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AFFILIATIONS
1 Department of Mechanical and Aerospace Engineering, Seoul National University, Seoul 08826, South Korea
2 Institute of Advanced Aerospace Technology, Seoul National University, Seoul 08826, South Korea

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I. INTRODUCTION

Flow control techniques improve the aerodynamic performance of aircraft without modifying their geometric structure. The goal of flow control includes drag reduction, lift enhancement, flow separation mitigation, and noise reduction. Practical achievements have been made in the field of low-speed flow. However, high-speed flow control remains a challenging problem, requiring extensive research across this field of study. In particular, plasma actuators are currently being heavily investigated because they offer several advantages over other types of flow control devices. First, a plasma actuator does not intrude into the external flow field because it is either buried under the surface or pasted onto it. This structural feature reduces disturbances in the main flow that might otherwise cause aerodynamic drag, aerodynamic heating, and unfavorable shock waves. Second, a pair of electrodes (or sometimes several pairs) is all that is needed to generate plasma, which can alter the aerodynamic characteristics and is a simple structure with no mechanically moving parts. These characteristics allow such actuators to respond quickly to the operating signal so that it can be actuated with the required timing. Third, and most important, the actuator can potentially disturb supersonic flow because it can generate a higher momentum than conventional flow control devices. It is this incredible potential that makes the plasma synthetic jet actuator such an interesting topic for so many researchers.

A SparkJet actuator is a type of synthetic jet actuator that uses plasma to generate momentum. Unlike other conventional synthetic
A SparkJet actuator consists of an orifice and cavity, with a pair of electrodes placed inside the cavity, as shown in Fig. 1. The figure also shows the operating mechanism of the actuator, which can be divided into three stages. Once a voltage above the breakdown voltage is applied to the electrodes, plasma is generated inside the cavity and transfers thermal energy into the air in the cavity. This is called the energy deposition stage. As energy is deposited, the pressure and temperature inside the cavity increase, which leads to the discharge stage. In the discharge stage, pressure waves and a jet are exhausted through the orifice exit, where they disturb the external flow field by producing momentum that is used for flow control. Given sufficient time, the cavity is reformed as reverse pressure and density cause air to flow into the cavity. This stage is called the refresh stage and makes the actuator a zero-net-mass-flow device. Figure 2 shows schematic diagrams of a SparkJet actuator disturbing the external flow field by exhausting pressure waves and a jet.

The SparkJet actuator was first proposed by the Johns Hopkins University Applied Physics Laboratory (JHU-APL) in 2003. They introduced the concept of the device based on a first-order model that they used to explain and predict its operation. Experimental and numerical demonstrations were also presented to prove their idea. Later, they measured the velocity and temperature of the exhausting jet by using particle image velocimetry and a depth, speed, and temperature transducer. They also developed an analytic model based on equations of state and isentropic relations. The results were compared with pressure measurements inside the cavity and with numerical computations.

ONERA developed a physical model for computation that is more physically "realistic" than the JHU/APL model. They assumed that the arc plasma used in a SparkJet actuator is an equilibrium plasma. Accordingly, they considered the thermal and chemical equilibrium properties of air, solved the resistor, inductor, capacitor (RLC) circuit equation, and found the radiation energy for the calculated plasma source term. Jet positions with respect to time were compared with experimental data to validate the model.

A research team at the University of Texas at Austin conducted an experimental study in a supersonic wind tunnel and showed that a SparkJet actuator can penetrate Mach 3 supersonic flow and can be used in the separation control that occurs upstream of a wedge in the supersonic flow. They also used optical measurements to show that some portion of the energy deposited by plasma excites the nonequilibrium phenomena of flow. This is detrimental to the operational efficiency of the actuator. Kim et al. from Seoul National University investigated the flow near the orifice and characterized the thrust and total impulse generated by the jet produced by a SparkJet actuator.

Recently, significant research on SparkJet actuators was being carried out in China. Air Force Engineering University and a research group from Xi’an Jiaotong University investigated how capacitor energy and geometric parameters affect the performance of SparkJet actuators. Three different jet patterns were found, depending on capacitor energy. The orifice diameter was found to affect the perturbation strength and duration, whereas the orifice throat length affects the frequency of the actuator’s performance but not the strength. The research group in the National University of Defense Technology and the Nanjing University of Aeronautics and Astronautics conducted an investigation on the effect of ambient pressure on a SparkJet actuator. Ambient pressure affected the breakdown voltage and thus the energy deposition amount transferred to air by plasma.

Despite the enormous work carried out by many institutes, the physical aspects of the SparkJet actuator’s jet and its performance are not yet entirely understood. Detailed jet flow characteristics and performance characteristics such as thrust and/or total...
impulse need to be further investigated. Additionally, factors that affect performance and its generation are required to design a SparkJet actuator. Cavity pressure wave behavior is clearly the main factor determining actuator jet performance. However, the detailed flow physics explaining how wave behavior influences the performance of a SparkJet actuator remains unclear. Consequently, in the current study, we investigate a SparkJet actuator in a single operation quantitatively and qualitatively by solving the unsteady three-dimensional Navier–Stokes equation numerically with the assumption of local thermodynamic equilibrium flow. First, the fundamental jet and the performance of a SparkJet actuator are characterized, and the numerical method is validated. The characterization includes analyses of flow structure, thrust, and total impulse. In particular, the frequency characteristics of the actuator are analyzed by applying a fast Fourier transform to the thrust. Second, the pressure wave behavior inside the cavity is investigated in detail to explain the frequency characteristics and how they affect the total impulse performance. Certain pressure waves reflected from the cavity wall generate specific frequency bands due to various configurations of the cavity and electrodes and thereby influence the total impulse of the actuator. The results of this work highlight important factors related to cavity and electrode geometry that influence the total impulse of SparkJet actuators and contribute to improving the configuration design of the cavity of SparkJet actuators to enhance performance.

II. NUMERICAL APPROACH

A. Governing equation

The unsteady three-dimensional Navier–Stokes equation is used as the governing equation. Energy deposition by plasma is added as a source term in the energy balance equation. The conservation form of the Navier–Stokes equation with the source term can be written as

\[
\frac{\partial Q}{\partial t} + \frac{\partial F}{\partial x} + \frac{\partial G}{\partial y} + \frac{\partial H}{\partial z} = \frac{\partial E}{\partial x} + \frac{\partial F}{\partial y} + \frac{\partial G}{\partial z} + S. \tag{1}
\]

Each convective vector and viscous vector can be written as

\[
Q = \begin{bmatrix}
\rho \\
p \\
\rho
\end{bmatrix},
\]

\[
E = \begin{bmatrix}
\rho u \\
\rho u v \\
(\rho c_{i} + p)u
\end{bmatrix},
\]

\[
F = \begin{bmatrix}
\rho v \\
\rho v w \\
(\rho c_{i} + p)v
\end{bmatrix},
\]

\[
G = \begin{bmatrix}
\rho w \\
\rho w v \\
(\rho c_{i} + p)w
\end{bmatrix},
\]

\[
H = \begin{bmatrix}
\frac{\partial E}{\partial x} + \frac{\partial F}{\partial y} + \frac{\partial G}{\partial z}
\end{bmatrix}. \tag{2}
\]

where \( S \) is the net energy deposited by plasma into the flow.

\[
E_{v} = \begin{bmatrix}
0 \\
t_{xx} \\
t_{xy} \\
t_{xz}
\end{bmatrix},
\]

\[
F_{v} = \begin{bmatrix}
0 \\
t_{yx} \\
t_{yy} \\
t_{yz}
\end{bmatrix},
\]

\[
G_{v} = \begin{bmatrix}
0 \\
t_{zx} \\
t_{zy} \\
t_{zz}
\end{bmatrix},
\]

\[
t_{ix} + t_{iy} u + t_{iz} v + t_{iw} w
\]

The vector \( S \) in the source vector is the net energy deposited by plasma into the flow.

B. Physical model

1. Gas dynamic model

A SparkJet actuator uses plasma to generate momentum and the jet and eject the pressure wave. Basically, the plasma is an arc plasma, which is also known as an equilibrium plasma. Plasma results from complex chemical reactions such as ionization, dissociation, and recombination. Thus, a numerical analysis of plasma requires analyzing complicated chemical reactions, and the species involved in those reactions must be taken into account when solving the Navier–Stokes equation in the form of the species conservation equation. However, when it comes to equilibrium plasma, electrons and heavy particles such as ions and neutral particles can be considered as a single species because they are at the same temperature, and the chemical reactions are in an equilibrium state. In this respect, if we are dealing with an air plasma, air and plasma in equilibrium share the same thermodynamic properties and transport coefficients. This type of approach has been taken by other researchers and is referred to as the “real gas” approach. In this study, equilibrium thermodynamic properties and transport coefficients are obtained from the Chemical Equilibrium with Application (CEA) database provided by NASA Reference 1311. The CEA database provides thermodynamic properties and transport coefficients for an equilibrium state by using the minimization-of-free-energy formulation and the essential

\[
\begin{bmatrix}
e_{t} = c_{\text{internal}} + c_{\text{huy}} + c_{\text{kinetic}},
\end{bmatrix}
\]

where \( e_{t} \) is the total energy and can be represented as \( e_{t} \).
coefficients to calculate them. Detailed descriptions of calculating equilibrium states and related subjects are explained in NASA Reference 1311. To reduce computational time, the equilibrium properties are tabulated in advance so that they do not have to be calculated by the minimization-of-free-energy method in every cell and iteration. For temperatures below 150 K, the calorically perfect gas assumption is used because the CEA database is no longer valid. For pressure, the equation of state $p = \rho (\gamma - 1) \varepsilon_{\text{internal}}$ is used, whereas Sutherland’s law is used for viscosity and thermal conductivity. Viscosity and thermal conductivity in equilibrium and calculated by Sutherland’s law are shown in Figs. 3 and 4, respectively.

2. Source term model

The energy deposited by plasma is represented as an energy source term $S_{\text{plasma}}$ in the source term vector $S$ in Eq. (1). In general, it can be expressed as $S_{\text{plasma}} = \eta S_{\text{joule}} = S_{\text{joule}} - S_{\text{rad}}$, where $S_{\text{joule}}$ is the thermal energy generated by the Joule heating process of plasma. The Joule heating energy can be calculated by using $\sigma E^2$, where $\sigma$ is the electrical conductivity of the plasma and $E$ is the electric field intensity. In the present study, the net energy source $S_{\text{plasma}}$ is applied directly as a time-dependent source term rather than considering the complicated process of obtaining the Joule heating energy, radiation energy, and energy transfer efficiency. In this manner, we can intuitively estimate how much energy is needed to obtain the desired performance from a SparkJet actuator. Contributions to the draft design and construction of the plasma-generating circuit are also available. However, for the detailed design of the circuit, considering complicated physical phenomena is necessary. There are three ways to obtain the Joule heating energy. The first is by measuring the voltage and current of the plasma-generating circuit. The second is to use the measured current to compute the energy and solve Gauss’s law. In this way, the electric field intensity is acquired. Electrical conductivity can be obtained from the thermodynamic data. The third method requires solving the RLC circuit equation, from which the electric field intensity is obtained. The Joule heating energy can be calculated in the same way as in the second method. When solving the RLC circuit equation, adequate assumptions and/or measurements are needed for certain elements of the plasma-generating circuit, such as resistance, capacitance, and inductance. The factor $\eta$ is the energy transfer efficiency from plasma to flow and is reported to range from approximately 5%–30%. This efficiency is affected by the energy loss from radiation energy, $S_{\text{rad}}$. Usually, because radiation loss is a function of many variables, it is difficult to be calculated. Thus, in many cases, the use of the energy transfer efficiency $\eta$ with appropriate assumptions is preferred, despite some uncertainties. Many studies have been carried out by other researchers to...
determine $S_{\text{plasma}}$ and $\eta$, with the consideration of proper physical aspects. 25–26

C. Conditions for numerical analysis

1. Numerical method

We simulate a SparkJet actuator operated in quiescent air. Energy deposition causes the temperature and pressure to increase inside the cavity and thus generates a jet and pressure waves. Therefore, the AUSMPW + flux scheme is used for the spatial discretization of the governing equation. 27 This flux scheme controls the advection characteristics of the flow by using a pressure-weighting function, which makes the scheme advantageous for controlling and removing the oscillations near walls and/or shock waves. Analyzing the actuator as applied to supersonic flow is also taken into account when using the AUSMPW + scheme and is planned for future work. The viscous flux is discretized by using the central differencing method. To improve spatial accuracy, the MUSCL scheme with a minmod limiter is used. 28 For time integration, the third-order TVD Runge–Kutta scheme is used. 29

2. Configurations and grid system

Figure 5 shows the SparkJet actuator used in the current study, and Table I lists the values for each design variable. The baseline configuration is selected based on research carried out at ONERA. 10 Essentially, the cavity is cylindrical with a taper angle. The diameter and height of the cavity are 4.6 mm and 4.0 mm, respectively, which equates to a total cavity volume of 66.47 mm$^3$. The diameter of the orifice is 1 mm, and the length of the orifice throat is 4 mm. The cavity and orifice are offset by a taper angle of 45°. Two electrodes 1.0 mm in diameter are placed 1.2 mm apart. The shaded region in Fig. 5 shows the energy deposition region, which is the gap between the electrodes. The length of the energy deposition region is the same as the gap between the electrodes, as indicated in Fig. 5(a). Similarly, the diameter of the energy deposition region, indicated in Fig. 5(b), is 1.0 mm, which is the same as the electrode diameter. The energy source term due to plasma energy deposition is applied in this region. For the baseline configuration, the aspect ratio of this region is close to unity, and its ratio to cavity diameter is also very close to unity. The ratio of electrode diameter to cavity diameter is 0.22, which is similar to the ratio of electrode gap to cavity diameter, which is 0.26.

Six other configurations are analyzed to study the pressure wave behavior inside the cavity and the frequency. For cases A, B, and C, the electrode gap and diameter are varied while maintaining a constant energy deposition volume to verify the effect of the pressure wave propagating radially inside the cavity. For case A, the configuration is selected based on research carried out at ONERA. 10
### TABLE I. Design variables of a SparkJet actuator.

| Design variables                    | Baseline | Case A | Case B | Case C | Case D | Case E | Case F |
|-------------------------------------|----------|--------|--------|--------|--------|--------|--------|
| Orifice exit diameter (mm)          | 1        | 1      | 1      | 1      | 1      | 1      | 1      |
| Orifice throat length (mm)          | 1        | 1      | 1      | 1      | 1      | 1      | 1      |
| Orifice taper angle (°)             | 45       | 45     | 45     | 45     | 0      | 30     | 60     |
| Cavity diameter (mm)                | 4.6      | 4.6    | 4.6    | 4.6    | 4.6    | 4.6    | 4.6    |
| Cavity height (mm)                  | 4.0      | 4.0    | 4.0    | 4.0    | 4.0    | 4.0    | 4.0    |
| Electrode height (mm)               | 2.0      | 2.0    | 2.0    | 2.0    | 2.0    | 2.0    | 2.0    |
| Electrode gap (a) (mm)              | 1.2      | 0.54   | 1.8    | 4.0    | 1.2    | 1.2    | 1.2    |
| Electrode diameter (b) (mm)         | 1.0      | 1.5    | 0.82   | 0.548  | 1.0    | 1.0    | 1.0    |

*a* Marked as (a) in Fig. 5.

*b* Marked as (b) in Fig. 5.

The ratio of electrode diameter to cavity diameter is 0.33, and the ratio of electrode gap to cavity diameter is 0.11. For case B, the ratio of electrode diameter to cavity diameter is 0.18, and the ratio of electrode gap to cavity diameter is 0.39. For case C, the ratio of electrode diameter to cavity diameter is 0.12, and the ratio of electrode gap to cavity diameter is 0.87. In other words, the aspect ratio of the energy deposition geometry for case C is extremely far from unity, compared to other three cases. Compared with the baseline configuration, the aspect ratio of the energy deposition region of cases A and B are far from unity. Figure 5 shows the energy deposition configurations of cases A, B, and C. Cases D–F have different taper angles in order to investigate the consequences of the pressure wave propagating in the vertical direction in the cavity. Although an argument may exist that the total volume, including the cavity and converging section, has changed, a limited opportunity exists in changing the vertical element while maintaining the cavity height because all geometric factors are coupled together. Therefore, modifying the taper angle is the only option to vary the height of the cavity and to change the effective distance in the z direction.

To generate the computational domain, we use the structured grid system, as shown in Fig. 6. Because reflecting the electrodes in a structured grid is quite difficult, they are omitted. The formation and symmetry of the ejected jet is not affected by the presence of electrodes. Laurendeau et al. reported that the jet is almost axisymmetric and presence of the electrodes has no significant effect on the symmetry. Moreover, to reduce the computation time, only a quarter of the entire computational domain is simulated because of the axial symmetry. The total number of cells is on the order of 580,000. About 300,000 of them are present in the cavity, and 280,000 of them are present in the external flow field. Grid points on the wall are clustered by 0.001 mm order in order to capture the boundary layers including the orifice where the jet is being ejected. The external flow field right above the orifice exit is also clustered in the z direction in order to ensure enough number of cells exhausting the jet is properly captured.
3. Initial conditions, boundary conditions, the energy source term, and the operation condition

Since the analyses are carried out in quiescent air, there is no initial flow. The initial conditions are 101 325 Pa for pressure and 300 K for temperature. Accordingly, the initial density is $1.171 \text{ kg/m}^3$. To simulate the operating environment of a SparkJet actuator, the initial conditions are applied on the computational domain of the cavity and external flow field. An adiabatic nonslip boundary condition is applied at the cavity wall and to the bottom of the external domain, and a pressure outlet condition is applied at the outer boundary of the external domain. Finally, symmetric boundary conditions are applied on each symmetry plane.

As mentioned earlier, many ways to calculate the energy source term generated by plasma exist, and they are quite challenging. Essentially, measured data of voltage and/or electric current are needed, or supporting evidence is needed to determine the factors of the electric circuit element. Determining an accurate source term is beyond the scope of the current study. Instead, we use a curve-fitted time-dependent energy source term, as reported by ONERA. The total energy deposited is $3 \text{ mJ}$ in $10 \mu s$. The spatial distribution of the energy source term is uniform in the energy deposition region (see Fig. 5). Energy deposition is shown in Fig. 7. If the energy transfer efficiency is calculated based on the literature, it would be 3.5% with a total of $84 \text{ mJ}$ of Joule heating energy. The energy is deposited over the energy deposition region in the cavity.

In the current study, a single operation of a SparkJet actuator is investigated. Thus, the operational frequency is assumed to be 1 kHz so that individual pulsing does not affect other in plasma generation. There is a report that 5 kHz pulsing frequency is achieved for stable repetitive actuation. Thus, 1 kHz assumption for pulsing frequency is appropriate for independent operation of a SparkJet actuator.

III. RESULTS AND DISCUSSION

A. Characteristics of a SparkJet actuator

1. Characteristics of jet flow

The numerical analyses carried out in the current experiment were based on an in-house code developed in a previous study. The analysis conditions of the baseline case were selected according to the experimental and numerical studies of ONERA as a part of code validation. ONERA compared the time history of the jet-front position, as measured by Schlieren images, and computed the results. The jet front is distinguished by density gradient where the density change is large. The detailed method and processes are described in the cited literature, and the same method is used in the current paper. Figure 8 compares the jet-front positions, which are consistent with the experimental results of the reference (i.e., within the error bars). As a result, it is reasonable to use the in-house code to analyze the SparkJet actuator. Moreover, Fig. 8 shows the jet-front positions calculated by assuming a calorically perfect gas, which has a specific heat ratio, $\gamma$, of 1.4. Although an equilibrium arc plasma is assumed in the SparkJet actuator, nonequilibrium effects should exist in the energy deposition phase. The following physical aspects are checked: the specific heat ratio $\gamma$ for a nonequilibrium gas is somewhere between that of a calorically perfect gas and an equilibrium gas at a certain pressure and temperature. Thus, to analyze any nonequilibrium effects in the SparkJet actuator, we assume a calorically perfect gas, and then, the jet-front positions are compared with the jet-front positions obtained when assuming an equilibrium gas. Until about $40 \mu s$, the result for the calorically perfect gas falls on the upper bound of the error bars in the experimental results from the reference, whereas the equilibrium gas result falls on the lower bound of the error bars. Since a calorically perfect gas can be considered an extreme nonequilibrium gas, the experimental
results that lie between the equilibrium gas result and the calorically perfect gas result can be interpreted to have nonequilibrium effects in the earlier phase of energy transfer from plasma to the surrounding gas. Nevertheless, the entire analysis assumes an equilibrium gas because the accuracy of this assumption is quite acceptable. In addition, its computational cost is less than that when assuming a calorically perfect gas, where the computational time step is very small due to a higher temperature than for the equilibrium gas assumption.

Figure 9 shows the density contour and streamlines of the baseline at \( t = 60 \mu s \) as computed by the in-house code. The contour shows the jet being exhausted and propagating pressure waves. The jet front is indicated by a region of low density and a density gradient with a vortex, which is called the jet-front vortex in the figure. Another vortex forms near the orifice exit, which is called the orifice exit vortex. The orifice exit vortex is generated by the expansion of flow at the orifice exit. A train of vortices develop at the orifice exit and travel upward along the main body of the jet. Three pressure waves expelled intermittently from the orifice exit are distinguishable in the figure. The first one is the ongoing pressure wave farther from the jet front, the second one is going through the jet front, and the third one is at the entry of the orifice throat and is expelled later. The three pressure waves indicate that pressure waves are being exhausted even during jet discharge. These aspects of jet and pressure waves affect the thrust and total impulse of the SparkJet actuator and are addressed in the following sections.

2. Characteristics of thrust and total impulse

The jet and pressure wave of the SparkJet actuator generate the thrust and total impulse. Thrust may be considered a typical performance factor that may be calculated by

\[
T = m_{ori}V_{ori,n} + (p_{ori} - p_{\infty})A_{ori},
\]

where \( m_{ori} \), \( V_{ori,n} \), and \( p_{ori} \) are the mass-flow rate, normal component of velocity, and pressure at the orifice exit, respectively, \( p_{\infty} \) is the ambient pressure, and \( A_{ori} \) is the area of the orifice. With the current cavity geometry, we use \( w \), which is the velocity in the \( z \) direction, instead of \( V_{ori,n} \). The thrust equation implies that thrust results from the combination of jet momentum, which is expressed in the \( m_{ori}V_{ori,n} \) term, and pressure, which is expressed in the \( (p_{ori} - p_{\infty})A_{ori} \) term. The sign of each term is with respect to outflow of the ejected jet. Thus, the mass flow rate \( m_{ori} \) is positive when the flow is going out through the orifice exit and negative when the flow is coming in through the orifice exit. Also, the pressure term becomes positive when the orifice exit pressure becomes greater than the freestream pressure and becomes negative when it is less than the freestream pressure. Based on this equation and the jet and pressure wave trends mentioned in Sec. III A 1, thrust is expected to oscillate in time, even when the jet is being exhausted due to the pressure term. Thus, total impulse is used as an alternative factor for the performance of the actuator and is calculated by integrating the thrust over time,

\[
I_{total} = \int_0^\tau [m_{ori}V_{ori,n} + (p_{ori} - p_{\infty})A_{ori}] \, dt.
\]

The total impulse is expected to increase monotonically and converge at a certain value because the jet and pressure exhaustion are terminated at some point. The following average total impulse is used in order to specify a certain value for impulse:

\[
I_{ave} = \frac{\int_0^\tau I_{total} \, dt}{t_{cycle}}.
\]

Here, \( t_{cycle} \) is a period of a single operation for a SparkJet actuator. In the current study, pulsing frequency of a SparkJet operation is assumed to be 1 kHz, which makes the \( t_{cycle} \) equal to 1 ms. Thrust and total impulse performances are shown in Fig. 10.

Three temporal “regions” are designated based on thrust behavior and are used to explain the performance characteristics. Region I shows the first 71 \( \mu s \) where most of the primary peaks of the thrust occur. Region II shows the range from \( t = 71 \mu s \) to \( t = 213 \mu s \) where the thrust oscillation decreases, and the total impulse stops increasing and levels off. Region III is the combination of region I and region II. Thus, it has the overall characteristics of a SparkJet actuator in operation. Region III is covered in the frequency analysis, along with the full range, region I and region II, which are addressed in Sec. III A 3. Typical time windows for each region differ for each case analyzed, which is addressed in Sec. III B. The time windows for regions for each case are chosen based on the characteristics mentioned for each region.

In region I, both the thrust and total impulse start to increase at approximately \( t = 8 \mu s \). The local minimum of thrust increases up to the end of this period, at which point it starts to decrease. More than half of the total impulse is generated in region I. Specifically, 57% of the total impulse is generated in about one third of the total time of generation. The thrust shows highly oscillating phenomena with some thrust loss and negative thrust while actuating. Oscillating thrust with thrust loss implies that complicated interactions between pressure waves and direction change of velocity are occurring in region I, which are very dynamic. While negative thrust is a very local fraction when the entire jet-generation
phase is considered, it is not a refresh phase since the jet and pressure waves are still being ejected. The loss of thrust and negative thrust can be explained by Fig. 11, which shows an enlarged picture near the orifice. Figure 11(a) shows the pressure contour of the baseline at $t = 26 \mu s$, and Fig. 11(b) shows the z-direction velocity with the streamline of the baseline at $t = 30 \mu s$. As shown in Fig. 11(a), the pressure wave just exhausts through the orifice. Consequently, a pressure drop occurs so that the pressure dropped below the ambient pressure, which is 101 325 Pa. This results in negative thrust. For thrust loss, there are two possible reasons, as shown in Fig. 11(b). First, due to adverse pressure, flow separation occurs in the entire domain of the orifice throat wall. Second, a part of the vortex just above the orifice exit penetrates through the exit, causing the flow direction to oppose the jet direction. Changing the orifice exit design should prevent such a vortex flow from re-entering the orifice.

In region II, the thrust gradually decreases, while a net positive thrust is maintained. This indicates that pressure–wave interactions inside the cavity are fairly diminished and the strength of the pressure wave bursting out of the orifice decreases. From this, we deduce that only the steady-state components of pressure-waves remain inside the cavity, whereas the dynamic components fade away. After this period, only a small perturbation exists for the thrust, which oscillates near zero. Since no net positive thrust is retained, the total impulse stops increasing and converges to a certain value. The average total impulse for the baseline is 2.09 $\mu$Ns.

### 3. Characteristics of frequency components

The frequency components of a SparkJet actuator are analyzed by applying a fast Fourier transform (FFT) to the thrust for the regions mentioned (see Fig. 11). These frequency components, as shown in Fig. 12, likely originate from the pressure wave inside the cavity. Thus, the frequency components in this section are explained in terms of the state of the pressure wave inside the cavity. For the FFT analysis, a Hanning window function is applied since the signal pattern of thrust is unknown before the analysis and in order to reduce leakage of thrust when the FFT is performed. The time interval between the data points of thrust is $5 \times 10^{-10}$. The number of sampling data for each FFT analysis is $2 \times 10^6$. This 2 GHz sampling rate makes the FFT results reliable.

The FFT result for region I, as shown in Fig. 12(a), shows a variety of peaks that are spaced approximately 50 kHz apart starting at around 100 kHz. In particular, the peak near 100 kHz is also shown in the full range, which means that this frequency component is maintained until the end of operation of the SparkJet actuator. However, an exceptional peak near 40 kHz does not appear in region I although it appears in the full range. It seems that the frequency components close to 40 kHz are mixed up in region I; therefore, a single remarkable peak is not distinguishable. This indicates that the thrust and total impulse generation in this stage result from extremely complicated interactions between a number of pressure waves propagating inside the cavity. The frequencies of such pressure waves cover a wide range. Region I is clearly a transient stage of SparkJet actuator operation where dynamic interactions occur between pressure waves. This is also deduced from the thrust behavior discussed in Sec. III A 2. To improve the performance of the SparkJet actuator, these pressure wave interactions should be sustained for as long as possible. The interactions can be inferred from the many peaks and from the positive amplitude of the FFT, which results from cavity pressure being maintained at a higher level. In addition, keeping the pressure evenly distributed throughout the cavity would reduce pressure perturbations and negative thrust, which would improve the performance of the SparkJet actuator. Such improvements include controlling the electrode height and volume. The electrode height may affect the overall average pressure in the cavity by inducing a higher stagnation pressure at the cavity wall. The electrode volume may be able to decrease the pressure perturbations inside the cavity when the electrode volume fills in entirely.

The region II FFT, as shown in Fig. 12(b), has two noticeable peaks, which also appear in the full range FFT. These peaks are at about 45 kHz and 100 kHz. The overall amplitude over the entire frequency range is less than that of the region I FFT. In particular, the higher-frequency components above 600 kHz in region I are almost imperceptible in region II. This result infers that significant fractions of complicated pressure wave interactions are fairly mitigated in region II. Dynamic components such as these are removed naturally by pressure waves and the jet ejecting out of the orifice exit, leaving only steady components. Viscous dissipation may also play a role in weakening the pressure wave strength. By comparison with the full range FFT, the 45 kHz and 100 kHz components are
deduced to be the stable components. The only difference is that the 45 kHz component shifts to 40 kHz. The same conclusion is reached in Sec. III A 2. Region II may thus be labeled the stable stage of SparkJet actuator operation. Being a stable component, it should last until the end of operation of the SparkJet actuator; thus, its generation period is of no concern.

In region III, which is a sum of regions I and II, the two peaks located in region II appear along with several other peaks, as shown in Fig. 12(c). The frequency components at 45 kHz and 100 kHz are clearly related to the operation of the SparkJet actuator. The other peaks in region III are nearly imperceptible when compared to the full range. Consequently, the two obvious peaks at 45 kHz and 100 kHz may be designated as natural frequencies of the SparkJet actuator. Let the higher frequency be the first natural frequency $f_1$ and the lower frequency be the second natural frequency $f_2$. These frequency components likely originate from the pressure wave behavior inside the cavity, as mentioned throughout the section. Related investigations and explanations regarding their causes and effects are detailed in Sec. III B.

B. Pressure–wave behavior inside the cavity and origin of frequency components

1. Reflected pressure wave

Pressure wave ejection and jet discharge result from the complex behavior of pressure waves and their interactions inside the cavity. Correspondingly, thrust fluctuation is also caused by pressure wave interactions inside the cavity. These interactions may thus
contribute to increasing the overall driving pressure of a SparkJet actuator, thus affecting the performance. Consequently, we investigate in detail the behavior of the pressure wave inside the cavity by searching for correlations between causes and effects of natural frequencies since these would be key factors in increasing the performance of the SparkJet actuator.

As plasma deposits energy inside the confined cavity, pressure waves are generated that travel toward the cavity wall and are reflected from it. The reflected pressure waves interact and become another source of pressure increase, resulting in thrust and impulse. Thus, it is important to understand the behavior of the reflected pressure wave inside the cavity. According to the geometry of the cavity, there are conceptually, although not strictly, two possible propagation directions for the reflected pressure wave, as shown in Fig. 13. Figure 13(a) shows the pressure wave reflected from the side wall of the cavity in the $xy$ plane, which is perpendicular to the $z$ axis. The cylindrical geometry of the cavity imparts a circular shape on the reflected pressure wave. The pressure wave propagates in the radial direction and focuses in the center of the cavity. We can call this direction the $r$-axis direction.

Figure 13(b) shows the pressure wave reflected from the side and bottom walls in the $xz$ plane, which is basically the same as the $yz$
FIG. 13. Schematic diagrams showing directions of the reflected pressure wave inside the cavity: (a) the r-axis direction, (b) the z-axis direction.

FIG. 14. Pressure contour of the baseline case at $z = 0.002$. 

$\rho (\text{Pa})$

- 200000
- 180000
- 160000
- 140000
- 120000
- 110000
- 100000

$r$ - axis direction reflected pressure wave

Merged pressure wave

$[\text{m}]$
plane and is parallel to the $z$ axis. Now consider the reflection from the bottom wall. The planar geometry of the cavity bottom causes the pressure wave to reflect upward toward the orifice exit. This direction is called the $z$-axis direction. Some fraction of the pressure wave reflected in the $z$-axis direction exits the cavity through the orifice, while another fraction reflects back toward the cavity bottom after reflecting from the upper wall of the cavity. The upper wall could be flat, as in the case D configuration, but it could also have a taper angle and form a converging section like the baseline configuration. The pressure waves reflected in these two directions happen to interact together and produce additional driving pressure for the SparkJet actuator because they may merge after several reflections. Moreover, the reflection and merging of pressure waves occur continuously.

Those two patterns of conceptual pressure wave propagation and reflection are verified in the pressure contour of the calculated result (see Figs. 14 and 15). Figure 14 shows a cross-sectional view of the pressure contour for the baseline case in the $xy$ plane at $z = 0.002$ m. This plane is at the center of the electrodes where energy is deposited. The pressure wave generated by the energy deposition propagates in concentric circles and impinges on the cavity side wall before reflecting in the $r$-axis direction and merging at the cavity center, thereby increasing the pressure.

Figure 15 shows the pressure contour of the baseline case in the $yz$ plane at $x = 0$. The pressure wave propagates with a circular wavefront and reflects from the (planar) bottom wall, temporarily inducing high pressure at the bottom wall. It then reflects and propagates isotropically, so some fraction of the pressure wave propagates toward the orifice exit along the $z$-axis direction, and another fraction propagates in the $r$-axis direction. On its way to the orifice, it merges at the center of the cavity with the reflected pressure wave propagating in the $r$-axis direction. A fraction of the pressure wave reflected in the $z$-axis direction exits through the orifice while another fraction is reflected by the upper wall and returns to the center of the cavity. The pressure waves reflected by all parts of the cavity merge at the center and increase the pressure. The pressure waves reflected in the $r$-axis and $z$-axis directions are thus confirmed to be the main pressure wave components in the cavity.

2. Pressure wave reflected in the $r$-axis direction

To clarify the causes and effects of the pressure wave reflected in the $r$-axis direction, we compare cases A, B, and C with the baseline case. The four cases deposit the same amount of energy within the same volume and have the same initial conditions. However, their thrust, natural frequencies, total impulse, and average total impulse differ completely, as indicated in Table II and Fig. 16. The maximum thrust decreases from 0.146 N to 0.116 N for case A, which is $-20.54\%$, and from 0.146 N to 0.140 N for case B, which is $-4.43\%$. The maximum thrust of case C decreases from 0.146 N to 0.101 N, which is $-30.90\%$. The average total impulse of case A is almost the same as that of the baseline, that is, 2.09 $\mu$N s. It decreases from 2.09 $\mu$N s to 2.06 $\mu$N s for case B, which is $-1.54\%$, and from 2.09 $\mu$N s to 2.02 $\mu$N s for case C, which is $-3.21\%$.

Figure 17 shows the FFT analyses of the full range and of each region for the four cases compared. In region I, cases A, B, and C have numerous amplitude peaks at various frequencies, as shown in Fig. 17(a), including the first natural frequency $f_1$. The peak near 100 kHz for case C is reduced compared to the other three cases. Additionally, although no noticeable peaks appear near the second natural frequency $f_2$, the overall amplitude is positive at this frequency. This result indicates that cases A, B, and C have complicated pressure–wave interactions like the baseline case. Conversely, there is a discrepancy in amplitude of the 100 kHz band of region II, as shown in Fig. 17(b), which is the component at the first natural
frequency $f_1$. This fact indicates that influences of pressure wave reflections affecting the first natural frequency $f_1$ are different in each case. Pressure wave behaviors related to the first natural frequency $f_1$ occur relatively more for the baseline and case A than case B and case C. However, in region III, case B also has a peak near the 100 kHz band like the baseline and case A, as shown in Fig. 17(c). This is the remainder from region I since region III includes region I. Case C is the only one that have reduced first natural frequency $f_1$ in this region among the four compared cases. In the overall jet generation phase, effects of the first natural frequency $f_1$ is maintained for the baseline, case A and B. When the full range is considered, case C has the first natural frequency $f_1$ of 93.99 kHz. However, its amplitude is reduced by more than 80% compared to the baseline so that the effect of the frequency is reduced greatly. Thus, we conclude for case C that the component at the first natural frequency $f_1$ is present only at the very beginning of the operation of the SparkJet actuator and then decays in a short time (i.e., it is transient). Physically, this means that the pressure wave components at the first natural frequency $f_1$ are not maintained long enough and decay.

The pressure contour and streamline at $z = 0.002$ m in the $xy$ plane explains these differences in the frequency spectra (see Fig. 18). This figure shows where the center of the electrode lies and reveals different flow patterns. Since the only discrepancy between the baseline and other cases is the electrode shape, these different flow structures must originate from the electrode shape. The baseline, case A, and case B continuously generate pressure wave behavior in the $r$-axis direction. For case C, on the other hand, this pressure wave behavior dies out, and changes in the flow direction is made. The three cases produce the first natural frequency $f_1$ and a reflected pressure wave propagating in the $r$-axis direction. However, the amplitude of the first natural frequency $f_1$ of case C is reduced greatly, and the reflected pressure wave in the $r$-axis direction is nearly gone. These results indicate that the pressure wave reflected in the $r$-axis direction is what generates the pressure wave component at the first natural frequency $f_1$. Consequently, the reduced reflected pressure wave propagating in the $r$-axis direction in region II and beyond affects the average total impulse up to about 3.21%.

To maximize the total impulse in this sense, the electrode configuration must be designed such that the pressure wave reflected in the $r$-axis direction is continuously generated. Case B also has a pressure wave reflected in the $r$-axis direction, but it is reduced in region II. One way to achieve this and design the actuator in such a way, based on the current analyses, is to match (to the extent possible) the ratio of electrode gap to cavity diameter with the ratio of electrode diameter to cavity diameter. These ratios simply can be expressed as an aspect ratio of the energy deposition area. To some extent, the aspect ratio less than unity may also possibly generate maximum total impulse (case A). The electrode and cavity configurations of the four compared cases support this conclusion. For the baseline, the ratio of electrode gap to cavity diameter is 0.26, and the ratio of electrode diameter to cavity diameter is 0.22. These make the aspect ratio of the energy deposition area 1.2. In the same way, case A has an aspect ratio of 0.36, case B has 2.20, and case C has 7.30. According to the average total impulse and the aspect ratio, the average total impulse decreases for cases with an aspect ratio much greater than 1.

3. Pressure wave reflected in the $z$-axis direction

The causes and effects of the pressure wave reflected in the $z$-axis direction are verified by comparing cases D–F with the baseline

![FIG. 16. Thrust and total impulse as a function of time for different electrode configurations.](image-url)
FIG. 17. Fast Fourier transform of thrust for different electrode configurations: (a) full range and region I, (b) full range and region II, and (c) full range and region III.

Reduced 1st natural frequency for case C

Reduced 1st natural frequency for case C

Reduced 1st natural frequency for case C

The performance factors for these cases are listed in Table III and shown in Fig. 19. The maximum thrust decreases from 0.146 N to 0.131 N for case D, which is −10.18%, and from 0.146 N to 0.132 N for case F, which is −9.67%. However, it increases from 0.146 N to 0.149 N for case E, which is +1.90%. The discrepancy in maximum thrust is less than that for cases A, B, and C; however, the maximum thrust is not a critical factor because not only does it vary significantly over time due to pressure oscillations but all four cases compared also have the same operating conditions. Thus, the total impulse is compared.

The average total impulse decreases from 2.09 μN s to 1.91 μN s for case D, which is −8.49%, and from 2.09 μN s to 1.97 μN s for case E, which is −5.64%. Case D, which has the smallest taper angle and the shortest effective distance in the z direction, has the smallest average total impulse. The average total impulse increases with the taper angle. Case F has the largest total impulse, taper angle, and effective distance in the z direction. It increases from 2.09 μN s to 2.10 μN s, which is +0.54%. In the vicinity of \( t = 250 \) μs, when the thrust is terminated and oscillates around zero, the total impulse...
FIG. 18. Pressure contours and streamlines for different energy depositions in the $xy$ plane: (a) the baseline case, (b) case A, (c) case B, and (d) case C.
TABLE III. Comparison of performance for the pressure wave reflected in the $z$-axis direction.

| Case | $T_{\text{max}}$ (N) | $\Delta T_{\text{max}}$ (%) | $I_{\text{ave}}$ (μN s) | $\Delta I_{\text{ave}}$ (%) | $f_1$ (kHz) | $\Delta f_1$ (%) | $f_2$ (kHz) | $\Delta f_2$ (%) |
|------|----------------------|-----------------------------|------------------------|-----------------------------|-------------|-----------------|-------------|----------------|
| Baseline | 0.146 | . . . | 2.09 | . . . | 96.99 | . . . | 40.99 | . . . |
| D | 0.131 | −10.18 | 1.91 | −8.49 | 93.99 | −7.32 | 49.99 | +21.95 |
| E | 0.149 | 1.90 | 1.97 | −5.64 | 95.99 | −2.44 | 41.99 | +2.44 |
| F | 0.132 | −9.67 | 2.10 | +0.54 | 98.99 | +4.88 | 34.99 | −14.63 |

of case F is a little smaller than that of the baseline case, as shown in Fig. 19. However, it eventually increases gradually and becomes a bit larger than the total impulse of the baseline case because the amplitude of the thrust oscillating around zero is larger for case F. This situation is rarely seen in the other cases. As the taper angle increases, the amplitude of oscillating residual thrust gets greater, resulting in a slight increase in total impulse, even after thrust termination. This may be deduced from the slightly greater oscillating amplitude for cases with a taper angle after 250 μs (see Fig. 19 which is enlarged). This result indicates that the difference in total impulse between the baseline case and case F is not significant when only the jet generation phase is considered. Instead, the taper angle of 45° used in the baseline case suffices in the view of the total impulse.

Figure 20 shows why zero taper angle (or a small taper angle) reduces the total impulse. Figure 20(a) shows the flow structure near the taper angle for the baseline case. Due to the taper angle, flow is smoothly directed toward the orifice along the upper cavity wall. Also, flow does not expand significantly between the orifice throat and upper wall of the cavity, so the area of the flow path is maintained. Case F, which has a taper angle of 60°, produces results similar to those of the baseline case. However, case D produces different results because it has a taper angle of zero, as shown in Figs. 20(b) and 20(c). In Fig. 20(b), a fraction of the flow heading upward is blocked by the upper wall of the cavity, forming a stagnation point. Thus, the flow direction is changed by the upper wall of the cavity, as shown in Fig. 20(c). Moreover, the flow expands, and flow separation is occurred because of the right angle at the orifice throat, so the flow path is narrowed, as shown in Fig. 20(c). The narrowed flow path results in decreased orifice throat area, which causes a reduction in the mass flow rate. These phenomena might not have happened if there was an appropriate taper angle. These factors explain why the

FIG. 19. Thrust and total impulse as a function of time for different taper angles.
FIG. 20. Effect of the taper angle on flow structure: (a) smooth flow in the baseline case, (b) the stagnation point in case D, and (c) flow expansion and change in direction in case D.
total impulse is reduced in a cavity with zero taper angle (or with a small taper angle).

The second natural frequency also depends on the taper angle. Figure 21 compares the FFT of cases D–F with that of the baseline case. The first natural frequencies $f_1$ for the four cases are similar: close to 96 kHz, with a difference of about 7% at its maximum. The amplitudes peak near the first natural frequency for all three regions with no remarkable differences except for their specific magnitude, as shown in Figs. 21(a)–21(c). This means that all show complicated interactions in region I and decay in region II, just like the cases discussed in the previous sections. However, significant differences appear at the second natural frequency $f_2$. When compared with the baseline case, the second natural frequency $f_2$ increases by 21.95% for case D and 2.44% for case E, whereas it decreases by 14.63% for case F. Amplitude peaks near the second natural frequency in regions II and III differ from each other, as shown in Figs. 21(b) and 21(c). In particular, the amplitude peaks near the second natural frequency are shifted as the taper angle decreases, as marked in Fig. 21(a). This phenomenon is related to the distance propagated by the pressure wave in the $z$-axis direction. This distance, which is the effective $z$ distance for pressure waves to propagate from the cavity bottom to the upper wall of

![Figure 21. FFT of thrust for different taper angles: (a) full range and region I, (b) full range and region II, and (c) full range and region III.](image-url)
the cavity, depends on the taper angle. A smaller taper angle allows the pressure wave to travel a shorter distance in the $z$-axis direction. The similar first natural frequencies $f_1$ and different second natural frequencies $f_2$ mean that these two frequency components are independent from each other. Thus, the pressure wave reflected in the $r$-axis direction and the $z$-axis direction can be dealt with independently.

Because the same amount of energy is deposited at the same ambient pressure, the speed of the pressure wave inside the cavity must be similar for the four cases (cases D–F and the baseline case). Thus, the pressure wave has a shorter distance to travel at the same propagation speed. Unfortunately, the speed of the pressure wave cannot easily be specified because of the very complicated flow inside the cavity. However, we do know that the travel time decreases, which means that the frequency related to the $z$-axis direction increases. Also, because the second natural frequency increases as the taper angle decreases, we can conclude that the second natural frequency $f_2$ depends on the pressure wave reflected in the $z$-axis direction.

However, unlike the first natural frequency and the pressure wave reflected in the $r$-axis direction, the second natural frequency and the pressure wave reflected in the $z$-axis direction have no direct correlation with the total impulse. Although the total impulse increases as the taper angle increases, a larger taper angle does not always lead to better total impulse performance. The maximum taper angle is 90°, at which point the orifice becomes straight like a shock tube, and the cavity becomes indistinguishable from the orifice. Because this geometry is not confining, the pressure wave formed by the initial energy exits and no jet develops, which means that a geometry with a 90° taper angle would not act as a SparkJet actuator. For this reason, the cavity should retain a confining geometry with an appropriate taper angle in order to generate a jet and maximize the total impulse. Based on the present study, a taper angle of 45° is a good configuration. Finally, note that a confining cavity always generates a pressure wave component at the second natural frequency and a pressure wave reflected in the $z$-axis direction.

### C. Effects of the reflected pressure wave

Unlike from a general steady jet, the thrust of a SparkJet actuator has very strong oscillations due to pressure waves generated inside the cavity. These oscillations must be considered when predicting and/or estimating the total impulse of the actuator. In this section, quantitative effects of the oscillations on the total impulse of a SparkJet actuator are analyzed by smoothing the thrust of the baseline.

From the investigations in the earlier sections, the baseline case has two natural frequencies: 96.99 kHz and 40.99 kHz. Results of smoothing of the thrust by using these two frequencies as cutoff frequencies are shown in Table IV and Fig. 22. Smoothing by the first natural frequency $f_1$ as a cutoff frequency is smoothing $A$, and smoothing by the second natural frequency $f_2$ as a cutoff frequency is smoothing $B$. For smoothing $A$, the effect of the first natural frequency $f_1$ is eliminated, and the second natural frequency $f_2$ is remained, whereas, the effects of overall natural frequencies are eliminated, and only a convective flow effect is remained for smoothing $B$. The maximum thrust decreases from 0.146 N to 0.025 N for smoothing $A$, which is −83.11%, and from 0.146 N to 0.020 N for smoothing $B$, which is −86.35%. Without oscillations, thrust decreases greatly. The average total impulse decreases from 2.09 μN s to 1.84 μN s for smoothing $A$, which is −11.65%, and from 2.09 μN s to 1.77 μN s for smoothing $B$, which is −15.35%. From the result of smoothing $A$, the pressure wave reflected in the $r$-axis direction affects approximately 11% of the total impulse. Also, overall oscillations influence approximately 15% of the total impulse based on the result of smoothing $B$. These remain among approximately 4% of the total impulse to the pressure wave reflected in the $z$-axis direction. As a result of smoothing analyses, at least 15% of errors will occur in SparkJet actuator performance if predicting it without considering the oscillations. Thus, it is essential to take the oscillations into account.

### TABLE IV. Comparison of performance for pressure wave reflected in the z-axis direction.

| Case     | $T_{\text{max}}$ (N) | $\Delta T_{\text{max}}$ (%) | $I_{\text{ave}}$ (μN s) | $\Delta I_{\text{ave}}$ (%) |
|----------|----------------------|-----------------------------|-------------------------|-----------------------------|
| Baseline | 0.146                | . . .                        | 2.09                    | . . .                        |
| Smoothing A | 0.025                | −83.11                      | 1.84                    | −11.65                      |
| Smoothing B | 0.020                | −86.35                      | 1.77                    | −15.35                      |
IV. CONCLUSION

This study characterizes the jet and performance of a SparkJet actuator. Furthermore, the cavity flow physics is closely investigated and correlated with the total impulse and frequency characteristics of the SparkJet actuator. To this end, a SparkJet actuator in quiescent air is numerically modeled by using an in-house solver that applies the equilibrium gas assumption. This solver is validated by comparing the position of the jet front with respect to time from the simulation with experimental data from the literature. We then use a fast Fourier transform to investigate the frequency characteristics of the SparkJet actuator and pressure wave behavior inside the cavity. Also, the quantitative effects of frequencies on total impulse performances are analyzed. To study in detail the causes and effects of natural frequencies, actuators with four different electrode configurations and four different taper angles are compared. The results lead to the following conclusions:

1. The simulation results for the jet front position with respect to time from the in-house equilibrium gas solver are consistent with the experimental data from the literature. Comparing the results from the calorically perfect gas solver implies that a nonequilibrium effect exists in the earlier phase of energy deposition. However, considering the overall accuracy and computational time, the equilibrium analysis suffices. Even during jet ejection, the pressure wave from the cavity is continuously exhausted. Thus, thrust oscillates significantly over time. Loss of thrust occurs because of flow separation at the orifice throat and temporary inflow at the orifice exit due to a vortex.

2. A fast Fourier transform in region I of the thrust confirms that approximately 57% of the total impulse is generated in the first 71 μs of thrust and that the thrust lasts until about 200 μs. A variety of frequency components indicates that complicated interactions occur in this region between pressure waves inside the cavity, so it is a transient stage. Thus, it is important to maintain pressure–wave interactions, which result in a higher cavity pressure, thereby producing better thrust and total impulse performance. In region II, the overall amplitude of all frequency components decay to zero, implying a stable stage. Two primary frequency components appear in region III and in the full range, which are the two natural frequencies of the SparkJet actuator and which originate from the pressure behavior inside the cavity.

3. The pressure wave reflected in the r-axis direction inside the cavity creates a pressure–wave component at the first natural frequency $f_1$. It is confirmed by changes in the first natural frequency $f_1$ and the pressure wave reflected in the r-axis direction according to electrode geometry. The total impulse increases as the generation of pressure wave reflected in the r-axis direction is promoted. According to the shape of the electrode, a total impulse performance difference of 3.21% was confirmed. To maximize the total impulse of a SparkJet actuator influenced by the reflected pressure wave in the r-axis direction, the aspect ratio must be close to one or a little bit less, which is formed by the electrode gap, electrode diameter, and cavity diameter.

4. The pressure wave reflected in the z-axis direction produces a pressure wave component at the second natural frequency $f_2$, which is independent from the first natural frequency $f_1$ produced by the pressure wave reflected in the r-axis direction. It is confirmed by the changes in the second natural frequency $f_2$ and the effective distance in the z direction which is varied by the taper angle. These factors are not directly related to the total impulse. However, the total impulse differs by up to 8% due to the changes is the flow structure by the taper angle. The present study indicates that a taper angle of 45° is appropriate for no reduction in the total impulse.

5. The effects of oscillations generated by pressure–wave behavior inside the cavity on SparkJet actuator performance is investigated by smoothing the thrust of the baseline case. Oscillation accounts for approximately 15% of the total impulse. The pressure wave reflected in the r-axis direction effects 11%, and the pressure wave reflected in the z-axis direction influences approximately 4%.

The results of this study contribute in two ways for SparkJet actuators. First, they contribute to improving the design of electrode and cavity configurations. In particular, this study proposes important design variables related to the electrode shape and cavity geometry that should be considered for the enhancement of the performance of SparkJet actuators. These parameters are the ratio of electrode diameter to cavity diameter, the ratio of electrode gap to cavity diameter, and the taper angle. Second, the oscillations must be considered in predicting the SparkJet actuator performance. Even in the simplified model of a SparkJet actuator, it is important and essential to consider oscillations not to underestimate the performance.

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