Effects of a Splitter and an Endplate on Flow-induced Vibration Characteristics of Cantilevered Rectangular and D-section Prisms

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Abstract The effects of a splitter and an end plate on the flow-induced vibration characteristics of cantilevered rectangular and D-section prisms with the different finite lengths (aspect ratios $LA/H$) and depth ratios (side ratio $D/H$ of 0.2 and 0.5) have been investigated in a water tunnel. In order to suppress the alternating vortex shedding in the wake of bluff bodies, a splitter plate was installed behind the prisms with a small gap and sufficient length to prevent vortex shedding intrusion. Meanwhile, to maintain a two-dimensional flow structure, an endplate was attached to the prism tip end. Mounting the splitter plate enhanced the response amplitude for all prisms. In this case, interferences of amplitude signal spectra for the period of displacement vanished on the prism with a side ratio of 0.5 yielding a uniform waveform on response amplitude. The attached endplate does not take an important role in enhancing the dynamic response of the prisms with a side ratio of 0.5 but it suppressed the response amplitude of prisms with $D/H = 0.2$.

1. Introduction
The features of rectangular prisms with sharp edges in a uniform flow are the generation of alternate vortices behind the prism and the separation bubble on the side surfaces. Flow characteristics of fluid forces and vortex shedding frequency are dramatically changed by the side ratio of rectangular prism [1,2]. Because of these features, the elastically mounted rectangular prisms yield the flow-induced vibration in the cross-flow direction by the vortex-induced and the galloping vibrations. The dynamic response of prism depends on some parameters such as the system damping and after body shape (i.e. the structural part of a bluff body downstream of the flow separation points) [3]. In the case of finite rectangular prism mounted elastically in the water tunnel, Kiwata et al. [4] investigated the effect of side ratio on the response amplitude characteristics of rectangular and D-section prisms with the side ratios of less than $D/H = 0.5$, where $D$ is the depth of a bluff body in the flow direction, and $H$ is the height of a bluff body normal to the flow direction. It is found that the response amplitude of D-section prism with $D/H = 0.23$ vibrated at lower reduced velocity than the rectangular prism with $D/H = 0.2$, and the increment rate of response amplitude of D-section prism with $D/H = 0.23$ were higher than the other prisms.
The flow features of prisms with low aspect ratios of $L/H \leq 5$, where $L$ is the span length of a prism, are considerably influenced by three-dimensional vortex structure from the tip of a prism and the alternating vortex shedding behind the bluff body [5]. If the endplate is installed on the tip of a prism, the three-dimensional flow structure of wake can be modified to be the two-dimensional flow structure of wake. The wake structure and the galloping properties for both attached and unattached endplate conditions can be found in the references [6, 7, 8]. Meanwhile, the suppression of alternating vortex shedding behind the prism around the critical side ratio was carried out by the installation of a splitter plate as references [9, 10, 11].

To develop the power generation system using the iron-gallium alloy and the flow-induced vibration, we focus on the low-speed galloping for the cantilever mounted rectangular and D-section prisms with side ratios of $D/H \leq 0.5$. Our main objective is to increase the response amplitude of prisms by installing a splitter and an endplate. The effects of a splitter and an endplate on the transverse vibration characteristics of the cantilevered rectangular and D-section prisms was investigated experimentally in a water tunnel.

2. Experimental Approaches

2.1 Experimental apparatus

The experiment of free vibration of cantilevered prisms was carried out in a water tunnel facility [4]. Figure 1 shows a schematic diagram of the test section in the water tunnel and measurement instruments. The rectangular test section of water tunnel had a height of 400 mm, a width of 167 mm, and a length of 780 mm. The uniform flow velocity $U$ was changed from 0.74 m/s to 2.7 m/s by controlling the pump’s rotational speed and opening of the control valve and measured by a pitot tube and a digital differential pressure gauge (NAGANO KEIKE, GC50). A splitter plate with 200 mm (= 10H) in length and 1.0 mm in thickness was installed behind the prism with a gap of about 6 mm. The splitter plate length is sufficient to suppress the interaction between the upper and lower sides of vortices shedding behind the prism [11]. Meanwhile, an endplate was attached at the tip of prisms. The endplate had a diameter of 60 mm (= 6H) and a thickness of 1.0 mm.

2.2 Test models and experimental methods

As shown in figure 1, the prism was mounted elastically to a plate spring made from stainless steel and attached to the case wall on the test section. The prism was only vibrated transversely to the flow direction. Table 1 shows the specifications of the test models with and without an endplate. The rectangular and D-section prisms had a cross-section height $H$ of 20 mm. As shown in figure 2, the side ratio $D/H$ ($D$: depth of the prism in the flow direction) of the rectangular prism was 0.2 and 0.5. The

| Cross section | Rectangular | D-section |
|---------------|-------------|-----------|
| $L/H$ | $f_c$ | $\delta$ | $C_n$ | $f_c$ | $\delta$ | $C_n$ | $f_c$ | $\delta$ | $C_n$ | $f_c$ | $\delta$ | $C_n$ |
| Attached endplate |
| 2.5 | 31.9 | 0.051 | 0.91 | 24.1 | 0.047 | 0.84 | 27.34 | 0.072 | 1.26 |
| 5 | 32.9 | 0.072 | 1.26 | 22.8 | 0.062 | 1.10 | 25.63 | 0.079 | 1.40 |
| 7.5 | 23.0 | 0.038 | 0.66 | 15.5 | 0.055 | 0.97 | 20.6 | 0.087 | 0.60 |
| 10 | 24.8 | 0.044 | 0.78 | 16.4 | 0.026 | 0.45 | 17.72 | 0.070 | 1.23 |
| Free end model |
| 2.5 | 38.5 | 0.022 | 0.39 | 26.4 | 0.023 | 0.40 | 29.79 | 0.013 | 0.24 |
| 5 | 38.7 | 0.026 | 0.46 | 24.8 | 0.026 | 0.46 | 28.08 | 0.014 | 0.25 |
| 7.5 | 26.4 | 0.050 | 0.89 | 16.5 | 0.030 | 0.52 | 20.8 | 0.074 | 0.60 |
| 10 | 26.5 | 0.026 | 0.46 | 16.4 | 0.031 | 0.55 | 19.04 | 0.011 | 0.20 |
side ratio \( D/H \) of the D-section prism was 0.23 and 0.5. The span lengths for both prisms \( L \) were varied between 2.5, 5.0, 7.5 and 10. The characteristic frequency \( f_c \) of the prism was adjusted to a constant value between 16 and 39 Hz by using the plate spring with different thickness and analyzed using FFT analyzer (ONO SOKKI, CF-5201). The reduced mass-damping parameter \( C_s (= 2\delta \rho_s/\rho) \) was measured considering the initial displacement which is obtained by hitting the prism with a hammer in the still water, where \( \rho_s, \delta, \) and \( \rho \) is the density of prism, the logarithmic decay rate of the structural damping parameter of a prism, and the water density respectively. Tip displacement \( y \) was measured using an acceleration sensor (Showa Measuring Instrument, 2302CW) implanted inside the tip of the test model and connected to the integrator (RION, UV-12 and UV-05). The signals output of the integrator was converted using 12-bit A/D converter with the sampling frequency of 2 kHz, for which 16,384 data points were recorded. The reduced velocity \( V_r (= U/f_c H) \) was varied from 1.3 to 5.0 by controlling the water velocity \( U \).

3. Results and Discussions

![Schematic diagram of the test section of water tunnel and the measurement instruments](image1)

(a) Installed splitter plate at test section  
(b) Attached endplate at the tip of model  
(Side view of the test section)  
(Front view of the test section)

**Figure 1.** Schematic diagram of the test section of water tunnel and the measurement instruments

![Overview and cross section of the test models](image2)

(a) Rectangular prisms  
(b) D-section prisms  
(c) Cross section of test models

**Figure 2.** Overview and cross section of the test models

### 3.1 The Effect of a splitter plate on response amplitude

The rectangular and D-section prisms with an aspect ratio of \( L/H = 2.5 \) has non-uniform amplitude, small amplitude, and low increment rate of the response amplitude. On the contrary, the prism with \( L/H = 10 \) has stable vibration and high increment rate of response amplitude as similar to the study in reference [3]. Hence, the prisms with aspect ratio \( L/H \) of 10 were a more suitable cross-section for harvesting energy from the transverse galloping vibration. Meanwhile, this paper focus on the effect of...
a splitter plate on transverse vibration characteristics of cantilevered rectangular and D-section with different aspect ratios of $L/H = 2.5$ to 10 to enhance the dynamic response of those prisms.

3.1.1 Rectangular prisms. The response amplitudes of rectangular prisms with side ratios of $D/H = 0.2$ and 0.5, and aspect ratios of $L/H = 2.5$, 5.0, 7.5 and 10 are shown in figure 3. The vibration onset of the prism without a splitter plate was almost the same value as that with a splitter plate. For the aspect ratios of $L/H \geq 5.0$, the increment rate of the non-dimensional response amplitude $\eta_{rms}$ after the vibration onset was almost the same value as that for the rectangular prisms with a side ratio of $D/H = 0.2$ and 0.5. For a side ratio of $D/H = 0.5$ with a short span length of the prism $L/H = 2.5$, the response amplitude of prism with a splitter plate increases more than that without a splitter plate. For the small side ratio of $D/H = 0.2$ with a short span length of $L/H = 2.5$, we did not find a meaningful improvement in response amplitude by inserting a splitter plate. However, the improvement in response amplitude was found in the prism with a side ratio of 0.5.

![Figure 3](image.png)

Figure 3. Response amplitudes of rectangular prisms without and with a splitter plate

Time histories and frequency spectra of the tip displacement for a rectangular prism with $D/H = 0.5$ are shown in figures 4 and 5. The rectangular and D-section prisms vibrated at the characteristic frequency $f_c$ defined in table 1. In the case of a rectangular prism with $D/H = 0.5$, without a splitter plate, the amplitude of the vibration is not stable. As shown in figure 4(a), the rectangular prism with $D/H = 0.5$ and $L/H = 10$ has two components of the characteristic frequency i.e. prism’s amplitude and the vortex shedding frequency. This phenomenon is causally related to the stationary rectangular prism with $D/H = 0.5$ in which it appears intermittently because of two different flow patterns yielding abruptly changes on pressure base suction [12]. However, when the splitter plate is inserted behind the prism, the vibration has uniform amplitude for each aspect ratio and those intermittent waveforms vanish for all aspect ratio and result in one sharp peak only on the FFT spectrum as shown in figure 4(b).

If the splitter plate was inserted behind a circular cylinder, the effect of vortex shedding interaction on the vortex-induced transverse vibration does not occur due to the suppression of the alternative vortex shedding. On the other hand, if the splitter plate was inserted behind a rectangular cylinder of $D/H \leq 0.5$, the low-speed galloping vibration occurs and instability increased. This is because the galloping instability does not relate to the frequency of the alternative vortex shedding, and it is closely related to the minus sign of the lift coefficient slop versus the attack of angle [13]. Vanishing a second peak adjacent to the sharp peak may represent increasing of the instability of galloping, and alter the critical point of this bluff bodies as mentioned in reference [14].
3.1.2 D-section prisms. The response amplitudes of D-section prisms with a side ratio of $D/H = 0.5$, and aspect ratios of $L/H = 2.5$, 5.0 and 10 are shown in figure 6. Inserting a splitter plate behind the D-section prism brings about high response amplitude response. In particular, the response amplitude of prisms with small aspect ratio of $L/H \leq 5.0$ was built up. Figure 7 shows time histories and frequency spectra of the tip displacement for a D-section prism with $D/H = 0.5$ and $L/H = 2.5$ without and with a splitter.

![Figure 6](image1.png)

**Figure 6.** Response amplitudes of a D-section prism without and with a splitter plate for $D/H = 0.5$

![Figure 7](image2.png)

**Figure 7.** Time histories and frequency spectra of the tip displacement for a D-section prism with $D/H = 0.5$ and $L/H = 2.5$
plate. The FFT spectrum of a D-section with $D/H = 0.5$ has one sharp peak only. It means that the galloping behavior of D-section prisms is purely instability type and free from alternating vortices interferences at the after body. This is distinctly different from the rectangular prism at a similar side ratio. The effect of free end on the vibration characteristics is also observed like the rectangular prism that the D-section prism with a small aspect ratio of $L/H = 2.5$ without a splitter plate exhibits a slightly unstable response amplitude though only one dominant peak on the FFT spectrum (figure 7(a)). By inserting a splitter plate, the response amplitude becomes stable and increases.

3.2 Effect of an endplate on response amplitude
As shown in table 1, the characteristic frequency of prism with an endplate decreases about 2 Hz due to the mass of endplate. The reduced mass-damping parameter $C_n$ of cantilevered rectangular and D-section prisms with attached an endplate also increases more than that without one. However, the endplate will be expected to diminish the swirling up vortex from the tip of prism [6]. This section focuses on the effect of an attached endplate on transverse vibration characteristics of cantilevered rectangular and D-section with different aspect ratios of $L/H = 2.5$ to 10.

3.2.1 Rectangular prisms. The response amplitudes of rectangular prisms with side ratios of $D/H = 0.2$ and 0.5, and aspect ratios of $L/H = 2.5, 5.0, 7.5$ and 10 are shown in figure 8. The vibration onset of the prism without an endplate is almost the same value as that with an endplate. For an aspect ratio of $L/H = 10$, the non-dimensional response amplitude $\eta_{rms}$ of the prism with attached endplate increases at the large value of reduced velocity than that without an endplate. For the rectangular prisms with $D/H = 0.2$ and $L/H \leq 5$, the $\eta_{rms}$ of the prism with attached endplate decreases than that without an endplate. The vibration of a rectangular prism with attached endplate for $L/H = 2.5$ suppress hardly while the prism with $L/H > 5$, the effect of attached endplate on the response amplitude is out of our prediction with any meaningless improvement on the response amplitude.

Time histories of the tip displacement for a rectangular prism with $D/H = 0.2$ and $L/H = 2.5$ and with an endplate are shown in figure 9. The amplitude of the vibration is not stable. As shown in figure 8(b), for the rectangular prisms with $D/H = 0.5$ and $L/H \leq 5$, the $\eta_{rms}$ of the prism with endplate is the same as that without an endplate in which attached endplate does not affect the amplitude of the prisms. Figure 10 shows the frequency spectra of the tip displacement at maximum response amplitude for a rectangular prism with $D/H = 0.5$ with the attached endplate. However, the rectangular prisms with $L/H = 2.5$ and 5.0 have one predominant spectrum of the characteristic frequency of the prism. This is in contrast with those without endplate which has two sharp peaks on the FFT spectra. By increasing the aspect ratio ($L/H=10$), two components of sharp peaks i.e. the characteristic frequency of the prism and the alternating vortex shedding frequency appear. The cause of increment of response amplitude (figure

![Figure 8. Response amplitudes of rectangular prisms without and with an endplate](image-url)
8(b)) for $L/H = 10$ may be attributed to the alternating vortex shedding frequency. We have to confirm the interference of wake fluctuation on the response amplitude of the prism with a large aspect ratio ($L/H = 10$) in further study.

3.2.2 D-section Prisms. Figure 11 shows the response amplitudes of D-section prism with a side ratio of $D/H = 0.5$, and aspect ratios of $L/H = 2.5$, 5.0 and 10. The non-dimensional response amplitude $\eta_{rms}$ of the prism with endplate increases slightly at the large value of reduced velocity rather than that without an endplate. Figure 12 shows the time histories and frequency spectra of the tip displacement for a D-section prism with $D/H = 0.5$ and $L/H = 2.5$, and with an attached endplate. The frequency spectrum has one predominate component of the characteristic frequency of the prism which is different from the rectangular prism in the similar side ratio. Okajima et al (2004) described that the endplate effect prolonged reduced resonant velocity range in case of the circular cylinder by resulting in two excitation regions. The steeper graph of response amplitude in figure 11 may be attributable to this phenomenon.

4. Conclusions
Free-vibration tests involving a cantilevered rectangular prism and a D-section prism with a side ratio of less than 0.5 were performed in a water tunnel. The effects of a splitter and an endplate on flow-induced vibration characteristics of prisms were investigated. However, further investigation about flow
wake structure behavior in presence of splitter plate and endplate for slender prism is curious for future research. The recent conclusions of the present study are as follows:

1. Inserting a splitter plate behind prism improve the response amplitudes for finite cantilevered rectangular and D-section prisms by stabilizing response.
2. Attaching an endplate on the tip of prisms does not affect the response amplitude for prisms with a side ratio of $D/H = 0.5$ and aspect ratios of $L/H \leq 5.0$. However, attached endplate can suppress the response amplitude for the rectangular prism with a side ratio of $D/H = 0.2$ and the aspect ratios of $L/H \leq 5.0$.

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