

CFD of flow characteristics of oscillating multiple flat plates

Nozomi Suzuki ^a, Hiroshi Hasebe ^b

^a MS Student, Nihon University, Chiyoda-ku, Tokyo, Japan, csno25008@g.nihon-u.ac.jp

^b Associate Professor, Nihon University, Chiyoda-ku, Tokyo, Japan, hasebe.hiroshi@nihon-u.ac.jp

SUMMARY

Propeller-type wind turbines generate turbulent wakes that reduce downstream efficiency and prevent close installation. To address this, we proposed a novel power generation system using multiple oscillating flat plates that harvests energy from flutter oscillations, allowing operation within these wakes. However, the aerodynamic mechanisms causing intense multiple-plate oscillations remain unclear. Therefore, we conducted CFD simulations on two tandem flat plates, setting the upstream plate to forced vibration and the downstream plate to free vibration. The results revealed that the downstream plate's behavior varied significantly with wind speed. At 6 m/s, its amplitude correlated with the upstream plate's amplitude. Conversely, at 7 m/s, the downstream amplitude became large and constant. This suggests that the wake structure is a critical factor, requiring further analysis to clarify the phenomenon.

Keywords: CFD, Flutter, Wind power, Multiple flat plates, Piezoelectric element

1. INTRODUCTION

While propeller-type wind turbines are widely used, they generate turbulent wakes that reduce the efficiency of downstream turbines and increase the risk of mechanical failures. Consequently, the need for large spacing between turbines makes them unsuitable for urban areas, despite the availability of consistent wind sources like subway platforms and factory ducts. To harness this untapped urban wind energy, our research group is developing a compact wind power system based on aeroelastic vibrations (Nomura, 2017). Specifically, we focus on flutter oscillation (Matsumoto, 2010), a phenomenon involving substantial energy that we hypothesize can be effectively harvested.

Our preliminary research identified a coupled oscillation phenomenon: placing a flat plate in the wake of a fluttering plate induces flutter in the downstream plate as well. This mechanism enables power generation even within a wake, making it ideal for confined urban spaces. Although we have successfully generated electricity using this system, the oscillation characteristics of multiple flat plates vary significantly depending on several parameters. Flow visualization has shown that differences in wake structures cause these amplitude variations. Furthermore, PIV analysis revealed that large-amplitude plate oscillations create upstream pulsations that further increase the amplitude, whereas a non-oscillating plate significantly reduces upstream flow velocity (Suzuki, 2025). To fully understand these complex interactions and achieve large-amplitude oscillations, the present study utilizes computational fluid dynamics (CFD) to clarify the detailed mechanisms of multiple oscillating flat plates.

Figure 1 shows an overview of our power generation system. A piezoelectric element was used as the power generation device. An oscillating flat plate with square bars touched piezoelectric elements. This contact deformed these elements and generated electricity. With a single flat plate, the maximum power generation was 0.016 W and the averaged power was 0.005 W. With three

flat plates, the maximum was 0.028 W and the average power was 0.008 W. We confirmed that using multiple flat plates increased both the maximum and average power generation.

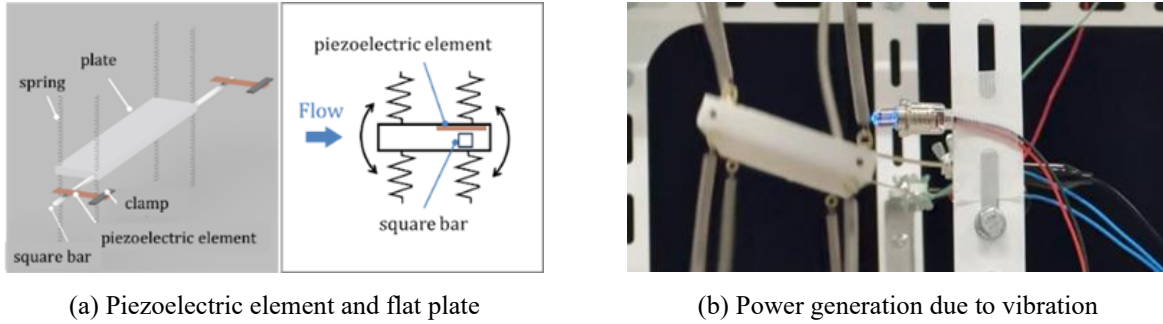
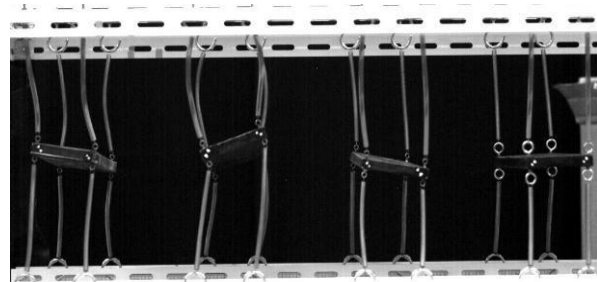
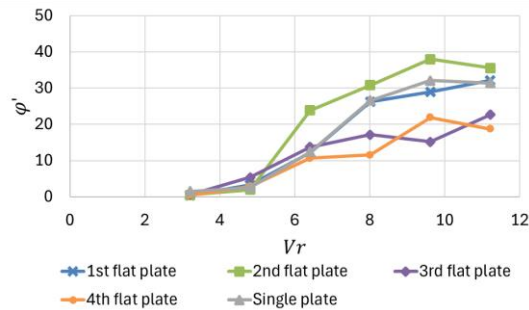


Figure 1: Power generation system using flutter vibration

2. OSCILLATION CHARACTERISTICS OF MULTIPLE FLAT PLATES

Initially, we investigated the oscillation characteristics of multiple flat plates through a wind tunnel experiment. The setup consisted of four flat plates arranged in series, supported by springs at eight points. The oscillation amplitudes were measured across a range of dimensionless wind speeds, $V_r = U/f_\theta Bf$ from 3.2 to 11.2 in increments of 1.6. These values correspond to wind speeds U of 2 to 7 m/s, a natural torsional frequency f_θ of 7.8 Hz, a plate width B of 80 mm, and a plate height D of 10 mm. The center-to-center spacing S was set to $2.5B$, and a spring constant of 0.01 N/mm was applied. The resulting torsional double amplitudes φ' are presented in Figure 2, alongside a photograph of the oscillating behavior. As shown, the first and second flat plates experienced large flutter oscillations. In contrast, the amplitudes of the third and fourth plates were approximately half of those observed in the upstream plates. Consequently, we employed CFD to elucidate the underlying oscillation mechanisms of these multiple plates.



(a) Measured torsional double amplitudes

(b) Photograph of the oscillating behavior

Figure 2: Results of measured torsional double amplitudes

3. CFD ANALYSIS

3.1. Computational Conditions

Using CFD, we investigated the underlying aerodynamic mechanisms responsible for the velocity-dependent oscillation characteristics of the multiple flat plates. To understand why these differences occurred, a detailed analysis of aerodynamic forces and pressure distributions is

required. Therefore, we analyzed the interaction between the plates by setting the upstream plate to forced vibration and the downstream plate to free vibration.

The simulations were performed using the CFD software OpenFOAM (v2406). The geometric parameters of the plates were identical to those used in the wind tunnel experiments. To enable large-amplitude oscillations, we employed the Arbitrary Mesh Interface (AMI) rotating boundary technique. The computational grid comprised 1,630,000 elements, with 100 elements resolving the plate height. The standard Smagorinsky model was adopted as the turbulence model.

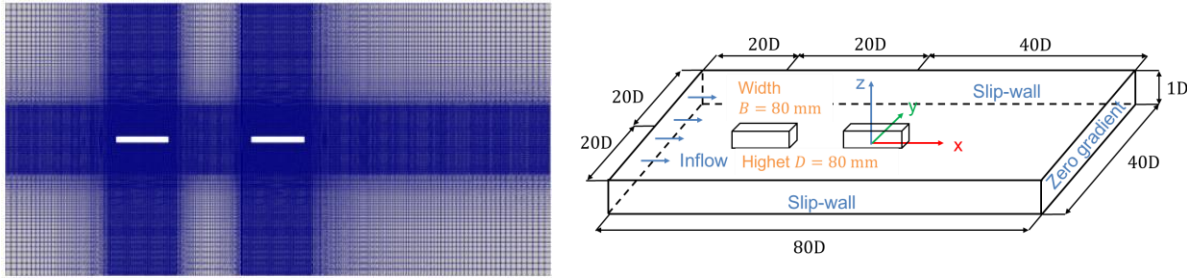
Plate motion was restricted to rotation along the Z-axis in the span direction, and an initial torsional amplitude of 1 degree was applied. We conducted the simulations at wind speeds of 6 m/s and 7 m/s. By varying the forced torsional amplitude of the upstream plate, we examined its effect on the amplitude of the freely vibrating downstream plate. For the 6 m/s wind speed, five forced torsional amplitudes were tested: 10, 20, 40, 60, and 80 degrees. For the 7 m/s wind speed, three cases were tested: 20, 40, and 60 degrees. The computational parameters are summarized in Table 1 and Table 2.

Table 1: Upstream plate parameter (Forced vibration)

Torsional natural frequency	11.7 Hz
D.O. F	1-DOF torsional

Table 2: Downstream plate parameter (Free vibration)

Moment of inertia	$6.8257 \times 10^{-7} \text{ kg/m}^4$
Rigidity	$3.69 \times 10^{-3} \text{ Nm/rad}$
Damping coefficient	$1.96 \times 10^{-6} \text{ Nms/rad}$
Mass	$1.27 \times 10^{-3} \text{ kg}$
D.O. F	1-DOF torsional



(a) Computational mesh

(b) Computational conditions

Figure 3: Computational mesh and conditions

3.2. Computational results

Figure 4 presents the pressure distributions (Pa) and velocity streamlines. Figure 5 shows the relationship between the standard deviation of the torsional amplitude on the free-vibrating downstream plate and the torsional amplitude of the forced-vibrating upstream plate.

At a wind speed of 6 m/s, the amplitude of the downstream plate increased proportionally as the torsional amplitude of the upstream plate increased. Conversely, at 7 m/s, the downstream plate exhibited divergently large amplitudes. Consequently, its oscillation amplitude remained large and showed almost no change regardless of the upstream plate's forced amplitude. These results

indicate that while an increase in the upstream plate's amplitude can amplify the downstream plate's oscillation, this coupled behavior is highly dependent on the state of the wake flow.

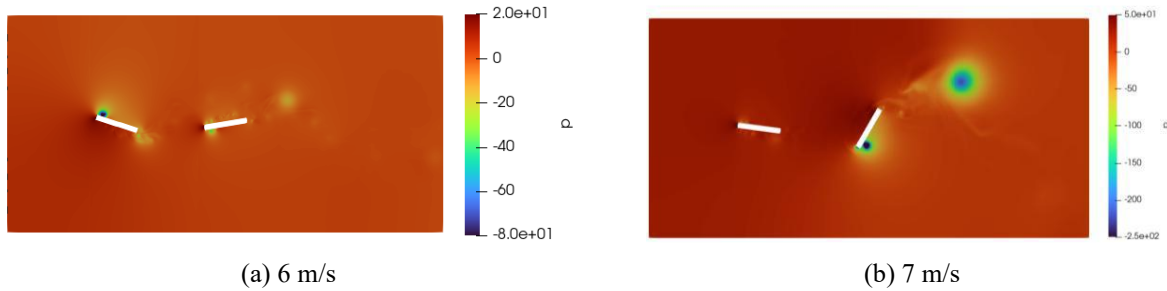


Figure 4: Pressure distribution (Unit:Pa)

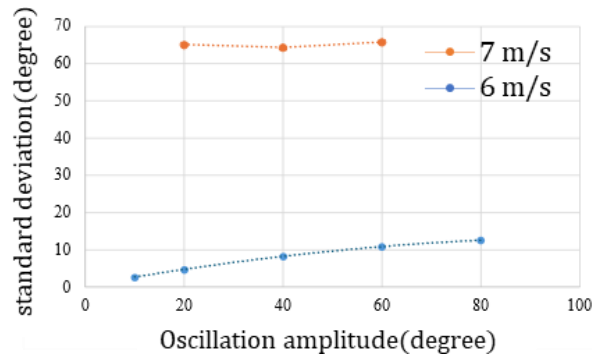


Figure 5: Relationship between standard deviation and oscillation amplitude

4. CONCLUSIONS

This study employed CFD to analyze the interaction between an upstream plate subjected to forced vibration and a downstream plate in free vibration. The findings demonstrated that the oscillation characteristics of the downstream plate are highly dependent on wind speed. Specifically, at a wind speed of 6 m/s, the amplitude of the downstream plate exhibited a clear correlation with the torsional amplitude of the upstream plate. Conversely, at 7 m/s, the downstream plate's amplitude became divergently large and remained relatively constant, regardless of the upstream plate's forced torsional amplitude. Future work will focus on clarifying the underlying factors driving these wind-speed-dependent differences, with a particular emphasis on analyzing the detailed wake structures.

ACKNOWLEDGEMENTS

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