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主　論　文　の　要　旨

論文題目　Large eddy simulations of a piston-driven high-speed synthetic jet
(ピストン駆動式高速シンセティックジェットのラージエディシミュレーション)

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論　文　内　容　の　要　旨

Flow control is crucial in both basic research and industrial application, owing to its potential to enhance performance and efficiency in fluid systems. For industrial applications, one of the typical applications is enhancing aircraft performance by reducing drag and increasing lift. Controlling flow usually uses two strategies, which are passive and active methods. The passive approach is provided with geometry changes, for example, vortex generators (VGs). The effectiveness of active flow control relies on the implementation of actuators, which necessitates extra energy. In the active approach, actuators such as fluidic devices, moving objects, plasma, or electromagnetic mechanisms are frequently employed.

The plasma actuator, which encompasses technologies like dielectric barrier discharge (DBD), offers several benefits due to its uncomplicated structure devoid of moving components and rapid responsiveness. Nonetheless, these DBD plasma actuators produced the induced ionic flow, which is generally sluggish at around 7 to 8 m/s by utilizing the 30 kW of voltage. Another commonly used technique in flow control within the fluidic field involves the utilization of piezoelectric synthetic jet actuators (SJAs) equipped with a membrane vibrating. The method has advantages in heat transfer by using a multi-orifice jet. In aerodynamics, it can delay flow separation on airfoils by reducing the surface boundary layer thickness. However, the piezoelectric synthetic jet also has certain disadvantages affecting jet performance such as the small volumetric displacement or the membrane material.

In active flow control, piston-driven synthetic jet actuators (PSJAs) are one of the methods used to overcome the above problems. The device generates a synthetic jet using an up-and-down of a piston within a cylinder. This motion creates pressure fluctuations, leading to the formation of a synthetic jet. Compared to other methods, it is characterized by its robustness in producing high-velocity jet flow and active control. Therefore, it plays a crucial role in achieving specific aerodynamic effects by manipulating airflow around the airfoil at higher flying speeds. Although high-speed synthetic jets have potential applications for flow control and fundamental studies of turbulence, such flows have hardly been investigated. The pressure measurement inside the actuator and flow visualization have been conducted. However, the flow field formed by the single jet and the interaction of the multiple synthetic jets has not been investigated in detail.

About jets interaction, the interaction of multiple continuous jets results in a complex flow field. An array of holes can be used to generate multiple jets for possible technical applications or further study. For example, four aligned jets are ejected within the boundary layer to reduce drag in film cooling. The jet interaction regions can be divided by converging, merging, and combining regions. The maximum of the mean streamwise velocity is reached at the combined point in the streamwise direction. There are also linear relationships between the nozzle spacing extension and the streamwise location of the combining/merging points. The jet spacing also has a significant influence on the production of vortices.

In this thesis, through the above investigation, the key focus of this research lies in studying the flow field of single/ multiple piston synthetic jet (PSJ). In addition, the pressure histories within the cylinder are analyzed, as it is one of the critical parameters associated with this particular type of synthetic jet.

In Chapter 1, the background of this research, motivation, and research objectives are introduced.

In Chapter 2, a single-orifice synthetic jet is modeled and analyzed. A large-eddy simulation (LES) with OpenFOAM is utilized to analyze the models of the piston synthetic jet actuator (PSJA), which is based on the experimental parameters. LES with the Smagorinsky model is employed. The working fluid is assumed to be an ideal gas. All domains use an orthogonal grid with a non-uniform grid spacing. The non-uniform grid spacing is used in the outflow domain to provide better spatial resolution in the jet. Therefore, the cell size is larger near the lateral and the top boundaries of the outflow domain. Regarding the results of this work, the LES was validated by comparing the time histories of pressure inside the cylinder with previous experiments with a similar model geometry of the PSJA. The pressure inside the cylinder and jet Mach number at the orifice exit hardly fluctuate among different cycles of the piston movement, and the characteristics of the jets are statistically identical for all cycles. The maximum and minimum pressures become larger and lower with increasing the actuation frequency f, respectively. The maximum Mach number is well represented as a function of the maximum pressure, and their relation is consistent with the theoretical estimation. The analysis of the phased-averaged velocity field suggests that the suction and blowing phases do not perfectly match with the downward and upward movements of the piston, respectively. Similarly, the time at which the cylinder pressure reaches the maximum does not coincide with the time of the maximum Mach number. The rms velocity fluctuations U_{rms} are large in the region where the flow is decelerated at the furthest location of the jet. The large U_{rms} in the near field is also related to the strong deceleration of the jet. When the Mach number becomes the maximum value, the turbulence level becomes high at the far-field. The velocity fluctuations are small in the suction phase because of small mean velocity gradients in the jet transverse direction.

In the Chapter 3, LES is conducted for the two-and-four-orifice model based on experimental data. The size of the piston/cylinder is the same as in the single orifice in Chapter 2, while the orifice side length is smaller. The numerical model is also the same as the case of the single orifice. The flow generated by the PSJA with multiple orifices is examined for a wide range of actuation frequencies. Regardless of the number of orifices and the frequency, temporal variations of the pressure inside the actuator and the Mach number at the orifice exit are almost identical for different cycles, confirming that the jets are repeatedly generated under the same conditions. The maximum jet Mach number observed in the blowing phase is related to the maximum pressure inside the actuator, and their relationship for both two- and four-orifice models is well described by the theory for a flow inside a nozzle. The interaction of synthetic jets generated by the two- and four-orifice models is investigated with the statistics conditioned on the phase. Slightly before the end of the blowing phase, the typical three regimes of the interaction reported for continuous jets are observed for the synthetic jets: the converging region, where the jets are inclined toward the other jets; the merging region, where the synthetic jets interact; a combined region with a single jet formed from the multiple synthetic jets. At the beginning of the blowing phase, the rms velocity fluctuations are large near the furthest locations where the jets reach. However, once the interaction of the synthetic jets occurs, large rms velocity fluctuations are observed at the downstream end of the merging region. As the merging region is shifted toward the downstream region with time in the blowing phase, the location where the rms velocity fluctuations attain the maximum also varies with time. We have also examined the PDF of velocity fluctuations. For a fixed frequency, the flow generated by the two-orifice model has stronger intermittency in the blowing phase than that for the four-orifice model. This intermittent behavior results in a skewed distribution of the PDF.

Chapter 4 summarizes the common characteristics of the single and multi-orifice. Additionally, in these simulations, synthetic jets can become supersonic flow in both the blowing and suction phases when frequency f is greater than 100 Hz. The interaction of high-speed synthetic jets is investigated, giving rise to the emergence of converging, merging, and combined regions akin to those observed in continuous jets.

Chapter 5 raises some potential works related to this study. The interaction between a synthetic jet or arrays of jets and an external cross flow over the surface on which they are installed can alter the nearby streamlines and modify the surface shape. This phenomenon holds significant importance in the field of flow control applications. Therefore, prospects can go in this direction.