Study on fluttering characteristics of articulated flat plate flag

Masaki Yamagishi¹ and Hiroki Shida²

¹ Department of Mechanical Engineering, Toyohashi University of Technology, 1-1 Hibarigaoka, Tempaku, Toyohashi, 441-8580, JAPAN
² Electric & Mechanical System Engineering Advanced Course, National Institute of Technology, Nagaoka College, 888 Nishikatakai, Nagaoka, Niigata, 940-8532, JAPAN

yamagisi@nagaoka-ct.ac.jp / yamagisi@me.tut.ac.jp

Abstract. For wind/water power generation, we have been trying to harness flow-induced vibration, and we used a flag as the oscillating body. The flag was made of flat plates joined by articulations. To achieve a suitable design in engineering, it is important to clarify the fluttering characteristics of this articulated flat plate. The fluttering characteristics were therefore investigated experimentally in a wind tunnel. In the experiment, several rectangular plates were tested in several conditions of stream-wise length, span-wise length, thickness, and density. To investigate the fluttering characteristics, the fluttering frequency in a uniform flow velocity was focused on. The fluttering mode was observed simultaneously. It was found that an articulated flat plate flutters in a uniform flow and has a steady fluttering mode. The fluttering frequency increases with increasing uniform flow velocity for all conditions. The frequency was higher when the streamwise-length was short, thickness was thin, and density was small. It was found that there were two modes of fluttering: node-less mode and one-node mode. Furthermore, the dimensional analysis was performed, and the results show that the non-dimensional number consisting of the Strouhal number, Reynolds number, and mass ratio became constant.

1. Introduction
Oscillations induced by flow lead to many serious accidents in mechanical and structural engineering, such as the famous accident of Tachoma Bridge. Many researchers tried to reduce or control those oscillations. Oscillation power, however, could become the source of energy from the flow. Some examples were proposed to get the kinematic energy of flow by transforming to the oscillating energy [1-3]. These examples utilize the oscillation that is caused by the elasticity of the oscillating body as restoring forces. Thus, the oscillating body may be destroyed due to fatigue after repeated oscillation. Furthermore, from the viewpoint of the energy source, a controllable oscillation is required.

In this study, for the oscillating body, a flag-like body composed of several sized flat plates joined by articulations called multi-articulated flat plate was proposed [4], as shown in figure 1. The multi-articulated flat plate flutter in the uniform flow like a flexible sheet flag, and its fluttering motion is two-dimensional. Since the motion of the multi-articulated flat plate is more regular and periodic than that of a sheet flag, it is suitable for wind/water power generation by using fluttering. Generating electricity was attempted by attaching the piezo-generator on this multi-articulated flat plate. It was expected for an independent power source like as the water level sensor.

Many studies on sheet flags have been performed by researchers. For the pioneering study, Taneda investigated experimentally the motion and characteristics of sheet flags in several materials and showed
that a non-dimensional parameter consisting of Strouhal number, Reynolds number, and mass ratio is nearly constant independent of the Reynolds number [5]. Sato et al. investigated the motion of hard and soft flags [6]. They suggested that the fluttering frequency of the hard flag could be approximately predicted by using the kinematics of oscillation. In their study, the fluttering frequency of the hard flag is proportional to the flow velocity and inversely proportional to the square root of the mass per unit area and the length of flag. Eloy et al. studied experimentally and theoretically the flutter instability of cantilevered flexible plates in the uniform flow [7]. They clarified the relationship between the critical velocity, aspect ratio, and mass ratio. Zhang et al. carried out a two-dimensional experiment on the flexible filament in a soap film flow [8]. They indicated that there were two stable states in the waving motion of the filament: stretched-straight state, and flapping state. There exists a critical length of the filament in these two different stable states. On this hysteresis, Eloy et al. [9] and Nishiura et al. [10] also focused and studied experimentally and analytically. Nishiura et al. [10] and Huang and Sung [11] carried out numerical simulation on the flow around the flapping flag and showed the vortex structures and flapping mode of flag. Hiroaki et al. investigated on the flutter speed of the flexible sheet experimentally and analytically [12]. On a flexible cantilevered plate, Fujita and Matsumoto investigated on the relationship between the critical velocity and the mass ratio [13].

Although there are many studies on flexible flag motions in a flow as described above, a study on the oscillating characteristics of an object that is discontinuously deformed, such as articulated rigid plates, has not been reported so far. To use the oscillation for a wind/water power generator, it is important for design to clarify the fluttering characteristics of the multi-articulated flat plate. The aim of this paper is to clarify the frequency characteristics. In this work, as the first step, variations of the fluttering frequency against the flow velocity were investigated for several flat plate lengths and density. The characteristics of the fluttering frequency were estimated by the traditional non-dimensional parameters. The fluttering mode of the multi-articulated flat plate was also observed.

![Figure 1. Schematic illustrations of the basic Multi-articulated flat plate.](image)

2. Experimental apparatus and measurement method
In this study, all tested multi-articulated flat plates were composed of three plates of the same rectangular shape. They were made of polystyrene flat plates sandwiching a polyethylene sheet, as shown in figure 2. The gaps between the plates were 1 mm, and the naked polyethylene sheet at the gaps bended smoothly to provided articulations. Since the polyethylene sheet was very thin and flexible, the flexural rigidity and damping resistance of the articulations were neglected in this study. The plates are called the first plate, the second plate, and the third plate in order starting from upstream. The articulations are called the first articulation, the second articulation, and the third articulation. The first articulation
corresponds to the support shaft. The standard shape of the unit plate had stream-wise length $l = 50$ mm, span-wise length $b = 50$ mm, and thickness $h = 1$ mm. The standard shape was decided based on the size of the piezo-generator [14][15]. The plate was made of polystyrene plate, which had a density $\rho_s = 1.056 \times 10^3$ kg/m$^3$. To investigate the effect of the size and material on the fluttering characteristics, different shapes and materials were tested. The tested conditions are shown in table 1.

Figure 2. Making of Multi-articulated flat plate.

Figure 3. Schematic illustration of the experiment apparatus. Multi-articulated flat plate is settled horizontally in the flow.
Figure 4. Shifted pin for acquisition of the displacement in the fluttering of multi-articulated flat plate. Laser displacement sensor acquired $y$-direction displacement of the shifted pin.

Table 1. Material and scale of shape of unit flat plate.

| Material         | Density $\rho_s$ [×10$^3$ kg/m$^3$] | Length $l$ [mm] | Width $b$ [mm] | Thickness $h$ [mm] | Mark |
|------------------|------------------------------------|-----------------|----------------|-------------------|------|
| Polystyrene      | 1.056                              | 30              | 50             | 1                 | ▲    |
|                  |                                    | 40              |                |                   | ▼    |
|                  |                                    | 50              |                |                   | ●    |
|                  |                                    | 60              |                |                   | ■    |
|                  |                                    | 70              |                |                   | ◆    |
|                  | 1.056                              | 30              | 50             | 1                 | △    |
|                  |                                    | 40              |                |                   | ▽    |
|                  |                                    | 50              |                |                   | ●    |
|                  |                                    | 60              |                |                   | □    |
|                  |                                    | 70              |                |                   | ◇    |
|                  |                                    | 50              | 50             | 0.4               | △    |
|                  |                                    | 1.056           | 50             | 0.4               | △    |
| Magnesium        | 1.738                              | 50              | 50             | 1                 | 1    |
| Aluminum         | 2.699                              | 50              | 50             | 1                 | 2    |
| Zinc             | 7.130                              | 50              | 50             | 1                 | 3    |
| Stainless steel  | 7.639                              | 50              | 50             | 1                 | 4    |
| Brass            | 8.250                              | 50              | 50             | 1                 | ●    |
| Copper           | 8.960                              | 50              | 50             | 1                 | ●    |
The arrangement of the wind tunnel experimental apparatus and the coordinate system are shown in figure 3. The wind tunnel was open-jet type with a nozzle of 400 mm $\times$ 600 mm square cross-section. The wind velocity could be varied to 7 m/s. The measuring section had upper and lower walls, while its sides were open. The distance between the walls was 200 mm. A multi-articulated flat plate was fixed on a 3 mm diameter shaft supported with bearings at the walls.

On one end of the support shaft, as shown in figure 4 (a), a small pin of diameter $\phi = 4$ mm attached with a 11 mm shift. The shifted pin will swing with the fluttering frequency of the articulated flat plate. The $y$-displacement of the shifted pin was acquired with a laser displacement sensor, as shown in figure 4 (b). The laser displacement sensor detects the distance of the center position of the object that obstructs the laser sheet from one side of the laser sheet. The displacement was recorded by the time-dependent signal, and the fluttering frequency $f$ was obtained from the power spectrum of that signal.

The fluttering mode in the $x$-$y$ plane was observed from the photographing by digital camera. For the fluttering mode, the amplitude distribution and the trajectory curve were observed. The amplitude distributions were obtained by synthesizing 60 pictures, which were photographed in sequence with 1/60 s intervals. For obtaining the trajectory curves, 4 s exposure photographing was conducted in a darkroom with a black light. The fluorescent paint was painted on the articulations and trailing edge of the multi-articulated flat plate. The trace lines of the shining fluorescent paint were recorded on the photograph as the trajectory curves.

3. Results

3.1. Relation between flow velocity and fluttering frequency

The multi-articulated flat plates fluttered in all cases. Figure 5 shows the fluttering frequency $f$ against the uniform flow velocity $U$ for the standard shape. The frequency was measured in increasing and decreasing uniform flow velocity. From the results, it was found that there is hysteresis in the fluttering motion of the multi-articulated flat plate. This hysteresis was also seen in the fluttering motion of a flag \[6\][7]. Zhang et al. expressed this hysteresis as bistability of the stretched-straight state and the flapping state \[7\]. The critical velocity at which the multi-articulated flat plate began to flutter depended largely on the small disturbances. In the low-turbulence wind tunnel, the disturbance was generated at the trailing edge of the flat plate oscillating due to the vortex street in the wake. There is another hysteresis in the higher velocity region. In higher velocity, the fluttering frequency discontinuously decreased because of the fluttering mode change, which is described in the next chapter.

3.2. Fluttering mode of articulated flat plate

Figures 6 - 8 show the fluttering mode of the standard shape articulated flat plate. In these figures, (a) is the amplitude distribution and (b) is the trajectory curves of the second articulation, the third articulation, and trailing edge of the multi-articulated flat plate. The amplitude increased with increasing uniform flow velocity. In higher velocity, it was seen that the trailing edge turned to the upstream, as shown in figure 7. This motion called whip was also seen in the fluttering motion of a sheet flag \[5\]. When the velocity exceeded some value, the fluttering mode changed. This was seen in the imperfect node on the second plate (the amplitude was not zero at the node). In this fluttering mode, the fluttering frequency increased. In this study, the node-less mode is called Mode I, and the mode with a node is called Mode II hereafter. On the trajectory curves, the second articulation naturally reproduces a circular arc. The third articulation and trailing edge traced a figure-of-eight trajectory. From these photographs, as the articulations and trailing edge traced the same trajectory curve at each cycle, it was found that the multi-articulated flat plate has a very steady fluttering mode.
3.3. Relation between fluttering frequency and plate conditions

The variations of fluttering frequency $f$ against uniform flow velocity $U$ in all conditions are shown in Figures 9 - 12. Because there was the hysteresis described above, the acquisitions were conducted while decreasing uniform flow velocity. In all conditions, the fluttering frequency increases with increasing the uniform flow velocity.

Figure 9 shows the results with different stream-wise length $l$. The frequency at the same velocity decreased with increasing stream-wise length. Except for the condition $l = 30$ mm, Mode II was appeared. The critical velocity at which the mode changed was decreased with increasing the stream-wise length. From the results when using the different span-wise length $b$, as shown in Figure 10, it was found that the fluttering frequencies were almost the same when using the different span-wise length. Hence, the critical velocity at which Mode II appeared was different depending on the span-wise length. The articulated flat plates that had longer span-wise lengths over 60 mm did not show Mode II in the experiment velocity range.

The fluttering frequencies were decreased with increasing the flat plate thickness $h$ as shown in figure 11. The articulated flat plate with thickness $h = 0.4$ mm fluttered at the highest frequency in all conditions. Mode II did not appear when the thickness was over 2.0 mm.

Figure 12 shows the variation of fluttering frequency $f$ with several densities $\rho$. The values of the frequency at the same velocity decreased with increasing density. Mode II did not appear when the density was over $7.6 \times 10^3$ kg/m$^3$.

These results suggest that fluttering frequency $f$ depends on stream-wise length $l$, thickness $h$, and density $\rho$. Interestingly, span-wise length $b$ does not affect the frequency.
Figure 6. Amplitude distribution and trajectory curve of the fluttering mode (Mode I) at the mean flow velocity $U = 2.5$ m/s. It has node-less fluttering mode.

Figure 7. Amplitude distribution and trajectory curve of the fluttering mode (Mode I with whip) at the mean flow velocity $U = 5.0$ m/s. It has node-less fluttering mode and the trailing edge turns to the upstream.

Figure 8. Amplitude distribution and trajectory curve of the fluttering mode (Mode II) at the mean flow velocity $U = 6.0$ m/s. It has imperfect node on the second plate and high fluttering frequency.
Figure 9. Relations between the velocity and frequency on the stream-wise length of the plate.

Figure 10. Relations between the velocity and frequency on the span-wise length of the plate.
Figure 11. Relations between the velocity and frequency on the thickness of the plate.

Figure 12. Relations between the velocity and frequency on the density of flat plate.
4. Dimensional analysis

The Strouhal number $St$, Reynolds number $Re$, and mass ratio $Mr$ were defined as follows.

$$St = \frac{f_l}{u}, \quad Re = \frac{u l}{v}, \quad Mr = \frac{\rho bh}{\rho l} \quad (1)$$

On the study of the flag, non-dimensional bending rigidity was also used. In this study, articulations were very smooth and freely bended. The rigidity of articulations, therefore, were neglected. From the dimensional analysis used by Taneda [5], it was found that the Strouhal number was proportional to $-1/4$ power of the Reynolds number and to $-1/2$ power of the mass ratio, as shown in figure 13 and 14. Furthermore, the values of $St\cdot Re^{1/4}\cdot Mr^{1/2}$ became constant, as shown in Figure 15. In Mode I, the values were about 1.5, and in Mode II, they were about 2.3. The results of the non-dimensional analysis indicate that the fluttering frequency is defined by the flow and the flat plate conditions.

![Figure 13](image1.png)

**Figure 13.** Relations between Reynolds number and Strouhal number on the stream-wise and the span-wise length of the plate.

![Figure 14](image2.png)

**Figure 14.** Relations between the mass ratio and Strouhal number on the thickness and the density of the plate.
5. Conclusions

To develop a wind/water power generator by using flow-induced vibration, a multi-articulated flat plate was proposed, and its fluttering characteristics were investigated by wind tunnel experiments. The articulated flat plate flutters and has a very steady fluttering motion in the uniform flow. When the flow velocity increases or decreases, there is hysteresis in the fluttering motion. The fluttering frequency increases with increasing the uniform flow velocity. The fluttering frequency is higher when the plate is shorter, thinner, and lighter. An articulated flat plate has the node-less fluttering mode and the mode with the node. The non-dimensional number which consisted of the Strouhal number, Reynolds number, and mass ratio became constant.

6. References

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