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PASSIVE SUPPRESSION OF CAVITY-INDUCED PRESSURE OSCILLATION IN AN AXISYMMETRIC SUPERSONIC FLOW

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ABSTRACT

This Cavity-induced pressure oscillations have been investigated numerically for a two-dimensional supersonic flow at Mach number 1.83 at the entrance of a straight channel connected to an axi-symmetric nozzle. The control is achieved using a passive suppression method that includes a cavity partially covered by a solid surface positioned at wall of the straight channel for supersonic flow. The results showed a good reduction of amplitudes of oscillations at the region of main flow and also at the inside position of the cavity in case of flow with control.

Keywords: Compressible Flow, Supersonic Cavity Flow, Shock Wave, Axisymmetric Nozzle, Passive Control, Numerical Simulation.

1. INTRODUCTION

It is well known that the supersonic air-intake flow tends to be unstable due to the separations induced by the shock wave /boundary layer or the shock wave/shear layer interactions [1-2]. The flow unsteadiness associated with boundary layer separation occurs in a variety of internal flows such as in the inlets of air-breathing engines, in Scramjet engines, in supersonic diffusers [3], and also in high pressure power plants [3]. The flow unsteadiness can also occur in case of transonic flows with periodic self-excited oscillations and in case of cavities with self-excited oscillations. The oscillations should be suppressed in order to avoid many undesirable phenomena associated with oscillations such as noise and vibration. Some passive control devices have been reported to control the flow unsteadiness associated with shock/boundary layer separations [4-5]. McCormick [4] studied shock/boundary layer interaction control with low-profile vortex generators and passive cavity. He observed that the passive cavity could substantially reduce the total pressure loss through the shock system by causing a more isentropic compression. Asbury et al. [5] studied passive cavity concept for improving the off-design performance of fixed-geometry exhaust nozzles. They concluded that passive cavity ventilation added the ability to control off-design separation in the nozzle. Pandey et al. [6] studied annular cavities to control base flow for supersonic flow through axi-symmetric nozzle expanded suddenly into circular duct of larger cross-sectional area. They reported that the cavity aspect ratio influenced the base pressure significantly for low area ratio of the flow passage. Wilcox Jr. [7] studied experimentally the effectiveness of passive venting system for modifying cavity flowfields at supersonic speeds by using a porous floor with a vent chamber underneath the floor. He showed that a passive venting system could be used to control supersonic cavity flow fields. He obtained a large drag decrease for cavity with length to depth ratio greater than 12. For a cavity with length to depth ratio equal to 17.5 and inlet Mach number M_{inlet} = 2.86, he obtained a steady reduction of drag with the increase of floor area and porosity percentage. Rathakrishnan et al. [8] investigated the effects of cavities on suddenly expanded subsonic flow field. They showed experimentally that the flow field as well as the base pressure depended on the cavity length to depth ratio. Tanner [9] conducted an experimental investigation with a base cavity at angles of incidence. He showed that a base cavity could increase the base pressure and thus decrease the base drug in axi-symmetric flow.

In the present computational study, a passive control method has been investigated for a supersonic flow at Mach number 1.83 at the entrance of a straight channel connected to an axi-symmetric nozzle. A good suppression of oscillations was obtained by the proposed control devices.

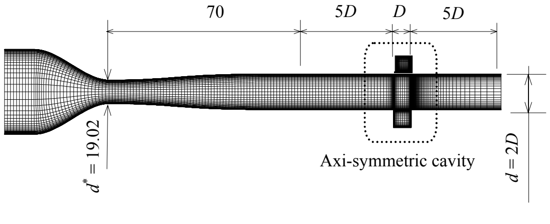
2. CFD ANALYSIS

The governing equations are two-dimensional unsteady compressible Navier-Stokes equations coupled with turbulence kinetic energy and eddy viscosity equations. The turbulence model used in this simulation is a modifed *k-R* (turbulent kinetic energy-eddy viscosity) model adopted from Goldberg [10-11] and Heiler [12], which is a pointwise turbulence model applicable to both wall bounded and free shear flows. This model is also applicable to both structured and unstructured grids involving complex geometries. A third-order TVD (Total Variation Diminishing) finite difference scheme with MUSCL [13] was used to discretize the spatial derivatives and a second order-central difference scheme for the viscous terms, and a second-order fractional step is employed for time integration.

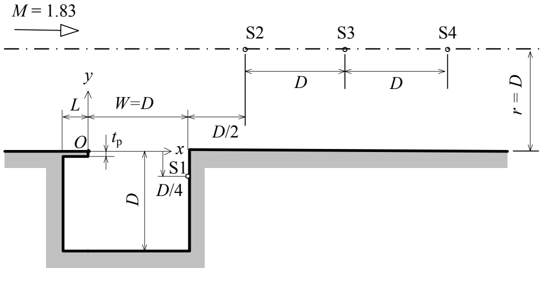
Figure 1 shows computational grids of a supersonic flow field with a cavity. The diameter of the main flow section at the entrance of the cavity d is 24 mm. The cavity depth D (=12 mm) and its length W are the same. S1, S2, S3 and S4 in this figure denote the measuring positions of static pressure. A solid surface of length L = 3 mm and thickness t = 0.6 mm which is most effective in reducing the oscillations [14] is attached at the leading edge of the cavity as shown in Fig.1(b).

The origin in x-y coordinate is located at the cavity leading edge. S1, S2, S3 and S4 in this figure denote the measuring positions of static pressure. Dry air is used as a working gas and assumed to be thermally and calorically perfect. Pressure p_0 in the reservoir is 101.3 kPa. The inlet Mach number M at the entrance of the straight channel is 1.83. On the solid walls, the no-slip conditions and no heat transfers were applied as the boundary conditions. Fixed conditions were set for the inflow boundary condition. Zero order extrapolation was used at the outflow boundary.

In order to validate the computational code developed for the present numerical simulation, a two-dimensional open square cavity of length to depth ratio W/D= 1.0 at Mach number M =1.83 at the cavity entrance was investigated in case without control and the solutions were compared with the existing results of previous researchers [15-18]. The comparison showed satisfactory results.



(a) Computational grids (Unit: mm)



(b) Details of axi-symmetric cavity configuration

Fig 1: Computational domain

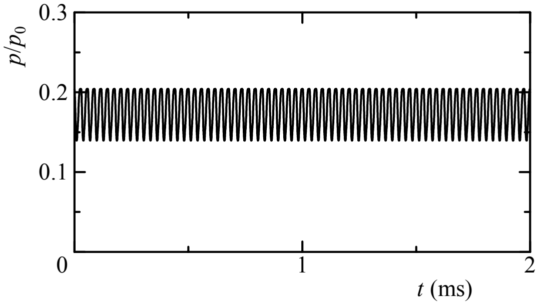
3. RESULTS AND DISCUSSION

3.1 Flowfield Oscillations without Control

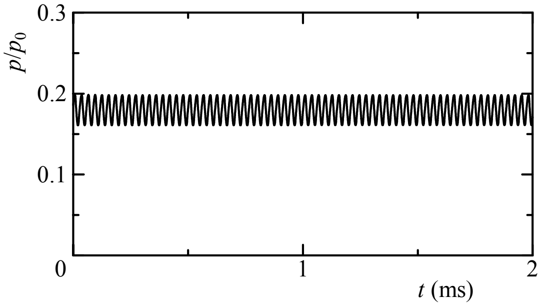
Figure 2 shows time history of static pressure at positions S2, S3 and S4 along the centerline of main flow without control. It shows that amplitudes of oscillations are significant in case of flow without control. However, the oscillations are larger at the position S2 (Fig.2(a)) than that of at S3 (Fig.2(b)) and S4(Fig.2(c)).

Figure 3 shows power spectrum density in case without control at each position. There are strong dominant peak frequencies in the flowfield without control.

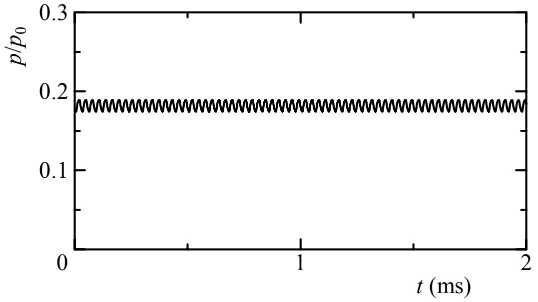
Figure 4 also shows time history of static pressure and power spectrum density at S1 in the cavity without control. There exist large amplitudes of oscillations at the position S1 without control in case of flow through asymmetric nozzle as shown in Fig.4(a). Distributions of PSD (power spectrum density) at the same position obtained from the static pressure histories are shown in Fig.4(b). There is a dominant frequency at 36.5 kHz in case of flow without control.



(a) S2

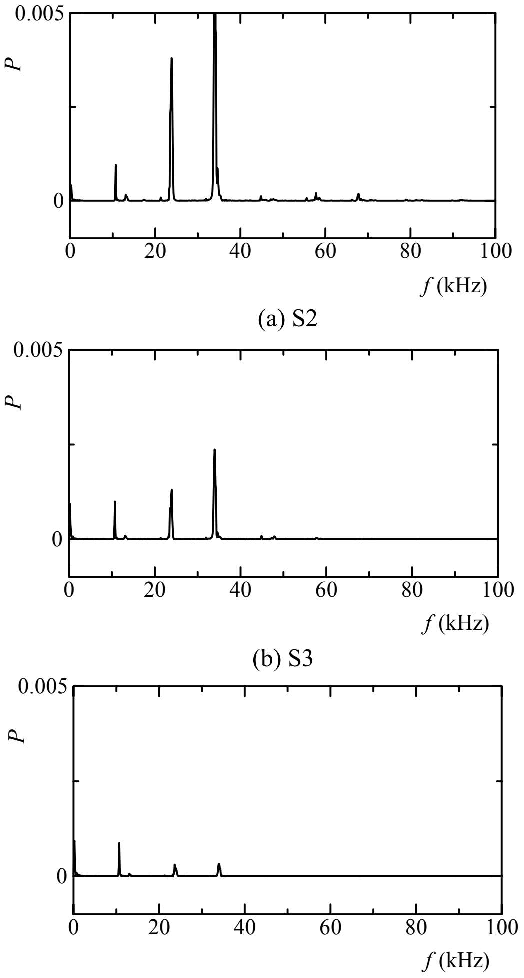


(b) S3



(c) S4

Fig 2: Time histories of static pressure(without control)

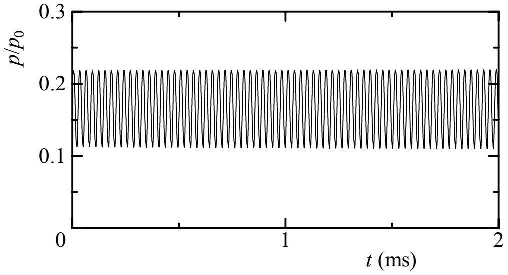


(a) S2

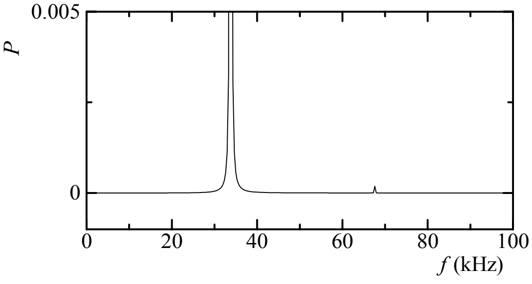
(b) S3

(c) S4

Fig.3: Power spectrum densities (without control)



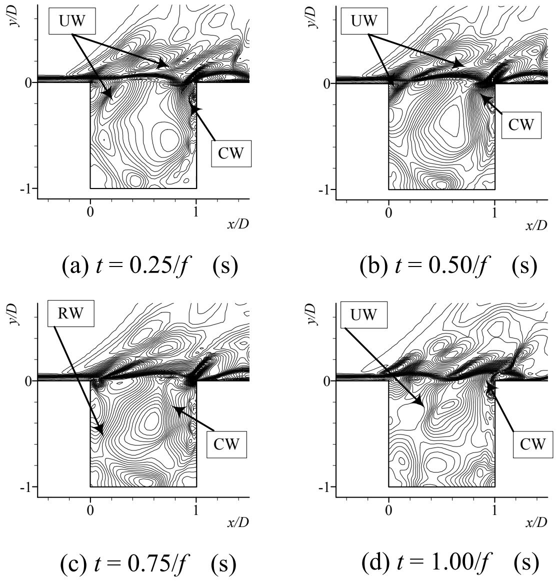
(a) Time history of static pressure



(b) Power spectrum density

Fig 4: Time history of static pressure and power spectrum density at S1 (without control)

Figure 5 shows contour maps of density during one period of flowfield oscillation in case without control. It shows sequences of events that form a typical feedback loop within the cavity. Here, *f* represents the dominant frequency, which is equal to 36.5 kHz (see Fig.4(b)). It is observed that a compression wave (CW) from the trailing edge moves upstream as time proceeds (Fig.5(a)). The upstream compression wave (UW) impinges on the leading edge (Fig.5(b)) and the reflection occurs (Fig.5(c)). The reflected wave (RW) disturbs the shear layer near the leading edge. This disturbance regenerates instability waves in the shear layer. While the shear layer reattaches at the rear wall, the compression wave (CW) is generated due to the impingement of instability waves on the wall as shown in Fig.5(d). The compression wave



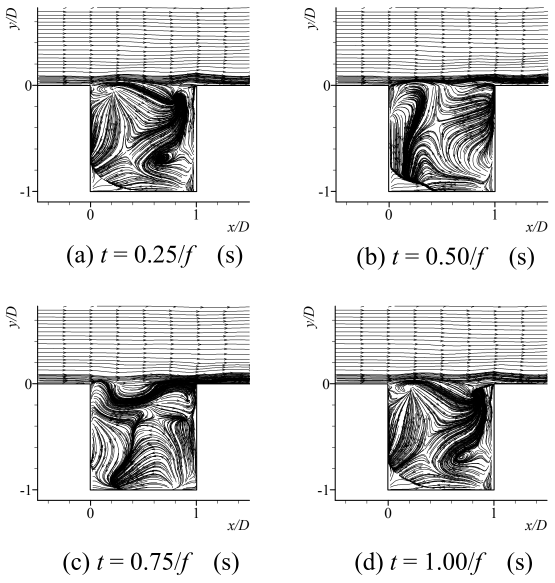
(a) $t = 0.25/f$ (s)

(b) $t = 0.50/f$ (s)

(c) $t = 0.75/f$ (s)

(d) $t = 1.00/f$ (s)

Fig.5: Contour maps of density (without control)



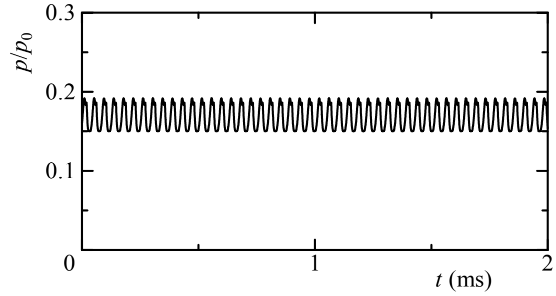
(a) $t = 0.25/f$ (s)

(b) $t = 0.50/f$ (s)

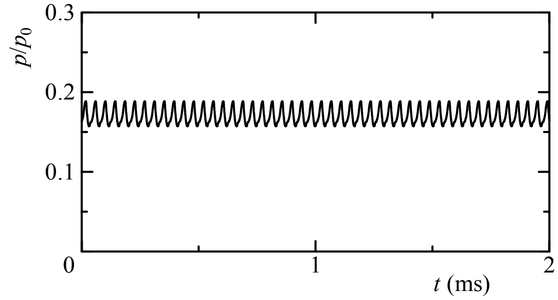
(c) $t = 0.75/f$ (s)

(d) $t = 1.00/f$ (s)

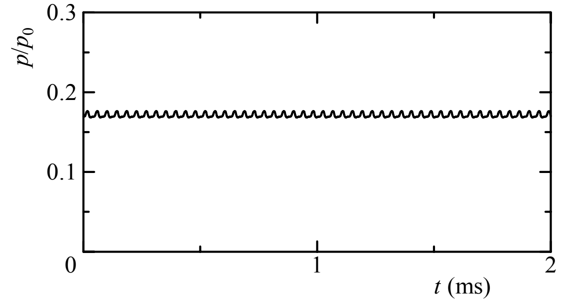
Fig 6: Streamlines (without control)



(a) S2

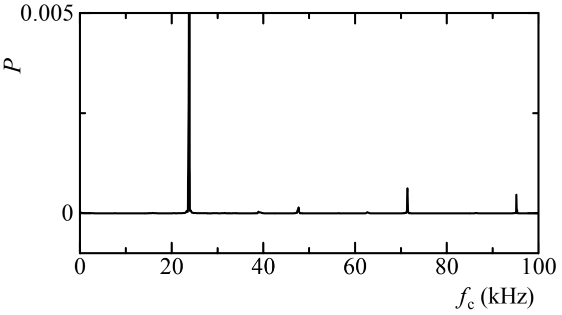


(b) S3

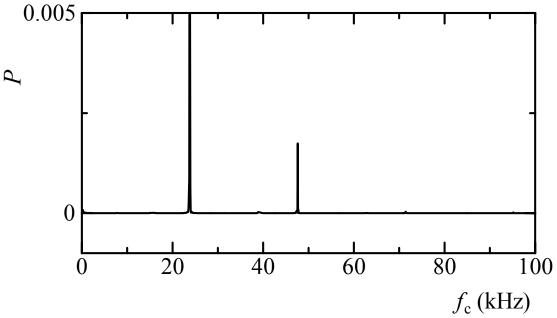


(c) S4

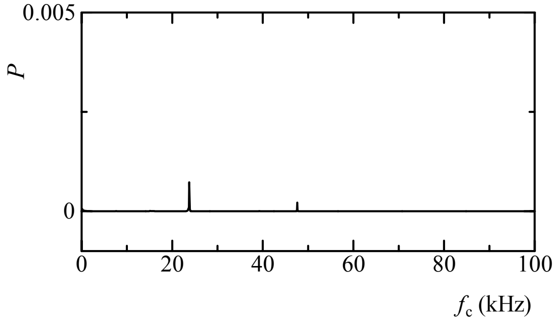
Fig 7: Time histories of static pressure (with control)



(a) S2



(b) S3



(c) S4

Fig.8: Power spectrum densities (with control)

thus produced, moves upstream and becomes the upstream compression wave (UW) as shown in Fig.5(d). This completes the formation of the feedback loop.

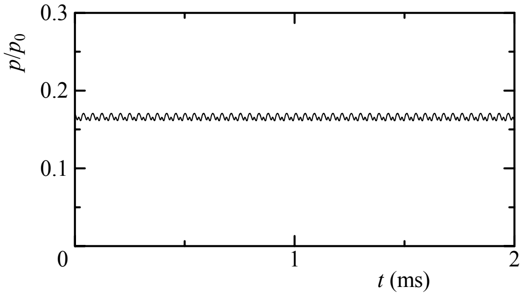
Figures 6 shows streamlines of the flowfield in case without control. It is observed that there is no tendency to develop a single, large vortex in the cavity.

3.2 Flowfield with Control

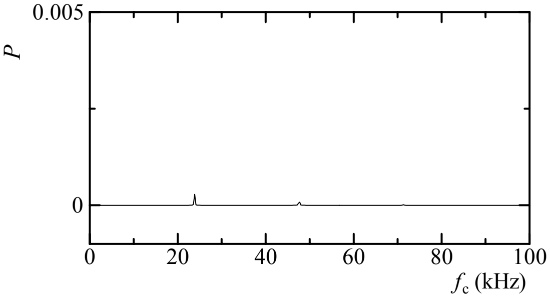
Time histories of static pressure and power spectrum densities are shown in Figs. 7 and 8 in case with control, respectively. It is observed that amplitudes of oscillations at the positions S2, S3 and S4 are reduced when the flow is controlled by a plenum chamber covered partially by a solid surface as shown in Fig.7. However, distributions of power spectrum densities in Fig.8 show that there are some dominant peak frequencies at S2, S3 and S4.

Figure 9 shows time history of static pressure and power spectrum density at S1 in the cavity with control. A significant amount of reduction of the amplitude of oscillations is obtained as shown in Fig.9(a). Distribution of power spectrum density is shown in Fig.9(b) and there is no dominat peak frequency at the position S1 in the cavity with control. Here, f_c represents the frequency in case with control. Therefore, a cavity covered partially by a solid surface can reduce the pressure fluctuations not only at the region of main flow of axi-symmertic nozzle (Figs.7and 8) but also at the inside position of the cavity (Fig.9).

Figure 10 shows density contours for the cavity with control. There exist a stable shear layer with no compression waves and no feedback loop as shown in Fig.10. The significant reductions of cavity-induced pressure oscillations that obtained by the present control device can be explained from the fact that the upstream compression waves that impinges on the front wall of the cavity below the leading edge surface cannot disturb the shear layer immediately after the reflection. It is found from Fig.10 that the compression wave becomes weaker when the flow is controlled by a solid surface fitted at the leading edge of the cavity. The upstream compression waves that impinge on the leading edge wall below the solid surface cannot disturb the shear layer immediately after the reflection. The reflected compression waves which are now below the solid surface and traveling downstream gradually become weaker and will be dissipated according to Tam et al. [19]. Therefore,

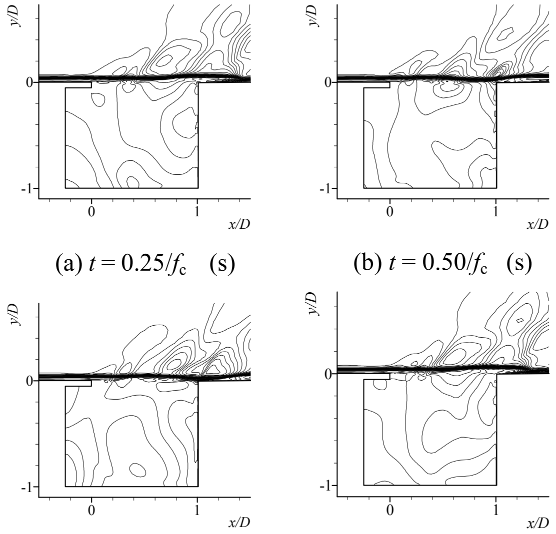


(a) Time history of static pressure



(b) Power spectrum density

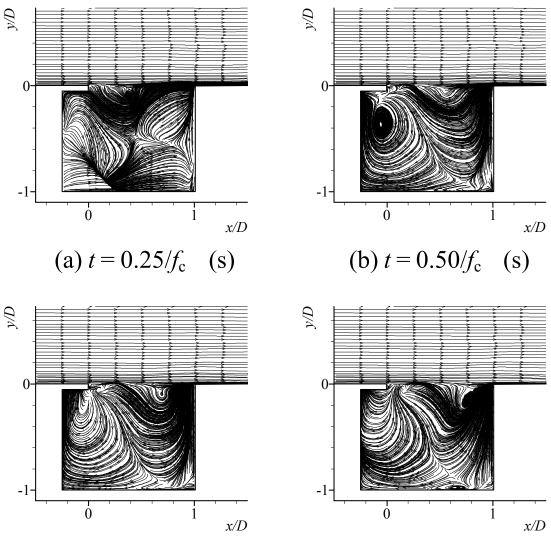
Fig 9: Time history of static pressure and power spectrum density at S1 (with control)



(a) $t = 0.25/f_c$ (s) (b) $t = 0.50/f_c$ (s)

(c) $t = 0.75/f_c$ (s) (d) $t = 1.00/f_c$ (s)

Fig 10: Contour maps of density (with control)



(a) $t = 0.25/f_c$ (s) (b) $t = 0.50/f_c$ (s)

(c) $t = 0.75/f_c$ (s) (d) $t = 1.00/f_c$ (s)

Fig 11: Streamlines (with control)

interaction of the reflected waves with the shear layer immediately after the reflection will not be possible in this case due to the obstruction imposed by the solid surface. Furthermore, after the reflection, the gradually dissipating compression waves [19], while propagating downstream, cannot excite the shear layer strongly enough to regenerate instability and the formation of feedback loop is discouraged in the cavity with control. Therefore, a reduction of oscillations (Fig.9(a)) and a more stable shear layer was found for a cavity with control as shown in Fig.10.

Figure 11 shows a sequence of representative instantaneous streamline contours resulting from the cavity with control. It is observed that there is also no tendency to develop a single, large vortex in the cavity.

4. CONCLUSIONS

A computational study has been carried out for a supersonic two-dimensional flow at Mach number 1.83 at the entrance of a straight channel connected to an axi-symmetric nozzle. A passive control method consisted of a square cavity covered partially by a solid surface was investigated to control cavity-induced pressure oscillations in a supersonic free stream flow. The results showed that oscillations occurred at the main flow down stream of the cavity as well as at the inside of the cavity. It was also observed that the amplitudes of oscillations were high in case of flow through axi-symmetric nozzle without control. The proposed control device can reduce the amplitudes of oscillations significantly not only at the region of main flow of axi-symmertic nozzle but also at the inside position of the cavity. However, the distributions of power spectrum densities showed some dominant peak frequencies in the flow field at the region of main flow.

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6. NOMENCLATURE

Symbol	Meaning	Unit
D	Cavity depth	(mm)
d	Dia. of main flow section at the entrance of the cavity	(mm)
d^*	Throat diameter	(mm)
f	Frequency of oscillation without control	(Hz)
f_c	Frequency of oscillation with control	(Hz)
k	Turbulent kinetic energy	(m^2/s^2)
L	Plate length	(mm)
M	Mach number	(-)
p	Static pressure	(Pa)
P	Power spectrum density	(-)
R	Eddy viscosity	(Pa · s)
t	Time	(ms)
t_p	Thickness of solid surface	(mm)
W	Cavity length	(mm)
x,y	Cartesian coordinates	(m)