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FLOW-INDUCED WAVE GENERATED ON A THIN FILM UNDER SHEAR LOADING

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ABSTRACT

This paper deals with an experimental study of flow-induced wave generated on a thin film under shear loading. The experiment is carried out to investigate the deformed shape of the thin film with various values of shear loading, and the wave propagation due to the interaction of the deformed shape of the thin film with the fluid flow in the narrow passage. As a result, it is clarified that the flow-induced wave occurs to the thin film caused by interaction of the corrugated shape of the corrugation due to the shear loading with the fluid flow in the narrow passage. Moreover, it is clarified that the traveling direction of the flow-induced wave is determined by the corrugated shape of the corrugation and fluid flow direction. The flow-induced wave propagates diagonally, almost across the fluid flow direction.

INTRODUCTION

In manufacturing process of flexible materials, such as paper, sheets and plastic films, the flexible materials are subjected to a fluid flow in a narrow passage for non-contact support and drying. However, it was reported that flow-induced wave, which reduces the product efficiency and quality, occurs to the thin film when the flow velocity in the narrow passage becomes higher, and the flow-induced wave occurs due to the interaction between the thin film in motion and the fluid flow. Moreover, most of flexible materials are very thin and prone to buckle or wrinkle, we need to consider the effect of corrugated shapes of the thin film for the stability of the wave (see Figure 1). In order to avoid quality defects, it is important to clarify the vibration characteristics of the flow-induced wave generated on the thin film under the corrugation due to the shear loading.

Up to this time, many researches have been conducted on flutter of flexible sheet and web subjected to axial air flow [1]-[21]. Chang and Moretti [1] studied flow induced vibration of free edges of thin films by using traveling-wave analysis based on the incompressible potential-flow. In their research work, stability and dynamic behavior of waves generated in the web were examined. Yamaguchi et al. [3, 4] developed a numerical model of a flexible sheet subjected to a high speed air flow and examined the flutter limits and the associated dynamic behavior. Carpenter et al. [9, 10] investigated the flow-induce surface instabilities of the compliant wall theoretically. Watanabe et al. [12, 13] developed a Navier-Stokes simulation and a potential flow analysis for investigation of paper flutter, and also performed experiments.

Many research works were conducted with respect to web wrinkles of flexible webs [22]-[26]. Gelhbach et.al [23] presented the prediction model for isotropic webs and compared the predicted results with the measured data. Hashimoto [25] developed a prediction model for anisotropic webs. The applicability of the model was verified by comparing the predicted results and measured date for various operation conditions. However, vibration characteristics and instability mechanism of the flow-induced wave under the corrugation due to the shear loading are not clarified.

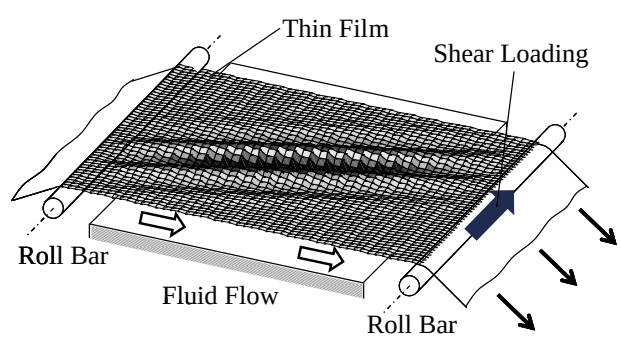


Figure1 Corrugated shape generated on the thin film

In this paper, vibration characteristics and mode shapes of the flow-induced wave generated on the thin film with various values of shear loading are examined experimentally. The experimental results show that the flow-induced wave occurs to the thin film caused by the interaction of the corrugated shape of the corrugation due to the shear loading with the fluid flow in the narrow passage. It is clarified that the traveling direction of the flow-induced wave is determined by the corrugated shape of the corrugation and fluid flow direction. Moreover, mode shapes of the flow-induced wave are investigated. Flow-induced wave propagates diagonally, almost across the fluid flow direction.

EXPERIMENT

Experimental Setup

A schematic illustration and photographs of the experimental setup are shown in Figure 2 and Figure 3, respectively. A schematic illustration and photograph of the film supporting mechanism are shown in Figure 4, and the major parameters used in the experiment are given in Table1.

In the experimental setup, the thin film #1 is supported at both of the upper and lower ends, and a tensile force is applied to the thin film using weights #2 and linear guide #3, which prevent twisting of the thin film. To apply a shear loading to the thin film, the upper end position of the thin film can be adjusted in the *x*-direction over a range of -20 mm ~ 20 mm by moving the rack-and-pinion stage #4. Here, the displacement at the upstream end will be referred to as the shear displacement in this paper. The air flows in the passage between the thin film and both sides. The thin film is subjected to the fluid flow in the narrow passage #5. The passage length is 300 mm. The fluid flow generated by a blower #8 and the flow rate is measured by a flow meter #7. The thin film is made of PET (Polyethylene terephthalate), and is 0.016 mm in thickness, 580 mm in length, and 140 mm in width. The vibration displacement of the thin film is measured with two laser displacement sensors #6.

In the experiments, firstly, the effect of the corrugation due to the shear loading on the dynamic characteristics of the flow-induced wave are examined by changing the tensile force S and the shear displacement δ. Then, mode shapes of the flow-induced wave are investigated to clarify the dynamic characteristics (phase velocity) of the wave.

Measurement System

A schematic illustration of a measurement system for the thin film displacement is shown in Figure 5. In the experiment, the vibration displacement is measured by laser displacement sensor-A. Sensor-A is set at the center of the thin film.

Mode shapes of the flow-induced wave are investigated using two laser sensors (Sensor-A and Sensor-B). First, laser sensor-A (reference sensor) is set at the center of the thin film and the laser sensor-B (movable sensor) is set at Point 1. The measurement of the thin film displacement is started at the same

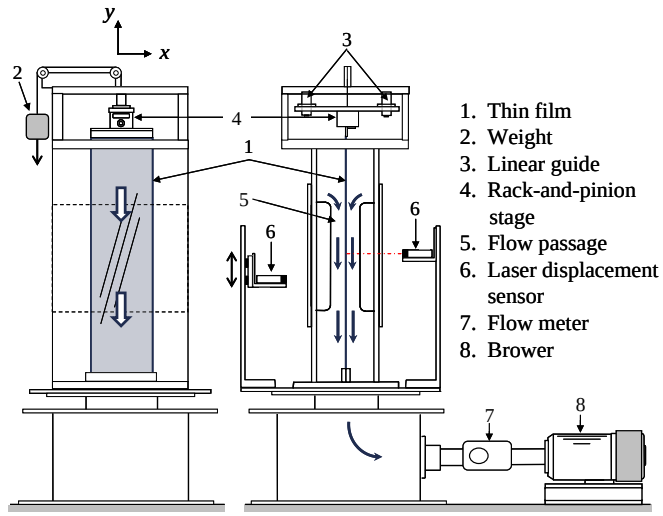


Figure 2 Schematic illustration of the experimental setup

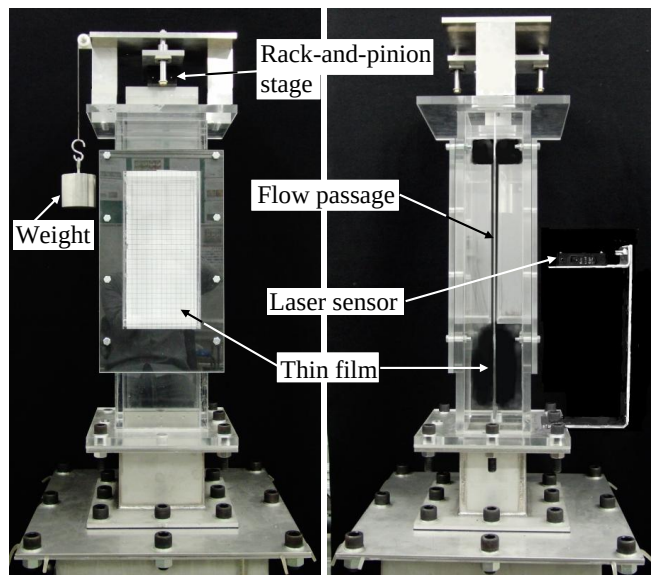


Figure 3 Photographs of the experimental setup

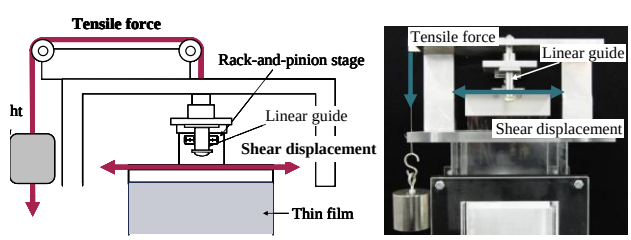


Figure 4 Film supporting mechanism

time. Then, the displacement at Point-1 is calculated by comparing the displacement data at reference point in arbitrary timing of phase. This procedure is repeated over the thin film surface at intervals of 10 mm by moving the laser sensor-B.

EXPERIMENTAL RESULTS AND DISUCUSION

Figures 6 (a), (b) and (c) show the variation of RMS displacement at the center of the thin film with changing flow velocity V in the case of tensile force S = 20, 60, 100 N/m, respectively. From these figures, it can be seen that the flow-induced wave occurs to the thin film with increasing flow velocity V. However, when the shear displacement δ = 0 mm, the flow-induced wave doesn't occur to the thin film. Moreover, the vibration displacement of the thin film increases with increasing shear displacement. On the other hand, the vibration displacement decreases with increasing tensile force.

Figures 7 (a) and (b) show the critical flow velocity V_{cr}

Table 1 Major parameters used in the experiments

Film material	PET	
Fluid	Air	
Width of film	140	[mm]
Length of film	580	[mm]
Thickness of film	0.016	[mm]
Tensile force	20 – 100	[N/m]

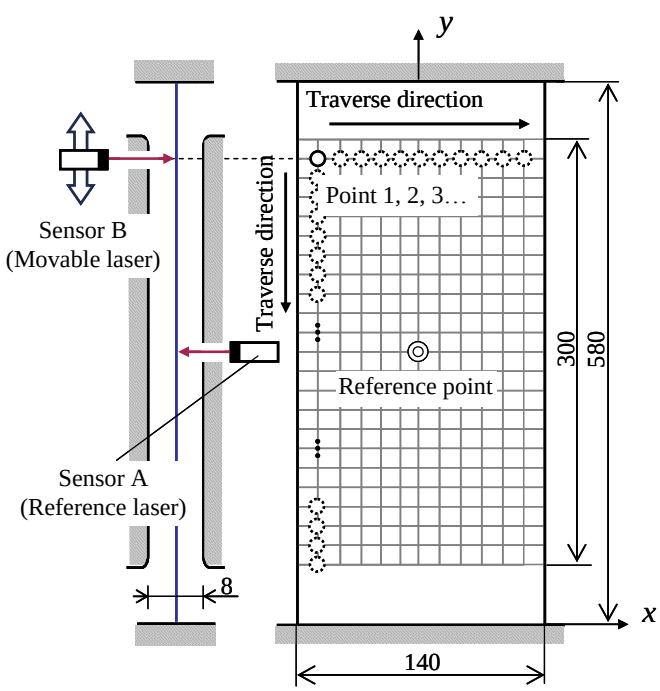
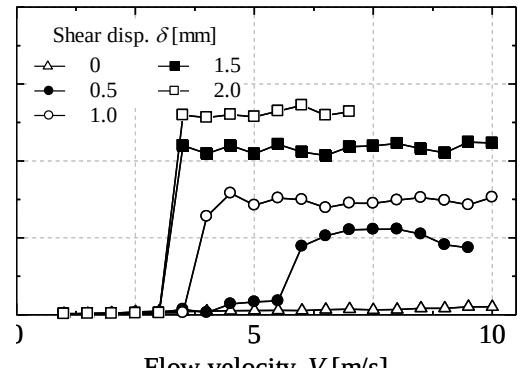
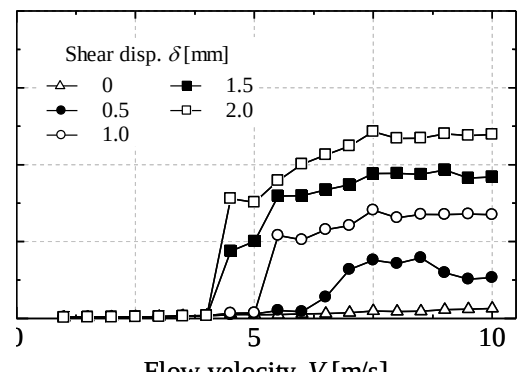


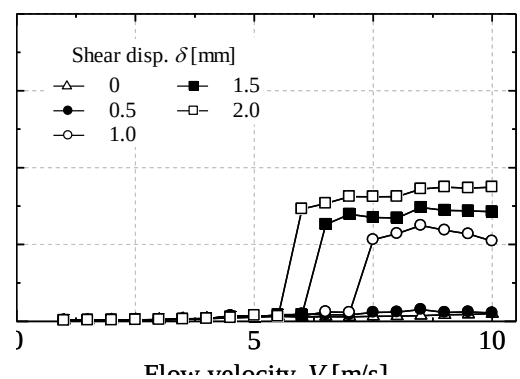
Figure 5 Schematic illustration of measurement system



(a) In the case of tensile force S = 20 N/m



(b) In the case of tensile force S = 60 N/m



(c) In the case of tensile force S = 100 N/m

Figure 6 Variation of RMS displacement with changing flow velocity V

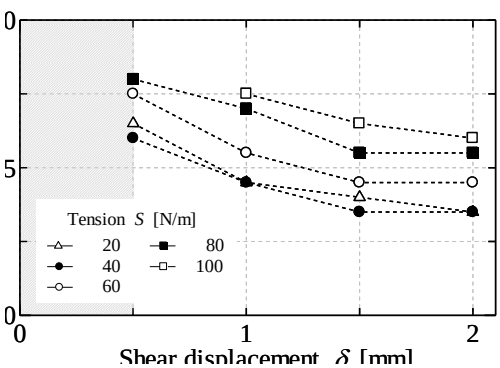
with changing shear displacement δ. From these figures, it can be seen that the critical flow velocity decreases with increasing shear displacement. On the other hand, the critical flow velocity increases with increasing tensile force. Moreover, when the shear displacement is small, the flow-induced wave doesn't occur to the thin film. From these results, the critical flow

velocity drastically decreases caused by the generation of the corrugation on the thin film due to the shear loading. These results indicate that the flow-induced wave occurring to the thin film is caused by the interaction of the corrugated shape of corrugation due to the shear loading with the fluid flow in the narrow passage.

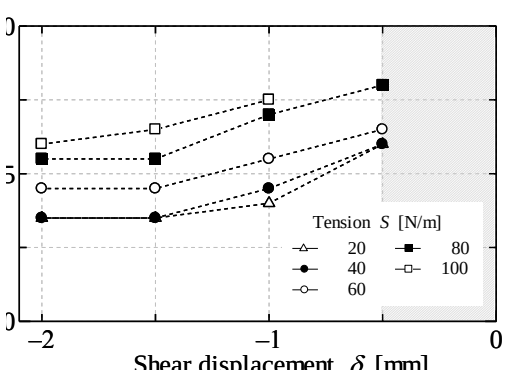
WAVE MOTION

Figure 8 and Figure 9 show mode shapes of the thin film with an interval of 1/8 period time successively in the case of the shear displacement δ = -1.5, +1.5mm, respectively. In these figures, mode shapes of cross-section along the traverse line A and B of the thin film are shown. From these figures, it is seen that the traveling-wave type flow-induced wave occurs to the thin film. Moreover, mode shapes in the horizontal direction are changed by the direction of the shear displacement. From these results, traveling direction of the flow-induced wave is determined by the corrugated shape of the corrugation and fluid flow direction.

Figure 10 and Figure 11 show the wave motion of the thin



(a) In the case of tensile force S = 60 N/m



(a) In the case of tensile force S = 100 N/m

Figure 7 Variation of critical flow velocity V_{cr} with changing shear displacement δ

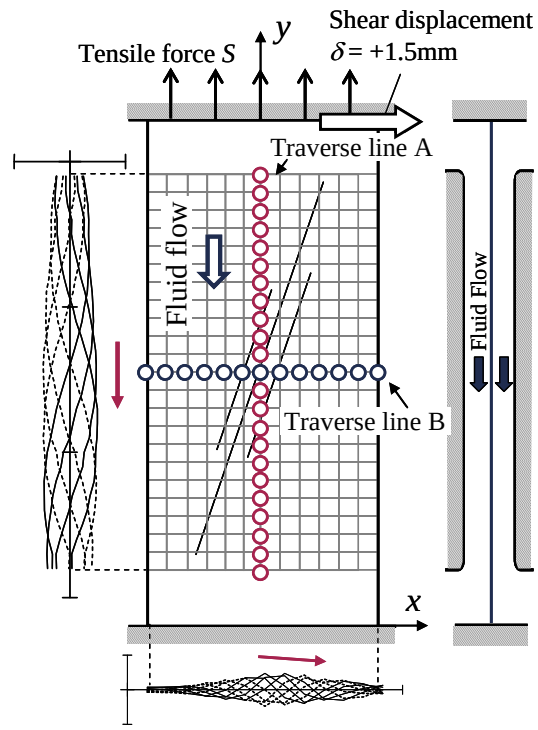


Figure 8 Mode shape of the flow-induced wave in x, y - directions (shear displacement δ =+1.5mm)

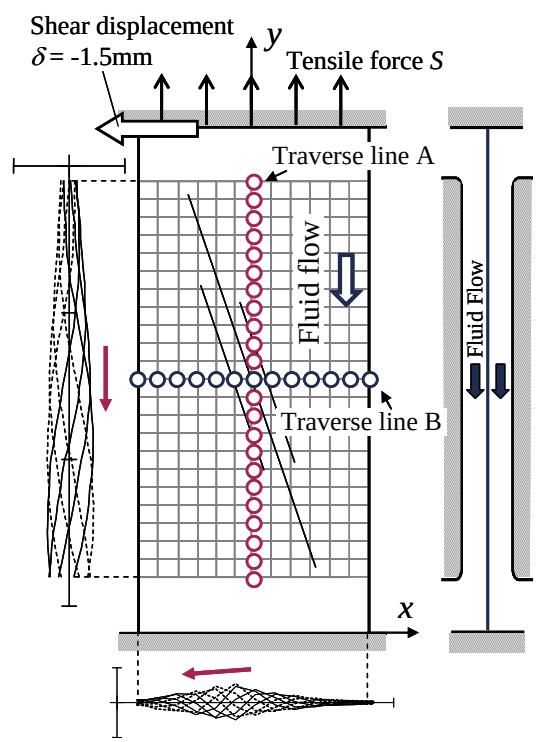


Figure 9 Mode shape of the flow-induced wave in x, y-directions (shear displacement δ =-1.5mm)

film in the case of the shear displacement δ = -1.5, +1.5 mm, respectively. In these figures, wave motion of the thin film with an interval of 1/8 period time successively are shown. From these figures, it can be seen that flow-induced wave propagates diagonally, almost across the fluid flow direction. When the shear displacement applied to the right, the flow-induce wave propagates diagonally right from the upstream side to the downstream side. On the other hand, when the shear displacement applied to the left, the flow-induced wave propagates diagonally left. From these results, it indicates that the traveling direction of the flow-induced wave is determined by the corrugated shape of the corrugation due to the shear loading and fluid flow direction. When the shear loading is applied to the thin film, the out-of-plane deformation is constrained by the generation of the buckling. Then, anisotropy of bending stiffness occurs to the thin film caused by the corrugated shape of the corrugation, and the flow-induced wave propagates in particular direction, in which is the bending stiffness is small.

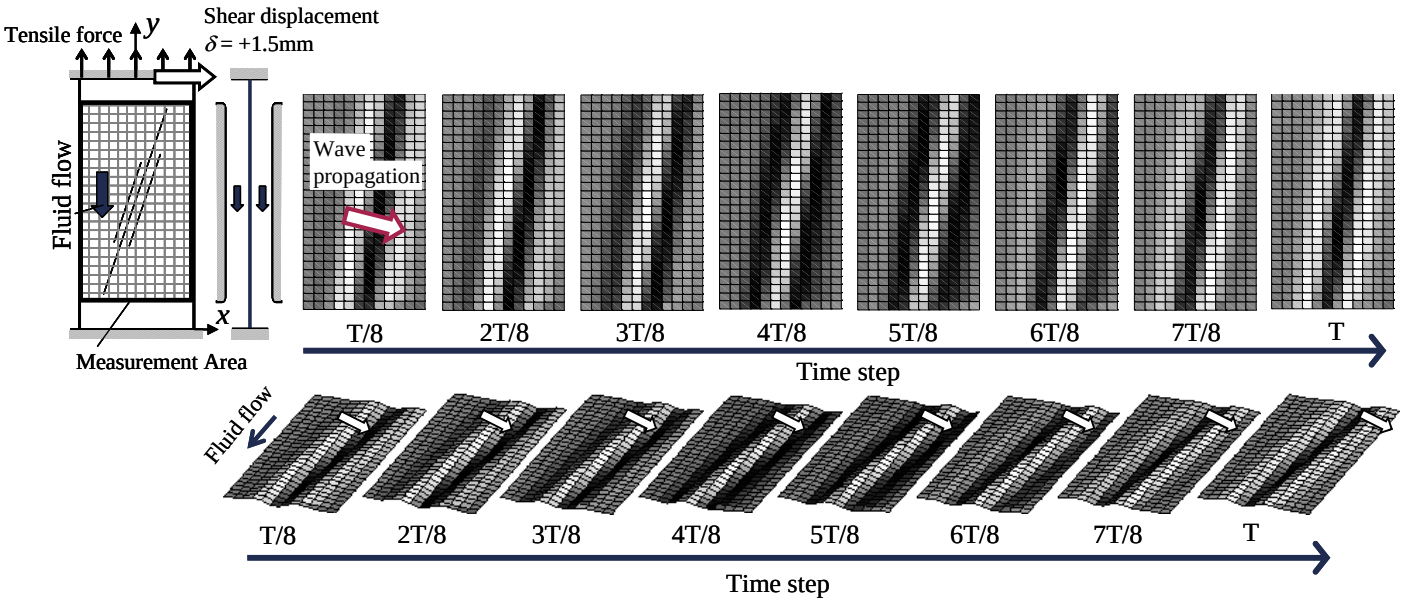


Figure 10 Wave motion of the thin film with an interval of 1/8 period (Shear displacement δ=+1.5mm)

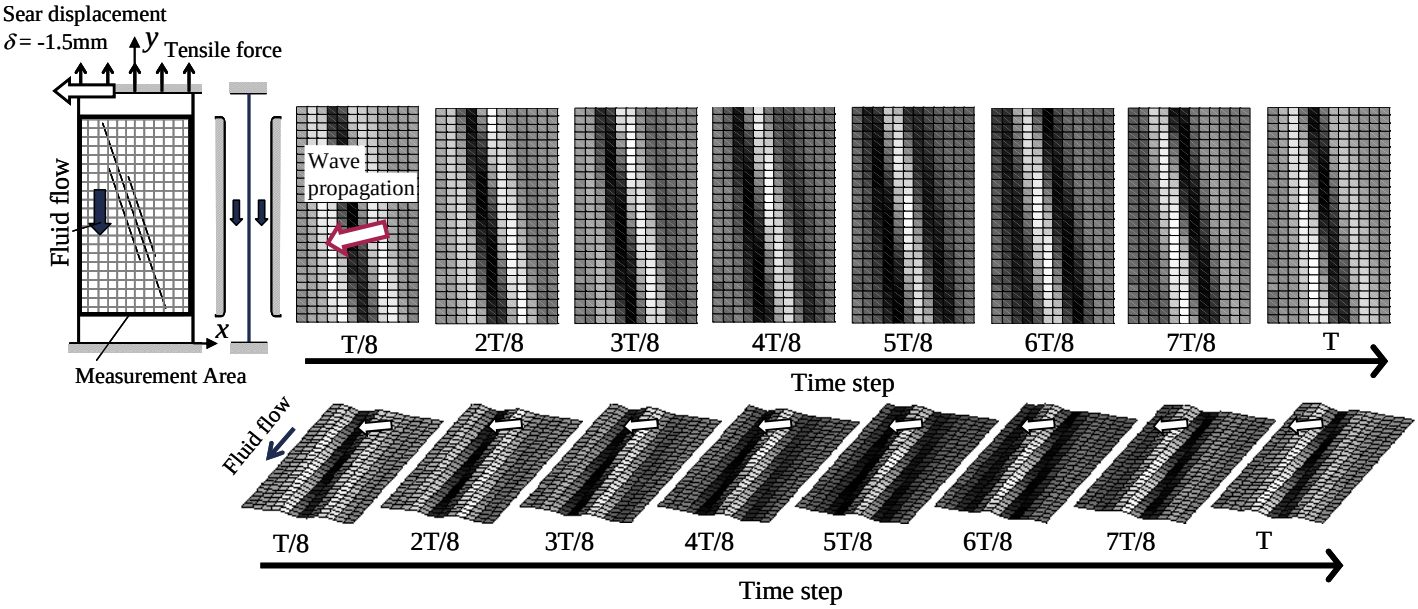


Figure 11 Wave motion of the thin film with an interval of 1/8 period (Shear displacement δ=-1.5mm)

WAVE CHARACTERISTICS

Figure 12 and Figure 13 show phase velocity of the flow-induced wave in the vertical direction and the horizontal direction with increasing flow velocity. In these figures, three types of mark denote the tensile force S = 20, 60, 100 [N/m], respectively. From these figures, the phase velocity of the flow-induced wave increase linearly with increasing flow velocity.

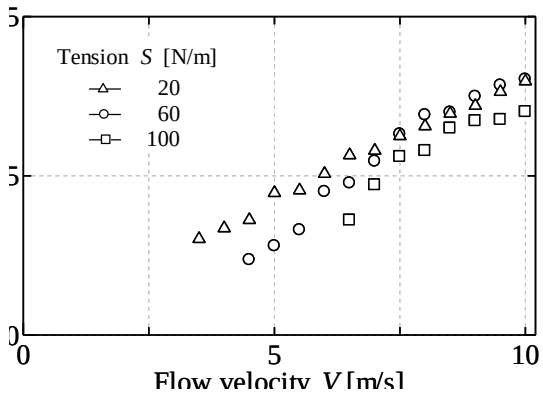


Figure 12 Variation of phase velocity in vertical direction with increasing flow velocity V

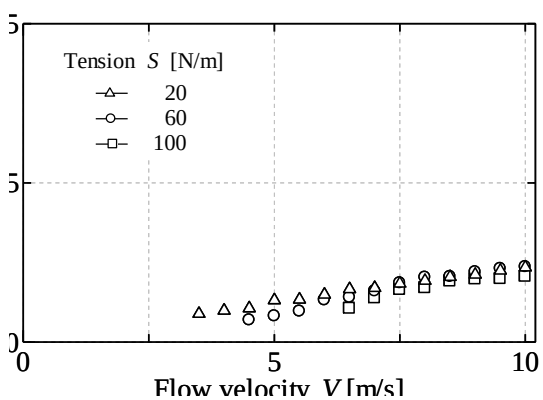


Figure 13 Variation of phase velocity in horizontal direction with increasing flow velocity V

CONCLUSIONS

The vibration characteristics and mode shapes of the flow-induced wave generated on the thin film under the corrugation due to the shear loading are examined experimentally. According to the experimental results, the following major things were clarified.

(1) When the shear loading is applied to the thin film, the corrugation is generated diagonally on the thin film. Then, the flow-induced wave occurs to the thin film caused by the interaction of the corrugated shape of corrugation due to the shear loading with the fluid flow in the narrow passage.

(2) The traveling direction of the flow-induced wave is determined by the corrugated shape of the corrugation and fluid flow direction. The flow-induce-wave propagates diagonally, almost across the fluid flow direction.

(3) The critical flow velocity of the flow-induced wave drastically decreases caused by the generation of the corrugation on the thin film due to the shear loading.

(4) The critical flow velocity decreases with increasing the shear displacement. On the other hand, the critical flow velocity increases with increasing the tensile force.

ACKNOWLEDGMENTS

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