Dissertation Abstract

Flow-induced Transverse Vibration Characteristic of Cantilevered Rectangular and D-section prisms

片持ち弾性支持角柱とＤ形柱の流れ直角方向の流力振動特性

金沢大学大学院自然科学研究科
Graduate School of Natural Science and Technology,
Kanazawa University

専攻（Division）: Mechanical Science and Engineering

氏名（Name） La Ode Ahmad Barata
Chief Supervisor Dr. Takahiro KIWATA, Professor
Date of Submission January 10, 2020

Abstract

This study is intended to enhance research field on developing energy harvesting from flow flow-induced vibration as well as physical insight concerning flow-induced vibration in the low flow regime. The results show that all the prisms oscillated below reduced resonant velocity (V_{rcr}). The prisms with aspect ratio $L/H \geq 5$ have reasonably identic on vibration characteristics. The prism with the aspect ratio of 10 and side ratio of 0.2 has a stable and large response amplitude with onset galloping at a low reduced velocity ($V_{\mathrm{r}} \geq 1.5$). In the case of the splitter plate effect, it has enhanced response amplitude, stable response, and diminished wake interferences effect on the prisms with critical side ratio D/H = 0.5. Attaching endplate at the tip end of a prism with critical aspect ratios ($L/H \leq 5$) has suppressed dynamic response, increased wake interferences, and promoted unstable amplitude. Attaching additional structure on the frontward and backward of the rectangular prism has shifted vibration onset, but the response amplitudes are similar to that of the plain prism. The discernible stability of response amplitude is found even if the side ratio of a stepped prism of 0.45 (nearly close to critical side ratio of 0.5).

1. Introduction

The remarkable research topics on flow-induced vibration recently are commonly found in the case of the effect of the aerodynamic/hydrodynamic shape of bluff bodies on dynamic responses as well as flow wake behavior around that structure which is correlated to galloping or aeroacoustics. Some of the bluff bodies shape such circular cylinder, rectangular shape, triangular, and D-shape are commonly found in the case of flow-induced vibration on such those structure. In the field of research point of view, a structure can be exposed to vibration in some situations which is its characteristics depend on mass, system damping, or aerodynamic shape. Controlling flow behaviors are a primary concern of many researchers to investigate flow features and it is widely found in the case of depth to width ratio, span-length ratio, and tandem arrangement effect on the flow field. Meanwhile, after body shape models of bluff body structure such as appended structures such as fin, end plate, and splitter plate are also commonly found on some literature both stationary and elastically mounted structure. Various types of flow-induced vibration on real engineering structures can be found in Naudascher and Rockwell (2005). Some of the considerable investigations on flow-induced vibration related to rectangular structures such as Blevins (1974), Naudascher and Wang (1993), Nakamura and Matsukawa (1987), and Manini et al (2016) has been found in many research articles. The investigations of flow-induced vibration on semi-circular or D-section bluff bodies have been also demonstrated by Feng (1968), Nakamura and Hirata (1989), Kiwata et al (2014), Wang et al (2015), Yamagata et al (2016).

The objectives of the present study are to improve the increment and stability of the response amplitude, and the decrement of the vibration's starting velocity by several methods. Those are using different aspect ratio and side ratio, installing a splitter, and an endplate, and attached additional structure (a plate and a fin) to the surface of a rectangular prism on cantilevered rectangular prisms with a side ratio of 0.2.

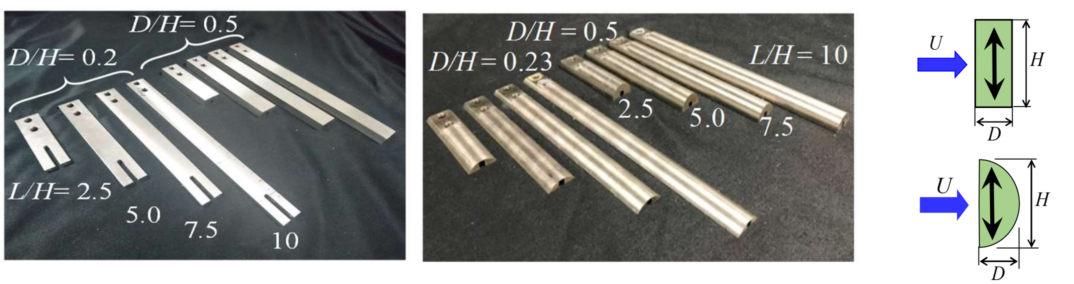
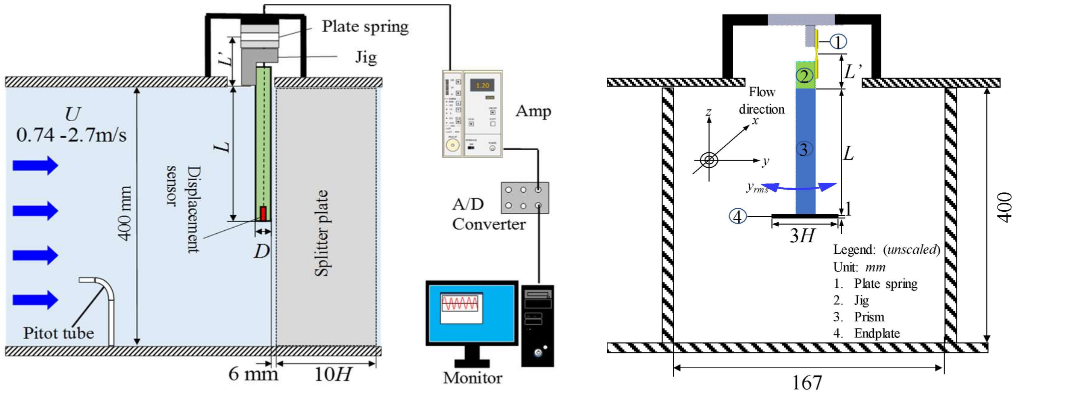


Figure 1.1. Overview of test models with different aspect ratio

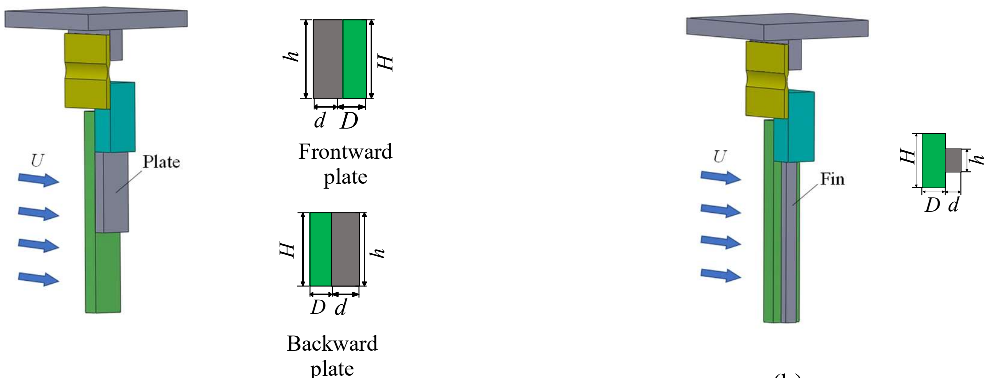
Figure 1.1 shows a schematic of the test section with different aspect ratios and side ratios. The prisms were made of stainless steel with smooth surfaces and had sharp edges. The rectangular prisms had a cross-section height H of 20 mm. The side ratio D/H of the rectangular prism was changed from 0.2 to 0.5, where D is the depth of the prism in the flow direction. The aspect ratio L/H of the prisms was varied from 2.5 to 10. The prism was mounted elastically to a plate spring attached to the ceiling wall of the test section with a jig as in figure 1.2. Table 1 shows the specifications of the test models without additional structures. Figure 1.3(a) shows side and cross-section views of a stepped rectangular prism that was joined to an additional plate with a thickness of d = 4 mm to the front or back of the cantilevered rectangular prism with D/H = 0.2. Figure 1.3(b) shows a cantilevered rectangular prism of D/H = 0.2 with a fin. The effects of the configuration of a fin fitted on the back of the cantilevered rectangular prisms to increase flexural rigidity during flow-



(a) Installed splitter plate at test section
(Side view of the test section)

(b) Attached endplate at the tip of model.
(Front view of the test section)

Figure 1.2. Schematic diagram of the test section of water tunnel and the measurement instruments



(a)

(b)

Figure 1.3. (a) Cantilevered rectangular prism of D/H = 0.2 with a plate. (b) With a fitted fin.

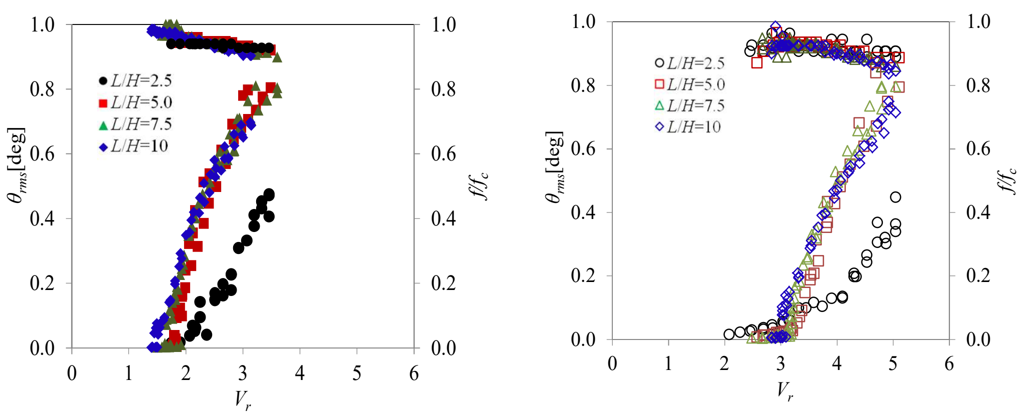
Table 1. Specification of test models without additional structures

L/H	Spring thickness (mm)	D/H = 0.2			D/H = 0.5		
		f_n (Hz)	δ	C_n	f_n (Hz)	δ	C_n
2.5	0.4	34.4	0.111	1.95	43.1	0.016	0.28
	0.6	31.1	0.044	0.77	26.4	0.023	0.40
5	0.4	23.8	0.035	0.61	15.1	0.036	0.63
	0.6	38.7	0.026	0.46	24.8	0.026	0.46
	0.8	-	-	-	33.9	0.017	0.30
7.5	0.6	26.4	0.061	1.08	16.5	0.030	0.52
	0.8	36.4	0.025	0.44	22.7	0.023	0.40
	1.0	46.1	0.023	0.41	28.8	0.017	0.30
10	0.8	26.5	0.026	0.46	16.4	0.031	0.55
	1.0	33.2	0.022	0.39	20.6	0.022	0.39
	1.2	38.9	0.020	0.35	24.3	0.025	0.44

induced vibration were investigated. The acrylic resin fin spanned the entire length of the prism. The fin-height-to-prism-height ratio (height ratio) h/H was varied from 0.25 to 0.5, and the fin-depth-to-prism-height ratio (depth ratio) d/H was varied from 0.15 to 0.4. All the experiments were performed in a water tunnel equipped with underground water, measurement instruments and a central processing unit (CPU) for data analysis.

2. Effect of the aspect ratios

Flow-field around cantilevered prisms is three-dimensional instead of two dimensional. Hence, the effect of aspect ratio L/H and side ratio D/H (where L is the span length of a prism, H is the height of a prism normal to the flow direction, and D is the depth of a prism) on a vibration characteristics of cantilevered rectangular and D-section prism models is investigated. In this research, the effect of after body shape was also considered by using two different cross-sections as mentioned above. All the experimental conditions were situated in the range of low-speed galloping due to instability of the separated shear layer origin from the sharp corner of the leading edge of the prism models. The results of the experiment show that all the prisms with different aspect ratios oscillated below reduced resonant velocity (V_{rcr}) as shown in figure 2.1. As a side ratio effect, the aspect ratio also affects the vibration onset of the prisms model with aspect ratio below the critical aspect ratio L/H = 2.5. While the prisms with aspect ratio $L/H \geq 5$ have reasonably identic on response amplitude, onset vibration, and stability of response amplitude. The distinctly different vibration characteristic appears on a prism with an aspect ratio of 2.5. In the range of low-speed galloping, all features of vibration characteristics are linear case over reduced velocity.



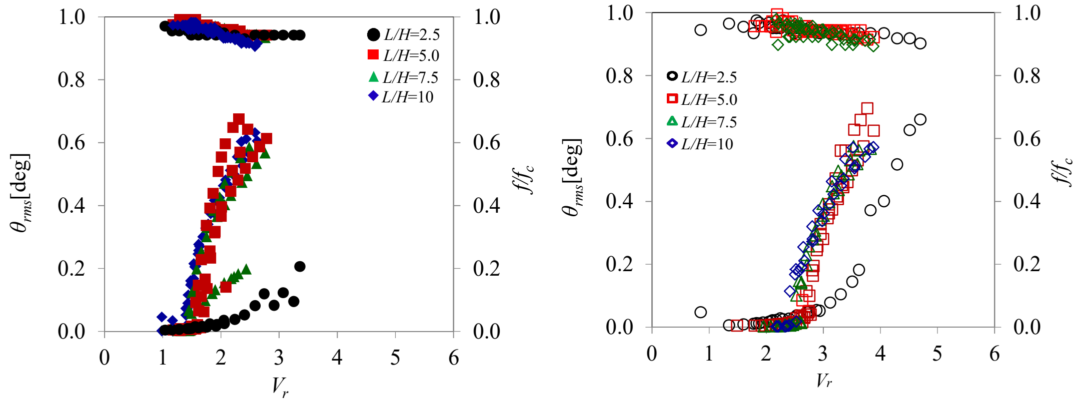
(a) Side ratio D/H = 0.2 (b) Side ratio D/H = 0.5

Figure 2.1 The angle of response amplitude and normalized frequency of cantilevered rectangular prisms respect to reduced velocity

In the case of different cross-section models, D-section prism shows a similarity to the rectangular prism behaviors on response amplitude characteristics as shown in figure 2.2. The distinctive difference between the rectangular and D-section is the onset galloping, increment rate, and the stability of response amplitude. The onset galloping of D-section is lower than the rectangular prism, which is around 1.3 and 2.2 for the side ratio of 0.23 and 0.5 respectively. While the onset galloping of the rectangular prism takes place 1.5 and 3.0.

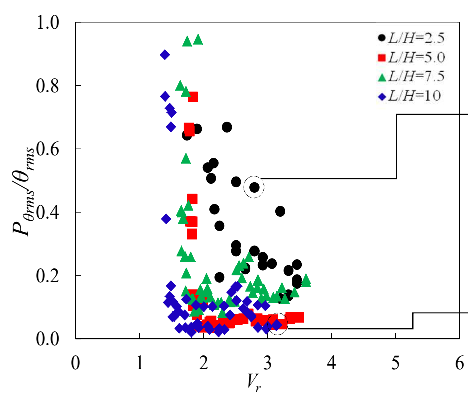
According to Nakamura and Hirata (1991), Nakamura and Matsukawa (1987), Kiwata et al (2014) that the rectangular and D-section are different in critical cross-section and side ratio can alter the onset of galloping behavior.

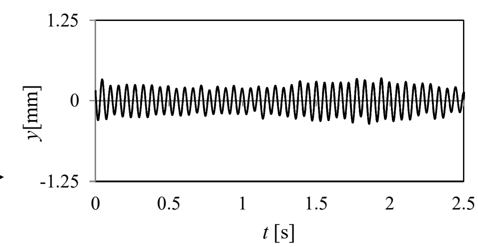
The aspect ratio affected the stability of amplitude response for $L/H \leq 5.0$ as shown in the following figure. However, the side ratio of 0.5 has a slightly high unstable peak amplitude rather than a small side ratio as shown in figures 2.3 and 2.4. Hence, the small peak response of the prism with small aspect ratio is found as shown in figure 2.4 below



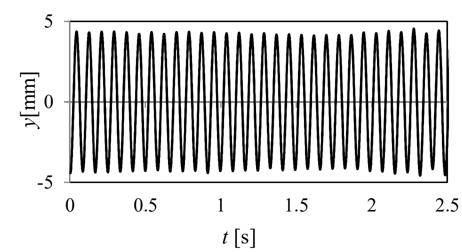
(a) $D/H = 0.23$ (b) D/H=0.5

Figure 2.2. Response angle amplitude of cantilevered D-section prisms





(a) $V_r = 2.5$ ($U = 1.93$ m/s) $L/H = 2.5$;



(b) $V_r = 3.1$ ($U = 1.66$ m/s), $L/H = 10$

Figure 2.3 Non-dimensional standard deviation of peak displacement $P\theta_{rms}/\theta_{rms}$ for Rectangular prisms $D/H = 0.2$ with respect reduced velocity V_r

Figure 2.4 Time histories tip displacement of the prism with a side ratio of 0.2

Figures 2.6 below describe the onset of galloping evolution over the aspect ratio of two different side ratios and cross-section models. The onset galloping decrease by decreasing aspect ratio and side ratio. However, D-section prim with aspect ratio and side ratio of 10 and 0.23 respectively has the lowest onset galloping. Figure 2.7 shows the effect of aspect ratio on-increment rate of response amplitude. The increment rate of response amplitude is changed by increasing the aspect ratio. The highest increment rate is taken place at D-section with an aspect ratio of 10 with a side ratio of 0.23.

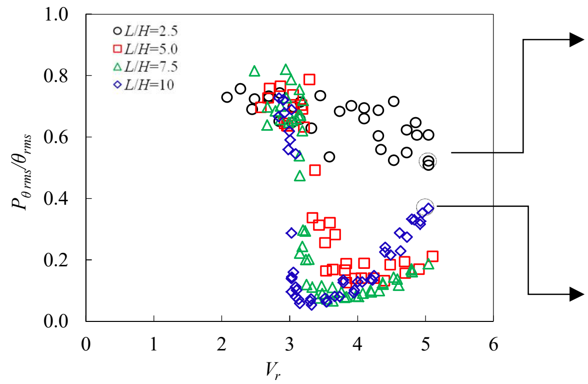
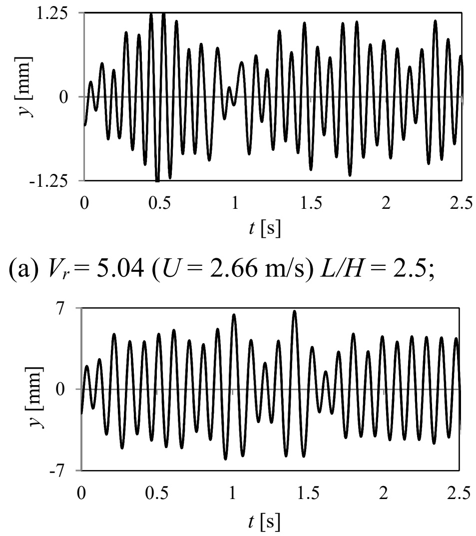


Figure 2.4 Non-dimensional standard deviation of peak displacement $P\theta_{rms}/\theta_{rms}$ for Rectangular prisms *D/H* = 0.5 with respect reduced velocity V_r



(a) V_r = 5.04 (*U* = 2.66 m/s) *L/H* = 2.5;

(b) V_r = 5.04 (*U* = 2.45 m/s) *L/H* = 10

Figure 2.5 Time histories tip displacement of the prism with a side ratio of 0.5

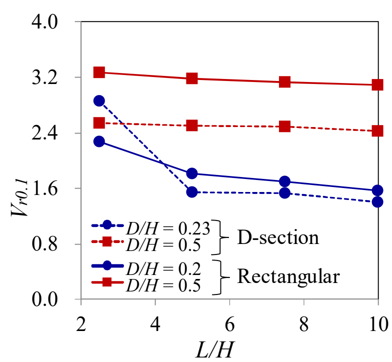


Figure 2.6. Reduced velocity at 10% of response amplitude

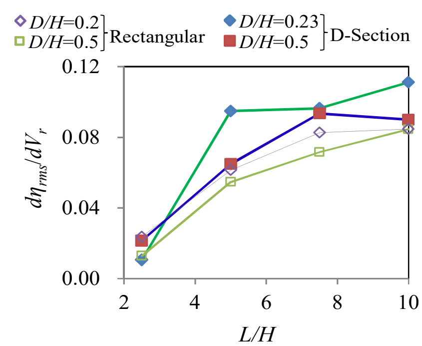
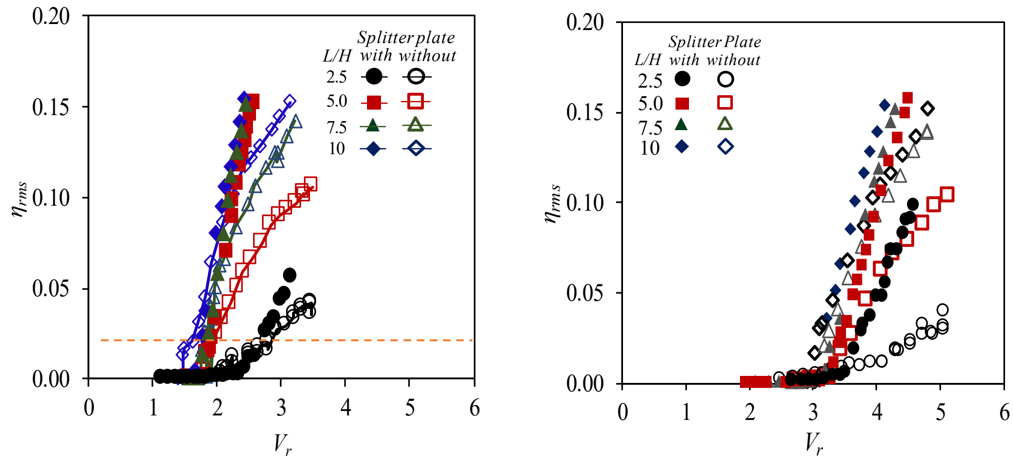


Figure 2.7. Non-dimensional increment rate of response amplitude angle $d\eta_{rms}/dV_r$ of prisms

3. The effect of attached splitter and end plate

In order to maintain a two-dimensional flow structure due to the free end effect, an end plate was also attached to the of the prism end separately. In this investigation, mounting a splitter plate enhances response amplitude for all prism models as shown in figure 3.1 and 3.4. inserting the splitter plate also successfully diminishes a discontinuity of wave form peak response amplitude which is attributable to dynamic response improvement. For D-section prism, inserting a splitter plate has improved stability of peak and response amplitude as shown in figures 3.2 and 3.3.

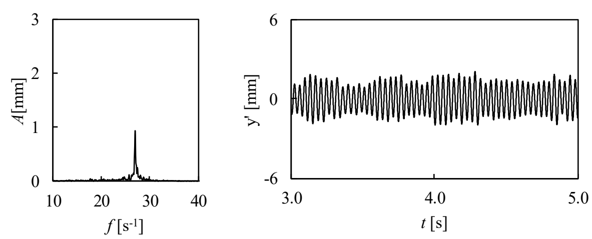
A peculiar characteristic of response amplitude takes place on the prism with critical aspect (*L/H*) ≤ 5.0 and side ratio (*D/H*) = 0.5 in which fluctuation of harmonic motion of response amplitude vanished over flow time. The phenomenon is also confirmed by using FFT spectra analysis that there is only one sharp peak on amplitude frequency as figure 3.4 which is distinctly different from the plain prism.



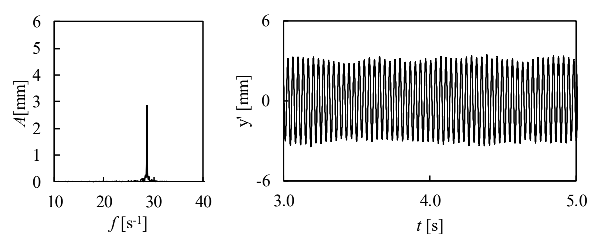
(a) $D/H = 0.2$ (b) $D/H = 0.5$

Figure 3.1 Effect of splitter plate on transverse vibration characteristics for rectangular prisms

Attaching an endplate at the end of prims does not influence the response amplitude characteristics both rectangular and D-section prisms with side ratio D/H = 0.5. (Figures 3.5 (b) and 3.56) even if peak amplitude response is slightly unstable for the prism with an aspect ratio of 2.5. Attached endplate at the prism with aspect ratio $L/H \leq 5.0$ and small side ratio (D/H 0.2 and 0.23 for D-section) has suppressed response amplitude both rectangular and D-section (figure 3.5(a) and 3.7). A non-linearity of the evolution response amplitude was found at the D-section prism with aspect ratio of 5.0 and side ratio of 0.23 when reduced damping parameter *Cn* value change from the forewent use over which a jumping response amplitude occur.



(a. Plain prism, $V_r = 4.7$, U= 2.8 m/s)



(b. with splitter plate V_r = 3.34 U = 2.4 m/s)

Figure 3.2. FFT spectra and time histories of the waveform for short D-section L/H = 2.5 with side ratio D/H=0.5 at maximum response amplitude

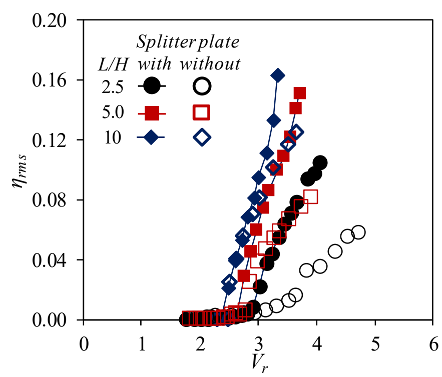
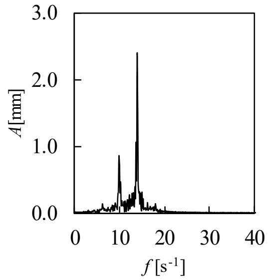
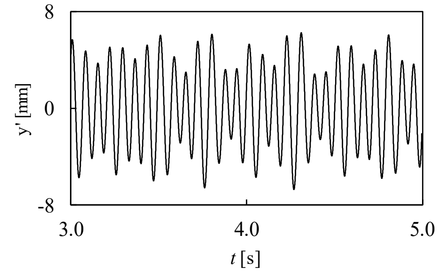


Figure 3.3 Effect of splitter plate on transverse vibration characteristics for D-section with critical side ratio D/H=0.5

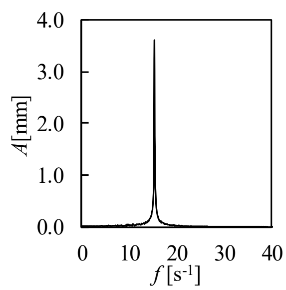


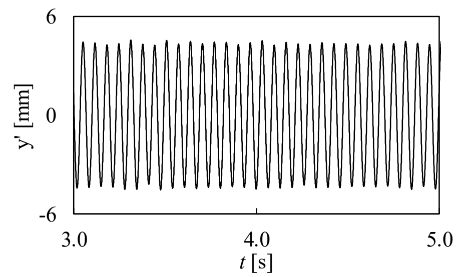
i. FFT Spectrum



ii. Time-lapses of the waveform

a. Plain rectangular prism, $L/H = 10$, $V_r = 4.95$



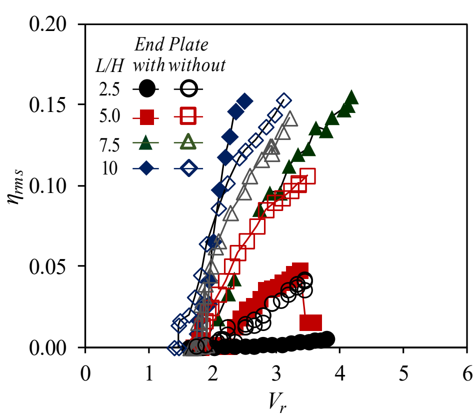


ii. Time-lapses of the waveform

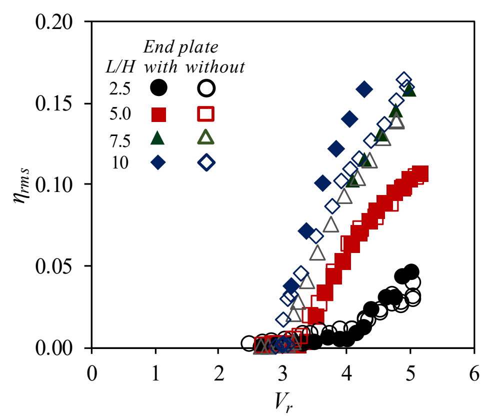
i. FFT Spectrum

a. Attached splitter plate for rectangular prism, $L/H= 10$, $V_r = 4.13$

Figure 3.4 FFT Spectra and time-lapses of response amplitude for the rectangular prism with splitter plate



(a) $D/H = 0.2$



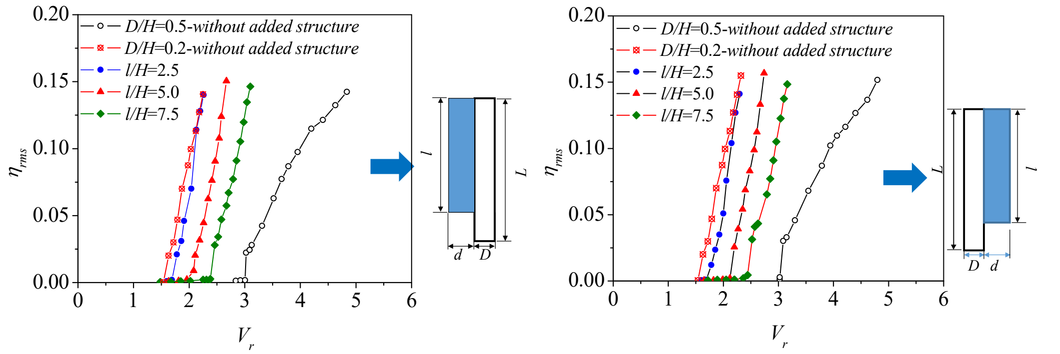
(b) $D/H = 0.5$

Figure. 3.5 Effect of end plate on transverse vibration characteristics for Rectangular

4. Effect of the additional structure

Attached the additional structure at the frontward or backward position on the prisms was not successful to increase response amplitude rather than shifting onset vibration as shown in figure 4.1. Presuming that effect of increasing rigidity of the prism was not in line with the initial prediction that attaching additional structure is supposed to put a hybrid response amplitude.

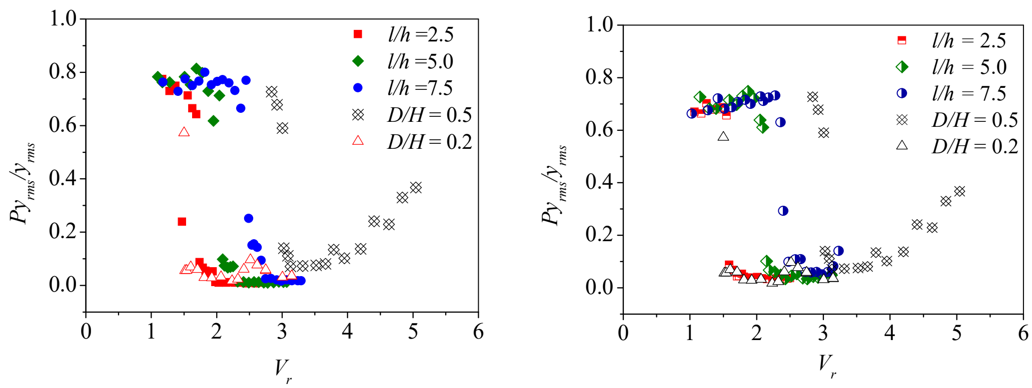
The effect of axial force on the vibration characteristic influences bending stress behavior acting on the span length of the rectangular prism. In this case, bending or deflection stress effect prediction on the free vibration characteristic was reduced by increasing rigidity of the prism by adding a lighter structure at backward and frontward of the prism. In this case, the rigidity was increased from 107 to 810 mm^4. As the result the stability of response amplitude is improved as indicated in figure 4.2. The evolution of onset galloping and stability of response amplitude was also found in Kiwata et al (2013) with various size of fitted fin.



(a) The added plate is located at the front of the prism

(b) The added plate is located at the back of the prism

Figure 4.1 Transverse vibration characteristic of a rectangular prism with a side ratio of 0.2 with added structure



(a) Plate put on the front surface

(b) Plate put on the back surface

Figure 4.2**.** The non-dimensional standard deviation of peak displacement for a rectangular prism of *D/H* = 0.2 with an added plate

5. Concluding Remarks

Based on the experiment result that vibration characteristic can be viewed into two groups i.e. the prisms with aspect ratio *L/H* of ≥ 5.0 have similar response amplitude and the prisms with aspect ratio below the critical aspect *L/H* = 2.5. The prisms with aspect ratios below critical aspect ratio show non-uniform amplitude peak displacement, unstable response amplitude, and low increment rate of response amplitude. The discontinuity of oscillation waveform is also introduced on the prism with critical side ratio *D/H* = 0.5 which is inverse with rectangular prism with a side ratio of 0.2. In the case mounting a splitter plate at prisms trailing edge, it has improved response amplitude for both cross-section models by modifying the vortex dynamic behind the prisms instead of allowing them to interact directly; hence which prevents wake interference on the response amplitude. As the result, the fluctuation of amplitude peak is uniform with only one sharp peak is found on the FFT spectra analysis. For rectangular prism below critical aspect ratio $L/H \leq 5.0$ and side ratio of 0.2 in which the galloping relies on instability, mounting splitter plate does not affect response amplitude. Attaching endplate at the end of prisms does not influence the uniformity of waveform amplitude for both prisms model with D/H of 0.5. Hence, there is not any meaningful improvement amplitude. However, attaching endplate at the prism with small depth section D/H = 0.2 (rectangular) and 0.23 (D-section) is a meaningless way related to amplitude improvement for aspect ratio $L/H \geq 5.0$. For the prism with $L/H \leq 5.0$, attaching endplate has suppressed response amplitude. Hardly suppressing on response amplitude was found in the prisms below critical aspect ratio, L/H = 2.5 and D-section with L/H = 5.0 and C_n property is 1.99. A non-linear response amplitude over reduced velocity was found at D-section prism with L/H = 5.0 and Cn = 1.09 which is indicated by suddenly jump of response amplitude.

Finned and stepped prism increase rigidity of the prism which indicated by the stability of response peak displacement. In case of response amplitude, fined prism and staggered has shift onset galloping regularly with increasing depth ratio, however, stepped prisms prolong galloping range with a small amplitude that changes the onset galloping. Staggered prism preserve peak amplitude stability remains stable even if the depth ratio approached to 0.45.

References

Kiwata, T., YAMAGUCHI, M., KONO, T., & Ueno, T. (2014). Water tunnel experiments on transverse-galloping of cantilevered rectangular and D-section prisms. *Journal of Fluid Science and Technology*, *9*(3), 1–5. https://doi.org/10.1299/jfst.2014jfst00

Mannini, C., Marra, A. M., Massai, T., & Bartoli, G. (2016). Interference of vortex-induced vibration and transverse galloping for a rectangular cylinder. *Journal of Fluids and Structures*, *66*, 403–423. https://doi.org/10.1016/j.jfluidstructs.2016.08.002.

Nakamura, Yasuharu, & Matsukawa, T. (1987). Vortex excitation of rectangular cylinders with a long side normal to the flow. *Journal of Fluid Mechanics*, *180*(1), 171. https://doi.org/10.1017/S0022112087001770

Nakamura, Y., & Hirata, K. (1989). Critical geometry of oscillating bluff bodies. *Journal of Fluid Mechanics*, *208*, 375–393. https://doi.org/10.1017/S0022112089002879\

Naudascher, E. Rockwell, D. (2005). *Flow -Induced Vibrations: an Engineering Guide*. Dover Publication Inc.

Naudascher, E., & Wang, Y. (1993). Flow-induced vibrations of prismatic bodies and grids of prisms. *Journal of Fluids and Structures*. https://doi.org/10.1006/jfls.1993.1021

Wang, Q., Li, M., & Xu, S. (2015). Experimental study on vortex induced vibration (VIV) of a wide-D-section cylinder in a cross flow. *Theoretical and Applied Mechanics Letters*, *5*(1), 39–44. https://doi.org/10.1016/j.taml.2015.01.002

Yamagata, T., Saito, N., & Fujisawa, N. (2016). Aeolian Tone from a Semi-Circular Cylinder in a Stream . *Journal of Flow Control, Measurement & Visualization*, *4*(4), 30–37. https://doi.org/10.4236/jfcmv.2016.41003.

令和２年２月４日

学位論文審査報告書（甲）

１．学位論文題目（外国語の場合は和訳を付けること。）

Flow-induced Transverse Vibration Characteristic of Cantilevered Rectangular and D-section prisms

（片持ち弾性支持角柱とＤ形柱の流れ直角方向の流力振動特性）

２．論文提出者　(1) 所　　属　機械科学専攻

(2) 氏　　名（ふりがな）　La Ode Ahmad Barata（ら　おで　あはまど　ばらた）

３．審査結果の要旨（600～650字）

当該学位論文に関し、令和２年２月４日に第１回学位論文審査委員会を開催し、提出された学位論文及び関係資料に基づき内容を検討した。さらに同日行われた口頭発表後に第２回学位論文審査委員会を開催し、協議の結果、以下の通り判定した。

申請論文は、流力振動発電に適する柱状物体形状を解明するために、低速ギャロッピング振動が生じる角柱、およびＤ形柱の流力振動特性を水槽実験により調べ、模型のアスペクト比や段付き角柱、及び模型の端板や後部仕切り板の有無が自由振動特性に与える影響を明らかにしたものである。模型のアスペクト比は５倍以上の細長い柱状物体、段無し・端板無し・仕切り板有りの扁平な柱状物体が最も低い流速から振動して、振動振幅が増加し、波形が安定する知見を初めて示し、磁歪材料を用いた流力振動発電の実用化に向けた有用な設計データを見出した功績は大きいと言える。

以上のように、本論文は、流体関連振動の分野のみならず、バッテリー不要なIoT技術普及のための環境発電分野への寄与が大きく、博士(工学)に値すると判定した。

４．審査結果　(1) 判　定（いずれかに○印）　合　格　・　不合格

(2) 授与学位　博　士（工　学）