Synthetic jet actuator using bubbles produced by electric discharge

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Abstract
Over the last decade, synthetic jets suitable for micro-machinery have received attention for their potential to replace continuous jets. The development of synthetic jet actuators with, for example, a diaphragm, a piston, a piezoelectric element, or a speaker cone instead of mechanical drivers, is required for the downsizing and weight reduction of flow control systems in fluid machines. In this study, an experimental prototype for a synthetic jet actuator that uses the nonlinear oscillation of bubbles produced by repetitive electric discharge is proposed. Numerical simulations are performed to clarify the fundamental flow behavior of the synthetic jets produced by bubble motion. The behavior of a bubble induced by a single discharge and the estimated change in nozzle exit velocity with time are shown, and typical flow patterns for synthetic jets produced by periodic electric discharge are discussed. The influence of the ratio of the bubble driving cycle period to the electric discharge cycle period (T∗) on the unsteady flow pattern and the time-averaged jet structure is investigated in detail. In addition, the flow characteristics of a synthetic jet with downtime are compared with those of a normal synthetic jet produced by linear oscillation under the condition that the strokes of both jets are equivalent.

Key words: Synthetic jet, Continuous jet, Unsteady flow, Electric discharge, Non-linear oscillation

1. Introduction

Synthetic jets are an alternative to continuous jets, and are especially suited to micro-machinery. Traditionally, continuous jets are generated by fans, blowers, and pumps that consist of many mechanical parts. In contrast, synthetic jets are lightweight and can be more easily downsized because they comprise relatively simple parts, such as piezoelectric actuators (Amitay, et al., 2001; Holman, et al., 2005; Smith and Glezer, 1998), speaker-driven actuators (Huang, 1996; Nishibe, et al., 2011), pistons (Whitehead and Gursul, 2006), or diaphragms (James, et al., 1996). Synthetic jet actuators using the plasma method have been proposed for boundary layer control for airfoils in recent years (Ogawara, et al., 2003, 2005). However, these actuators are still in the research stage; some aspects are not yet fully understood, including the conditions for jet flow production and the relation between the flow characteristics and the drive system of the actuators. Another important research issue is generating a flow with a large momentum, which is difficult for synthetic jets. Therefore, establishment of synthetic jet generation methods is essential to meet the demands of a wide range of fields in the future.

In the present study, a synthetic jet actuator that uses the non-linear oscillation of bubbles produced by an electric discharge in the liquid as the oscillatory flow generator is proposed in order to clarify the conditions for micro-synthetic jet formation and the subsequent flow characteristics, and to demonstrate the potential for a non-contact energy supply that utilizes the oscillation of bubbles. The advantages of the bubble-driven actuator are as follows: (1) the structure is...
simple, (2) a high actuator density can be achieved, and (3) high jet velocities can be achieved. In this study, an electric discharge is used to induce cavitation bubbles. (4) A variety of bubble generation methods have been proposed by many researchers (Kato, 1999). For example, it is expected that well-established techniques used in thermal (bubble-driven) inkjet printers can be adapted to synthetic micro-jets. The continuous generation of bubbles produced by cyclic suction and ejection is essential to synthetic jets. The continuous generation of bubbles produced by cyclic suction and ejection is essential to synthetic jets. In this work, metal or semiconductor particles are mixed into the liquid to improve the efficiency of the periodic breakdown and an attempt is made to meliorate the bubble generation probability of the actuator by applying a servo-drive mechanism to the electrodes. The temporal behavior of the velocity at the outlet of the slot is calculated from the volume fluctuation of the bubbles, and the behavior of the generated jet flow is observed with a high-speed camera. Since the continuous formation of a new bubble through electric discharge is difficult in a synthetic jet actuator, velocity fluctuations at the outlet of the slot are not sinusoidal, in contrast to conventional synthetic jets using a speaker or piezoelectric device. In addition, the flow velocity at the outlet of the slot during the downtime is approximately zero.

An experimental prototype of a micro-synthetic jet that uses bubbles produced by electric discharge is investigated. Numerical simulations are also performed by modeling the flow velocity at the outlet of the actuator with bubbles produced by electric discharge. An experimental model synthetic jet is also produced using a speaker drive, the waveform of which determines the bubble motion, to clarify the structure of the synthetic jet and ultimately examine the performance of the prototype actuator. The numerical simulation results are compared with the experimental results. Furthermore, the impact of the downtime on the flow structure of the synthetic jet is investigated.

2. Nomenclature

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\begin{align*}
\mathbf{b}_0 & : \text{slot width} \\
\mathbf{f} & : \text{frequency} \\
\mathbf{f}_d & : \text{electric discharge frequency} \\
\mathbf{h} & : \text{slot length} \\
\mathbf{H} & : \text{distance from slot to upper boundary} \\
\mathbf{I} & : \text{current} \\
\mathbf{I}_p & : \text{discharge current} \\
\mathbf{l}_0 & : \text{stroke length} = \mathbf{U}_0 f_d \\
\mathbf{l}_e & : \text{distance from slot to outlet boundary} \\
\mathbf{L}_o & : \text{dimensionless stroke length} = \mathbf{l}_0 / \mathbf{b}_0 \\
\mathbf{Re} & : \text{Reynolds number} = \mathbf{U}_0 \mathbf{b}_0 / \mathbf{v} \\
\mathbf{T}_b & : \text{bubble motion cycle period} \\
\mathbf{T}_d & : \text{electric discharge cycle period} \\
\mathbf{T}_p & : \text{downtime (pause time of the slot exit velocity)} \\
\mathbf{T}^* & : \text{ratio of bubble driving cycle period to electric discharge cycle period} = \mathbf{T}_b / \mathbf{T}_d \\
\mathbf{t} & : \text{time} \\
\mathbf{U}_0 & : \text{representative velocity} = \mathbf{f}_d \mathbf{l}_0 = \frac{1}{\mathbf{T}_d} \int_{0}^{\mathbf{T}_b \mathbf{T}_d} \mathbf{u}_0 (\mathbf{t}) d\mathbf{t} \\
\mathbf{U}_a & : \text{velocity amplitude in normal synthetic jet} \\
\mathbf{U}_{eb} & : \text{oscillation amplitude for the slot exit velocity by bubble motion} \\
\mathbf{U}_{ew} & : \text{oscillation amplitude for the equivalent slot exit velocity} \\
\mathbf{u} & : \text{velocity in the x-direction} \\
\mathbf{v} & : \text{velocity in the y-direction} \\
\mathbf{y}_{asw} & : \text{jet half-width} \\
\mathbf{\nu} & : \text{kinematic viscosity} \\
\mathbf{r}_0 & : \text{dimensionless time based on bubble motion cycle period} = \mathbf{t} / \mathbf{T}_b \\
\mathbf{r}_d & : \text{dimensionless time based on electric discharge cycle period} = \mathbf{t} / \mathbf{T}_d \\
\mathbf{m} & : \text{maximum velocity} \\
\mathbf{0} & : \text{outlet of slot (point)}
\end{align*}
\]
3. Experimental setup

A schematic diagram of the experimental apparatus used for producing bubbles and generating the synthetic jet is shown in Fig. 1. Figure 1(a) is a general view of the micro-synthetic jet generator. Figure 1 (b) and 1(c) are respectively a schematic of the synthetic jet actuator and a magnified view of the slot, which has a width \( b_0 = 0.3 \text{ mm} \). The power supply circuit is composed of an electric discharge circuit for generating the discharge pulse signal and a circuit for charging the capacitor. The discharge cycle of the continuous electric discharge and the pulse width are determined by the output of the function generator that is input to the gate signal of the field effect transistor (FET). Measurement of the voltage between the electrodes is performed using a digital oscilloscope with a bandwidth of 25 MHz and a maximum sampling rate of 100 MS/s. Furthermore, the electric discharge current (10 A, 1 V) is captured by an oscilloscope using a current monitor, which is insulated from the electric discharge circuit. To observe the behavior of the bubbles, images of their shadows are captured using a high-speed camera (Photon FASTCAM-MAX120) with a halogen backlight. In the case of a 100–200 V applied voltage under normal electric discharge conditions, dielectric breakdown occurs when the distance between the electrodes is several to several tens of micrometers. Continuous discharge is achieved by using a feedback control using a servo mechanism in the die-sinking electric discharge machine to shorten the distance between the electrodes. In addition, because the discharge frequency is increased by mixing silicon powder into the working fluid (Mohori, et al., 1991; Takezawa, et al., 2008), the experiment is conducted using an aluminum particle mixture.

A schematic diagram of the experimental apparatus for the speaker-driven actuator is shown in Fig. 2. The operating fluid is air and the synthetic jet is generated by a loudspeaker (Diecook D-15L) driven by a power amplifier with signals from a signal generator. As illustrated in Fig. 2(a) and 2(b), the slot is fabricated with acrylic plates and a two-dimensional jet is induced just downstream of the adjacent slot center. Specification of the slot is the length \( h = 100 \text{ mm} \), and its width is \( b_0 = 5 \text{ mm} \), the slot height aspect ratio is \( h/b_0 = 20 \) and the radius of curvature of the slot inside \( R = 20 \text{ mm} \). The synthetic jet velocity at the outlet of the slot is controlled by the signal generator. The oscillations are not identical for the case of the bubbles and the speaker, because mathematical modeling was used. The measurements of the jet velocities are performed using an I-type hot-wire anemometer (KANOMAX 0251R-25) with a probe support (KANOMAX 0104)

![Figure 1: Experimental apparatus for synthetic jet actuator using bubble produced by electric discharge.](image)

![Figure 2: Experimental apparatus for speaker-driven synthetic jet actuator.](image)
and a traverse device. Since the velocity \( u \) in the main flow direction is significantly greater than the other velocity components, \( u \) is considered to be the absolute velocity. However, measurements of flow velocities using a hot-wire anemometer are vulnerable to large errors in regions prone to local backflow, such as the complicated flow field near the slot.

4. Numerical simulation

The computer simulation code SCRYU/Tetra (Software Cradle Co., Ltd.) is employed for the numerical calculation. The simulation is conducted with a \( k-\varepsilon \) turbulent model using approximately 100,000 grid points. A two-dimensional, symmetric, incompressible viscous flow is employed for simplicity. Therefore, the influence of the shock waves emitted by the bubbles on the jet formation is not elucidated in this study and is thus an area for future investigation. Figure 3 depicts the numerical domain \((H = 320b_0, l_s = 640b_0)\) as well as the boundary conditions. For simplification, a time varying velocity condition is applied to the inlet instead of a moving boundary condition (Tang and Zhong, 2006). A uniform velocity \( v_\infty = -0.01U_0 \) is applied at \( H = 320b_0 \) as the infinite boundary condition to stabilize the calculation and avoid large-scale reverse flow at the outlet of the numerical domain, which is caused by jet entrainment. Constant pressure at the outlet, no slip at the wall surface and slip on the jet-center axis of symmetry were also employed as boundary conditions.

5. Results and discussion

In Fig. 4 and 5, the typical current and applied voltage waveforms for the continuous electric discharge device during the first nine charging cycles for oil with and without aluminum particles are shown. Here, the inter-electrode distance \( G = 50 \mu m \), and the electric discharge frequency \( f_d = 100 \text{ Hz} \), and no feedback control is provided by the servo mechanism. Figure 4 shows the results for the pure metal working oil and Fig. 5 shows those for the oil containing 30 mass% aluminum particles. The spikes in the current waveform corresponds to the occurrence of the sparks that induces the breakdown of the liquid. No electric discharge (no current spikes) can be seen for the pure working oil in Fig. 4. On the other hand, periodic electric discharge can be observed for the oil with 30 mass% aluminum particles in Fig 5. It is clear that the probability of electric discharge occurring is increased by the aluminum particles.

Figure 6 shows the process of bubble growth and collapse in the actuator for the case of a discharge current \( I_e \) of 40 A and discharge pulse width of 50 \( \mu \text{s} \). Panels (a) through (e) show the bubble cycle at dimensionless times based on the bubble motion cycle period \( t_b = T/T_b = 0.0, 0.1, 0.4, 0.8 \) and 1.0, respectively. The volume fluctuation of the bubble in the actuator can be confirmed from these figures. The bubble grows in panels (a) through (c), and collapses in panels (d) and (e). In panel (c), the bubble radius is approximately at its maximum value. Movement of the air bubble towards the lower left can be observed in panel (d). The flow field is asymmetric since the slot is located in the upper right of the actuator (see Fig. 10); hence the movement of the bubble forming the micro-jet in the lower left region, which is on the opposite side to the slot is confirmed by the moving image observation. The motion cycle period of the bubble \( T_b \) is defined from the breakdown time, which is set as \( t = 0 \) in panel (a), to the bubble collapse time in panel (e). In addition, a crescent-shaped shadow is shown near the right side of the lower electrode tip in panels (a) and (e), but the moving image observation confirms that the shadow is not a bubble. It is presumed that aluminum powder agglomerated and became attached to the electrode.
Figures 7 and 8 show the time variation of the bubble radius determined from observed the behavior of the bubbles, and the time variation of the slot exit velocity calculated from the temporal change in the bubble volume, respectively. The discharge pulse width is 50 μs and the discharge current values are \( I_p = 20 \, \text{A} \) (△), 30 A (○), and 40 A (●). Increasing the discharge current \( I_p \) increases the maximum radius as the bubble grows, and extends the bubble’s lifetime. Naturally, the amplitude for the slot exit velocity increases and the cycle of bubble motion \( T_b \) becomes longer as the time variation of the bubble radius increases as in Fig. 7. The slot exit velocity should be \( u > 0 \) (blowing) during the bubble growth and \( u < 0 \) (suction) during the bubble collapse in Fig. 8. The slot exit velocity does not vary smoothly and the time-averaged velocity is not exactly zero. With the present experimental equipment, it is difficult to measure the velocity of the micro-synthetic jet directly. Therefore, the slot exit velocity is estimated using the temporal behavior of the bubble volume.

Figure 4. Typical waveforms of electric discharge into the oil without aluminum particles (\( G = 50 \, \mu m, f_d = 100 \, \text{Hz} \)).

Figure 5. Typical waveforms of electric discharge into the oil with 30 mass% aluminum particles (\( G = 50 \, \mu m, f_d = 100 \, \text{Hz} \)).

Figure 6. Process of bubble growth and collapse in the actuator. (\( I_p = 40 \, \text{A} \), discharge pulse width is 50 μs, single discharge).

Figure 7. Oscillation of bubble radius produced by a single discharge in the actuator.

Figure 8. Time variation of the slot exit velocity calculated from the temporal bubble volume change.
based on the radii obtained from the high-speed photographs. Consequently, the results in Fig. 8 include the uncertainty associated with the measurement error for the bubble radius. In a theoretical analysis such as that using the Rayleigh-Presset equation where ideal behavior is assumed, the slot exit velocity varies smoothly and the time-averaged velocity is zero. It is known that the motion of a cavitation bubble is expressed as a nonlinear oscillation (Kato, 1999). In this paper, the first period (growth and collapse) of bubble oscillation is defined as the first motion and the second period is termed the rebound motion. Since the rebound motion of the bubble is smaller than the first motion, the amplitude of the velocity fluctuation is damped. For simplicity, the effect of the rebound motion on the flow characteristics of the synthetic jet is not considered.

Although the temporal change of the slot exit velocity produced by the oscillation of the bubble is not sinusoidal, the velocity variation can be regarded as sinusoidal to a first-order approximation if the downtime is excluded. In this study, a slot exit velocity model which neglects the rebound of the bubble is employed in the numerical simulation, as shown in Fig. 9. Figure 9(a) indicates that the temporal change in the slot exit velocity $u_0$ generated by the time variation of the bubble volume can be assumed to be sinusoidal. The model takes into account the effect of the cycle of electric discharge $T_d$, the period of the bubble motion $T_s$, and the downtime (pause time) $T_p$. The ratio of the bubble motion cycle period $T_b$ to the electric discharge cycle period $T_d$ is defined as $T^* (= T_b/T_d = (T_d - T_p)/T_d)$, during which the time variation of the slot exit velocity is zero, and corresponds to the slot exit velocity of a normal synthetic jet, represented by a sinusoidal wave for $T^* = 1.0$ (i.e., $T_p = 0$). The representative velocity $U_0$ is defined in accordance with a preceding study (Holman, et al., 2005), when $T^*$ equals unity:

$$U_0 = \frac{1}{T_d} \int_0^{T_d/2} u_0(t) \, dt. \tag{1}$$

In this paper, $U_0$ is defined as follows, when $T^* < 1.0$:

$$U_0 = \frac{1}{T_d} \int_0^{T_b/2} u_0(t) \, dt = f_d \int_0^{T_b/2} u(t) \, dt = f_d b_0 L_0. \tag{2}$$

Figure 9(b) shows the equivalent slot exit velocity change for the synthetic jet with downtime, where the dimensionless stroke length $L_0$ is made equivalent to that for a normal synthetic jet. The following relation is established for the velocity amplitudes:

$$U_{ae} = U_{ab} T^*. \tag{3}$$

where $U_{ae}$ is the oscillation amplitude for the equivalent slot exit velocity and $U_{ab}$ is the oscillation amplitude for the slot exit velocity produced by bubble motion. To demonstrate the impact of $T^*$ on the flow characteristics in this study, the oscillation amplitude of the slot exit velocity produced by bubble motion $U_{ab}$ is made equivalent to the non-dimensional stroke length $L_0$ and the characteristic velocity $U_0$ based on the Reynolds number $Re = U_0 b_0 / \nu$.

![Figure 9. Mathematically modeled velocity change with time at the slot.](image-url)
(a) $t = 0 \mu s$, $\tau_b = 0.00$, $\tau_d = 0.00$

(b) $t = 150 \mu s$, $\tau_b = 0.26$, $\tau_d = 0.05$

(c) $t = 300 \mu s$, $\tau_b = 0.48$, $\tau_d = 0.10$

(d) $t = 500 \mu s$, $\tau_b = 0.80$, $\tau_d = 0.16$

(e) $t = 600 \mu s$, $\tau_b = 0.96$, $\tau_d = 0.19$

(f) $t = 1300 \mu s$, $\tau_b = 2.08$, $\tau_d = 0.42$

(g) $t = 2100 \mu s$, $\tau_b = 3.36$, $\tau_d = 0.67$

(h) $t = 3000 \mu s$, $\tau_b = 4.80$, $\tau_d = 0.96$

Figure 10. High-speed photographs of micro-synthetic jet behavior ($L_0 = 8.11$, $T^* = 0.2$, $Re \approx 232$).
Figure 11. Velocity vectors over the cycle from the numerical simulation \((L_0 = 8.11, T^* = 0.2, Re = 232)\).
Figure 12. Vorticity distribution over the cycle from the numerical simulation ($L_0 = 8.11, T^* = 0.2, Re = 232$).
Figure 10 shows high-speed photographs of the micro-synthetic jet generated with a power-supply voltage of $V = 200 \text{ V}$, a discharge current of $I_p = 40 \text{ A}$, a pulse width of $T_p = 50 \mu\text{s}$, and an electrical discharge cycle period of $T_c = 0.005 \text{ s}$. The tracer is a mix of aluminum particles in order to improve the discharge probability. The dimensionless stroke length $L_0 = 8.11$, the Reynolds number $Re = 232$, and $T^* = 0.2$ are estimated from the oscillation characteristics of the bubbles generated under the same electrical discharge conditions. Four-fifths of the electric discharge cycle is the downtime, during which the slot exit velocity is almost zero. However, the time in which the velocity actually is zero is shorter than this in a strict sense because the bubble rebounds. In Fig. 10, panel (a) $t_s = 0.00$ is the moment of breakdown, where a bubble is generated in the actuator. Panel (e) $t_s = 0.96$ corresponds to the moment just before the bubble collapse. The slot exit velocity is deduced to be nearly zero in panels (f), (g), and (h) from the moving image observation. The aluminum particles can be observed near the slot immediately after ejection from the nozzle in panel (c) and the formation of vortex pairs can be confirmed in the vicinity of the nozzle in panels (d) and (e). Subsequently, the aluminum particles move downstream over time, elucidating the jet formation process. It is noteworthy that a vortex pair forms when the bubble collapses in panel (d) and (e).

Figures 11 and 12 are the numerical calculation results for $L_0 = 8.11$, $Re = 232$ and $T^* = 0.2$ corresponding to the experimental conditions in Fig. 10. These two figures are the time variations of the velocity vector and the vorticity distribution, respectively. Panels (a) through (e) in both figures approximately correspond to the bubble motion cycle and panels (a) to (c) and (c) to (e) are the blowing time and suction time, respectively. Panels (e) through (h) show the inactive actuator ($u_0 = 0$). During the suction time (Fig. 11(c) to (e)), vortex pairs that are generated during the blowing time (Fig. 11(a) to (c)) are seen to move downstream. Because the velocity induced by a neighboring vortex is greater than the slot exit suction velocity, the velocity along the slot center line is in the forward direction for the entire cycle just downstream of the slot exit.

The formation process of the vortex pairs and subsequent behavior can be clearly observed from the vorticity distribution in Fig. 12. The vortex pair formed in the previous cycle is present at $x/b_0 = 8$, in panel (a) $t_s = 0.00$, and a new vortex pair is generated near the slot exit in panel (b) $t_s = 0.25$. Whereas the vortex pair generated in panels (b) through (d) is translated downstream, migration of the vortex pair generated earlier is prolonged. It is seen that the newly formed vortex pair reaches $x/b_0 \approx 6$ in panel (e); this numerical result corresponds to the experimental result (see Fig. 10 panel (e)). Furthermore, it is inferred that the vortex pair formed in the previous cycle ($x/b_0 \approx 13$ in panels (f) through (h)) is viscously damped and the characteristics are mostly lost. Since a vortex pair is always present between $x/b_0 \approx 0$ and $10$ as shown by the above results, it is inferred that the time-averaged velocity at the jet center in this area is large due to the velocity induced by the vortex pair. In addition, since the generation, translation, and extinction of the vortex pair occurs entirely within $x/b_0 \lesssim 10$, the large velocity fluctuation corresponds to the velocity vector diagrams shown in Fig. 11. It can be seen that the generated flow has a relatively steady jet structure from these velocity vectors in the region $x/b_0 \gtrsim 10$, because the large time variation of the vorticity distribution is not apparent.

Figure 13 shows the relation between $x/b_0$ and $\bar{u}_{m}/U_0$. $\bar{u}_{m}$ is the time-averaged velocity along the jet center ($y = 0$). The squares, triangles and circles indicate the results for $T^* = 0.2, 0.6$, and 1.0, respectively. The open symbols ($\circ, \triangle, \triangle$) indicate the numerical data and the filled symbols ($\bullet, △, ●$) indicate the experimental results. In this figure, some
experimental data are not plotted because it was impossible to make measurements near the slot using a hot-wire velocity anemometer due to the change in the flow direction. The time-averaged velocity $\bar{u}_x/U_0$ is zero at the slot exit; however, the numerical results reveal that the mean jet flow from the vicinity of the slot is reached immediately. The numerical results indicated by open symbols are approximately distributed on one curve in the region $x/b_0 \lesssim 3.0$ for all values of $T^*$. On the other hand, the numerically obtained time-averaged velocities at the jet center depend on $T^*$ when $x/b_0 > 3.0$. This tendency becomes remarkable in the downstream region. The experimental and numerical results are in qualitative agreement.

It is a typical peculiarity of the synthetic jet ($T^* = 1.0$) that there are local maximal values of the velocity distribution curve for the jet center under the condition of $L_0 = 25$. The results reveal that the global maximum value of the time-averaged velocity $\bar{u}_x/U_0$ increases with decreasing $T^*$ in the case of identical $L_0$. In addition, the location at which the velocity reaches the global maximum value shifts downstream with decreasing $T^*$. In all cases, the velocities downstream of the maximum point were found to monotonically decrease with increasing $x/b_0$ in this investigation. Comparing the experimental and numerical results quantitatively, the numerical results tend to exceed the experimental results when $x/b_0 \geq 30$. This may be because the experimentally produced jet has three-dimensional velocity components, whereas a two-dimensional flow is assumed in the numerical simulations.

The relation between $x/b_0$ and the dimensionless jet half-width $y_{0.5 \text{med}}/b_0$ is shown in Fig. 14. The numerical and experimental conditions and parameters are the same as those in Fig. 13. However, the experimental results in the upstream region where the flow direction changes due to the passing of vortex pairs, making measurements using a hot-wire velocity anemometer impossible, are omitted in this figure. Therefore, the experimental plots are shown for $x/b_0 \geq 30, 60$ and $70$ for $T^* = 1.0, 0.6$ and $0.2$, respectively. The jet half-width increases approximately linearly in the downstream direction for all values of $T^*$ in both the experimental and numerical results. Hence, the jet half-width is not highly dependent on $T^*$ unlike the profile of the jet center velocity.

Although there is a small change in the jet half-width even when $T^*$ is reduced, the maximum velocity (flow rate) is increased. Therefore, it is implied that the entrainment amount of the synthetic jet increases as $T^*$ decreases. In other words, it is inferred that the momentum of the jet flow generated by the synthetic jet actuator with downtime is larger than that of a normal synthetic jet without downtime, assuming equivalent $L_0$ and $Re$.

Further research is necessary to clarify the effects of $T^*$ on the jet structure including the half-width and momentum. The momentum is related to the fluid force, which is important when considering the practical use of these non-sinusoidal synthetic jets.

6. Conclusion

In this study a micro-synthetic jet actuator that uses the non-linear oscillation of bubbles produced by electric discharge without a mechanical drive unit in liquid as the oscillatory flow generator was proposed. This study helped to clarify the conditions for micro-synthetic jet formation and the subsequent flow characteristics. The following conclusions were obtained:

1. Because it is possible to artificially shorten the distance between the electrodes by incorporating aluminum particles in the working oil, the probability of continuous electric discharge is improved.

2. It was confirmed that a synthetic jet could be produced by the actuator, despite the presence of a pause time.

3. Typical experimental flow patterns were compared with numerical results. In terms of the formation process of the vortex pairs, the experimental results qualitatively agree with the numerical results.

4. The effects of $T^*$ (the ratio of the period of the bubble motion cycle to the electric discharge cycle) on the flow characteristics of the synthetic jet indicate that the growth of the jet width does not highly depend on $T^*$, whereas the jet center velocity does depend on $T^*$.

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