vortex-induced heaving vibration.

The other type of aerodynamic interference is shown in Fig. 3 in the same way as the previous case. In this case, Scruton number for the torsional motion is rather larger than one in the previous case. Therefore, the onset wind velocity of torsional flutter becomes higher than before, see Fig. 3(b). The heaving response in Fig. 3(a) is almost same as the previous case in Fig. 2(a). Then, in 2DOF case, another type of interference between vortex-induced heaving vibration and torsional flutter can be

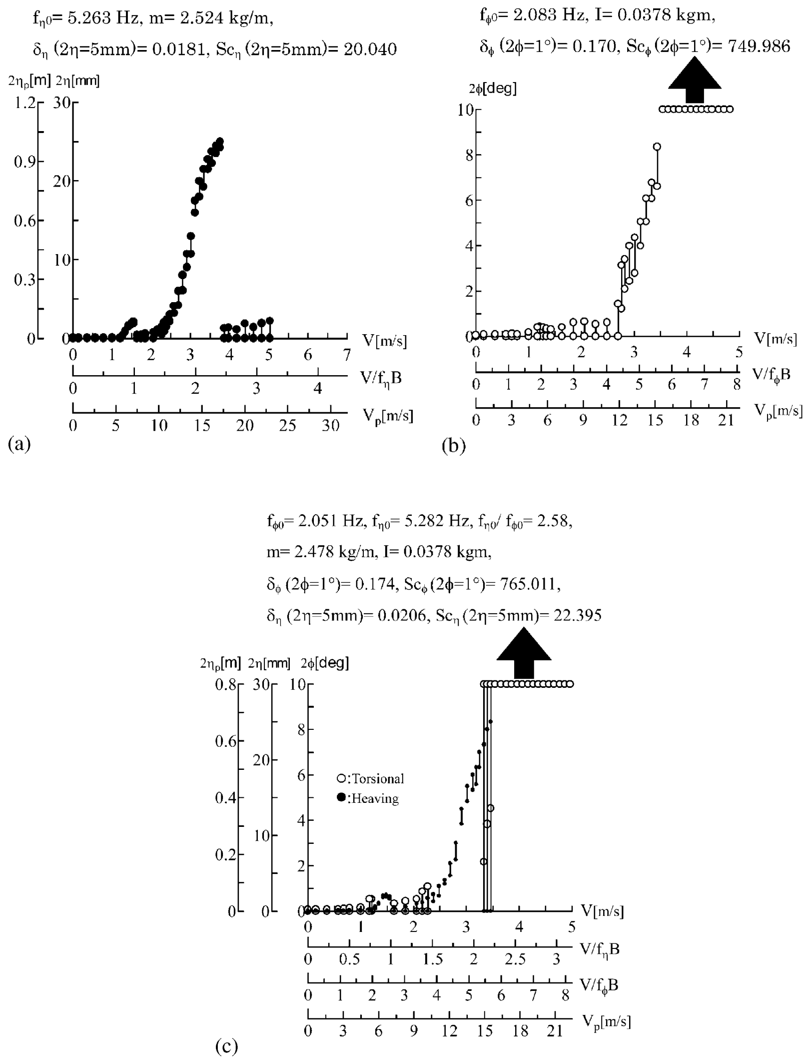

Fig. 3. Velocity–amplitude diagrams: (a) heaving 1DOF, (b) torsional 1DOF and (c) 2DOF.

observed, see Fig. 3(c). The onset wind velocity of torsional flutter in 2DOF became rather higher than that of 1DOF case, which means that the torsional flutter was suppressed by the vortex-induced heaving vibration. Then, this kind of interference might be able to interpret the question of Tacoma Narrows Bridge failure.

To understand the differences of above-mentioned interferences, a velocity–amplitude–damping diagram of torsional 1DOF case is shown in Fig. 4, which is the same case as Fig. 3(b). In this figure, contour lines of the logarithmic decrement δ of this system are plotted on a reduced wind velocity–amplitude plane. These

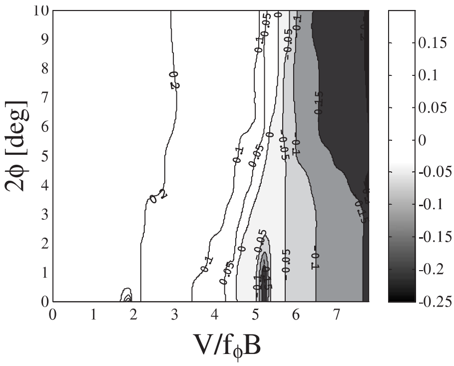

Fig. 4. Velocity–amplitude–damping diagram.

logarithmic decrements were measured by free vibration tests at each wind velocity. Then, it become clear that there is a velocity-limited low damping region around $V/f_{\phi}B = 5.0$–5.3, which was not confirmed from velocity–amplitude diagram of Fig. 3(b). Therefore, it seems that there are two types of torsional flutter in the reduced wind velocity region higher than $V/f_{\phi}B > 4.5$, one is low-speed torsional flutter, the other is high-speed torsional flutter [3]. The former one is generated by vortex convections on the side surface of body, and the latter is due to local separation bubble formed around the leading edge. These characteristics of torsional flutter can also be seen on H-shaped sections of bluffness ratio $B/D = 5$, which has very similar B/D of Tacoma Narrows Bridge [3,4]. Then, considering the wind velocity region of the above-mentioned interferences, following facts might be deduced as: (1) the vortex-induced heaving vibration can suppress the low-speed torsional flutter, (2) the high-speed torsional flutter can suppress the vortex-induced heaving vibration.

3.2. Torsional vibration induced by heaving vibration vortices

A special case, which shows a torsional vibration induced by heaving vibration vortices, is shown in Fig. 5 in the same way as the previous cases. In heaving 1DOF case of Fig. 5(a), there is a vortex-induced heaving vibration around $V/f_{\eta}B = 1.7$–2.6. Also, from a result of torsional 1DOF case shown in Fig. 5(b), these is only torsional flutter from $V/f_{\phi}B = 5.6$. However, in 2DOF case shown in Fig. 5(c), the velocity-limited torsional vibration and the vortex-induced heaving vibration occur at the same time. The onset wind velocity of this torsional vibration is about $V/f_{\phi}B = 4.4$, and this kind of vibration was never observed in 1DOF case shown in Fig. 5(b). Therefore, the generation mechanism of this vibration seems to be related to vortex-induced heaving vibration. This kind of torsional vibration has never been reported before.

The time series of heaving and torsional responses are plotted in Fig. 6. The positive values for heaving and torsional motions indicate downward and leading

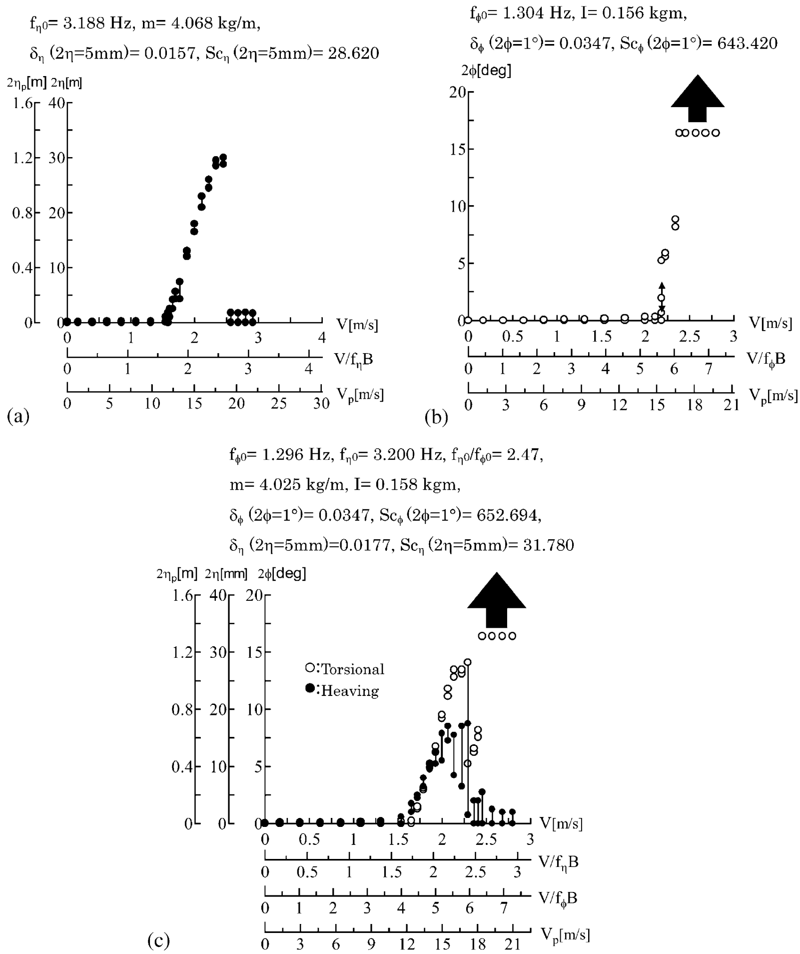

Fig. 5. Velocity–amplitude diagrams: (a) heaving 1DOF, (b) torsional 1DOF and (c) 2DOF.

edge upward, respectively. Also, T_η and T_ϕ are periods of heaving and torsional vibrations. It is clear that the 5 periods of heaving motion corresponds to 2 periods of torsional motion, because the frequency ratio of both motion is about $f_{\eta 0}/f_{\phi 0} = 2.5$. One of the significant points on this phenomenon must be the unsteady amplitude of heaving vibration. Furthermore, when the heaving and torsional motions simultaneously become almost the maximum position, the amplitude of heaving motion becomes comparatively large. This fact seems to explain the generation mechanism of this torsional vibration. Then, it can be concluded that vortices on the side surface of the body related to the heaving motion might generate the torsional vibration.

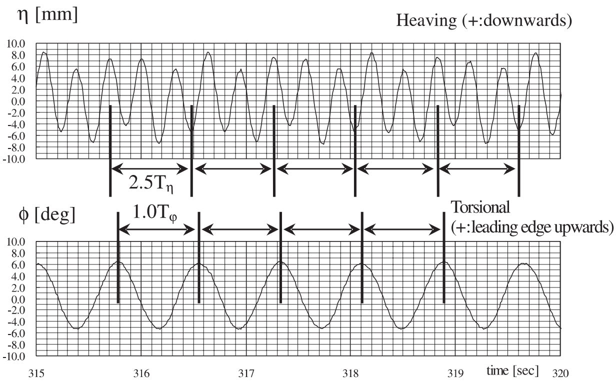

Fig. 6. Time-series responses.

4. Effects of Scruton number on aerodynamic interferences

The responses of Tacoma Narrows Bridge section in various Scruton numbers are plotted in Fig. 7. The experimental results for heaving 1DOF and torsional 1DOF are plotted in Fig. 7(a) and (b), respectively. In these plots, the results from previous studies by Farquharson and by Karman and Dunn [1] are also included. In heaving 1DOF case shown in Fig. 7(a), the shaded portion of the figure denotes the range of wind velocity region for vortex-induced heaving vibration. Also, the full-scale maximum amplitude of vortex-induced heaving vibration $2\eta_{p\max}$ is also plotted by a dashed line in this figure. Then, it becomes clear that this maximum amplitude is rather sensitive to the Scruton number. In torsional 1DOF case shown in Fig. 7(b), the dotted area shows the torsional vibration area, especially torsional flutter, and a dashed line denotes the critical flutter wind velocity calculated from aerodynamic derivatives.

Fig. 7(c) is a virtually combined plot of Figs. 7(a) and (b) against the torsional Scruton number. Then, at the overlapped area of the vortex-induced heaving vibration and the torsional flutter, the aerodynamic interferences are expected. Furthermore, 2DOF experimental results in this study are plotted together in Fig. 7(c) and shown in Fig. 7(d). Then, three kinds of aerodynamic interferences as mentioned above are observed in following Scruton numbers:

(1) Vortex-induced heaving vibration suppresses torsional flutter at $Sc_\phi = 700$–800.
(2) Torsional flutter suppresses vortex-induced heaving vibration at $Sc_\phi = 100$–200, 700–800.
(3) Torsional vibration is induced by heaving vibration vortices at $Sc_\phi = 600$–700.

5. Tacoma Narrows Bridge failure

Using the experimental data in this study, the situation of the bridge failure is reconsidered here. First of all, the consistency of flow condition in the wind tunnel

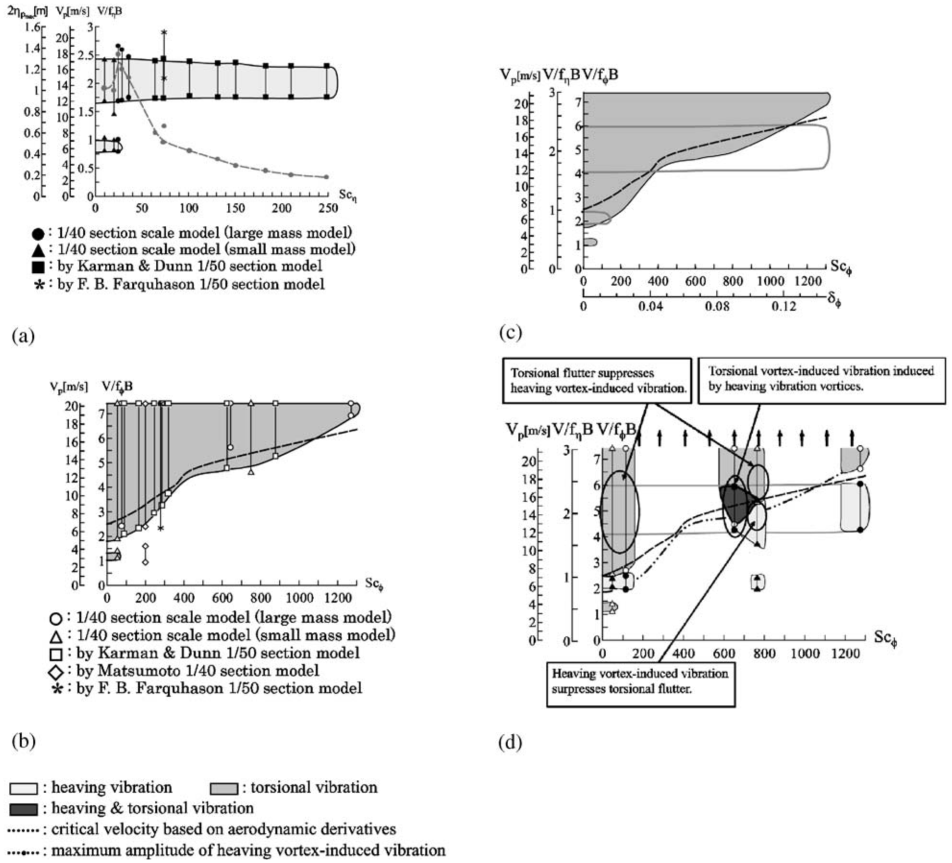

Fig. 7. Effects of Scruton number on aerodynamic interferences: (a) heaving 1DOF, (b) torsional 1DOF, (c) heaving 1DOF + torsional 1DOF and (d) 2DOF.

and the bridge site is considered. The wind tunnel tests in this study were conducted under smooth flow condition. On the other hand, wind at the bridge site must be turbulent flow. However, there are almost no effects of turbulence on torsional flutter of H-shaped section of bluffness ratio $B/D = 5$ [5], which is similar section as Tacoma Narrows Bridge. Therefore, the following discussion can be done using the data under smooth flow condition.

Considering the fact that the vortex-induced heaving vibration in 5th symmetrical mode was observed just before the occurrence of torsional flutter, the structural damping of torsional motion can be estimated as logarithmic decrement about $\delta = 0.05$–0.12, see Fig. 7(c). On November 7th, 1940, the wind velocity was at 12 m/s in the beginning and the vortex-induced heaving vibration in 5th symmetrical mode was observed. Then, it can be supposed that the wind velocity increased till the torsional flutter region, however, the vortex-induced heaving vibration suppressed the low-speed torsional flutter. After this failure, there are two hypotheses can be framed as follows:

(1) The wind velocity increased higher than the vortex-induced heaving vibration region, then, the torsional flutter started to vibrate.
(2) The wind velocity increased, but it was still in the wind velocity region of vortex-induced heaving vibration. Then, the type of torsional flutter was switched from the vortex-driven one (low-speed torsional flutter) to the separated bubble driven one (high-speed torsional flutter). Therefore, the vortex-induced heaving vibration was contrarily suppressed by the torsional flutter, and then the torsional vibration was dominated.

In any case, the onset wind velocity of torsional flutter can be estimated as less than 17 m/s from Fig. 7(c). Then, this velocity does not agree with 18.7 m/s, which Farquharson reported. However, the wind direction was not written clearly in his report [1]. Therefore, the wind direction at the moment of accident is still questionable. Furthermore, the axis of old Tacoma Narrows Bridge and the Tacoma Straits are not orthogonal and it has angle 20–25° from perpendicular line. If the wind had yaw angle 20–25° from the bridge orthogonal line, then the wind velocity to the bridge can be converted as 16.8–17.6 m/s. This is still a hypothesis, but it might be able to explain the mystery of old Tacoma Narrows Bridge.

Furthermore, the Farquharson report [1] says as follows, "The rather large amount of wind data collected during the life of the Tacoma Narrows Bridge is, unfortunately, of somewhat doubtful validity, especially with respect to the recorded wind velocities." It means that the wind velocity at the collapsing moment might be inaccurate.

6. Conclusions

On the old Tacoma Narrows Bridge section, there are three kinds of aerodynamic interferences were observed as follows: (1) Vortex-induced heaving vibration suppresses torsional flutter. (2) Torsional flutter suppresses vortex-induced heaving vibration. (3) Both of heaving/torsional vortex-induced vibrations can be observed simultaneously. Since torsional vibration is induced by heaving vibration vortices. Then, the mystery of Tacoma Narrows Bridge failure might be explained by one of these aerodynamic interferences, that is, the vortex-induced heaving vibration in 5th symmetrical mode might suppress the low-speed torsional flutter caused by vortex convections on the side surface of the bridge deck.

Furthermore, these facts derive a caution on realization of aerodynamic vibrations of bridge decks by a two-dimensional sectional model using two major structural modes, especially in the case that a vortex-induced vibration and a flutter type vibration occur in the similar wind velocity region.

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