# FLOW CONTROLLING ATTEMPTS AGAINST A SOUND GENERATING CAVITY FLOW AND A TRANSITIONAL BOUNDARY LAYER

Yu Fukunishi*, Seiichiro Izawa*, Yuzuru Yokokawa** and Takeshi Sakai***
*Tohoku University, Sendai, Japan **JAXA, Japan ***JR Hokkaido, Japan

## 1. Introduction

The work presented here focuses on the flow controlling technique using piezo-ceramic devices. The long-term aim of the research is to develop a flow controlling technique which can control a turbulent flow. When our research project started a little more than ten years ago, although we were interested in controlling the turbulent flow fields, we were aware that the basic techniques we possessed for flow control were not sufficient at all in order to control turbulent flow fields. The necessity to develop basic techniques which could be applied in various situations were strongly acknowledged. For the development of basic flow controlling techniques, two target flow fields were chosen, a cavity flow and a transitional boundary layer. The cavity flow was chosen because the separating flows tend to have high-receptivity and the effect of the control could be easily monitored by the change in the sound emission. The transitional boundary layer was chosen as a practice case towards controlling the fully developed turbulent boundary layer. It was found that both targets were not that easy to control.

## 2. Part 1. Reduction of Aerodynamic Noise from a Flow over a Cavity

### Introduction

The aerodynamic noise problems can be found in places such as buildings, automobiles and high-speed trains. In particular, the aerodynamic noise is the limiting factor for the maximum velocity of the high-speed train in Japan. Because the flow noise increases in proportion to the sixth or the eighth power of the velocity of the flow, it became an important problem as the speed of the vehicles increased. One of these aerodynamic noise problems is the noise caused by a flow over a cavity. When the cavity is exposed to a flow, the separating shear layer rolls up into vortices. Then, a pressure fluctuation is generated by these vortices hitting the downstream edge. This pressure fluctuation travels upstream and affects the beginning of the formation of the shear layer forming a feedback loop. As a result of this feedback loop, the aero-acoustic noise from a cavity is generally a sound of large amplitude and single frequency. Controlling the structure of this feedback loop is the main purpose of this research.

The cavity flow has been a subject of many investigations. Tani et al. [1], Rockwell[2] and Howe [3] are the examples, however, it is still very difficult to suppress the noise on such flows. Since the generation of such a noise originates in the velocity fluctuation of the separating flow, it can be assumed that controlling the separating flow is the effective way to control the feedback loop and thus suppressing the noise generation. And in order to control a separating flow, it should be very effective to control the flow at the separation point where the receptivity of the flow is high. Based on this idea, Cattafest et al. [4] were successful in reducing the level of the noise peak by changing the dominant frequency on the feedback structure in the cavity using the open-loop control technique. On the other hand, our group attempted reducing noise by controlling only the phases of the periodic flow patterns using the actuators attached on the leading edge of the cavity. Kikuchi et al. [5, 6] used a PVDF film and Yokokawa et al.[7] employed a piezo-ceramic device. These actuators were activated with the alternatively different phases along the spanwise direction so as to create the velocity fluctuations 180 degree out of the phase in this direction. Therefore the opposite-signed sound waves generated by these fluctuations eventually cancelled each other in the far field, and noise suppression was achieved. From the receptivity point of view, "bi-morph" type actuators attached on the upstream wall of the cavity should be able to have a similar effect, because the tip moves in the same direction. Compared with the "uni-morph type" actuators used before in Yokokawa et al.[7], which expands and shrink within the plane parallel to the surface, the "bi-morph type" actuators can move their edges with larger strokes through the bending motion. So a control using "bi-morph" type actuator was attempted and is reported.

## Experimental Setup

The facility used in the experiment is a closed circuit, low-turbulence wind tunnel at the Institute of fluid Science (IFS), Tohoku University. It has an octagonal cross-section nozzle (293mm from wall to wall) and a 911mm long open test section. At the test section, the turbulence level of freestream is about 0.1$\%$ of the uniform flow velocity $U_\infty$ at 20.0 m/s. The experimental model with a cavity is horizontally mounted in the test section. The model is shown Fig. 1. The size of the model is 900mm long, 250mm wide and has a rectangular cavity (width($L_c$)=50mm, depth($H_c$)=30mm ) with a resonator (length($L_r$)=190mm) 300mm downstream from the leading edge. The origin is at the spanwise-center of the upstream edge of the cavity. The coordinate system is $x$, $y$ and $z$ to the streamwise, the wall-normal and the spanwise directions, respectively. The boundary layer is turned turbulent by an area of rough surface and a trip wire near the leading edge of the plate. In the first part of this research, based on the idea that the velocity fluctuations should be introduced where receptivity is high for the most effective control, aluminum plates with actuators are placed very close to the upstream wall of the cavity. As shown in Fig. 1, two plates are attached side-by-side in the vicinity of the upstream wall of the cavity. The size of each actuator piece is 0.5mm thick, 60mm wide and 25mm high. The alternating current voltage is supplied between the electrodes attached on the two large surfaces of the actuator. By supplying the voltage, tip of the actuator vibrates few micrometers parallel to the freestream. The gap between the plates and the upstream wall is 1.0mm. Partition plates are inserted inside the resonator creating cells with the same spacing as the actuator piece. A single hot-wire probe on a three-dimensional traversing mechanism, controlled by a computer, is used for the velocity fluctuation measurements. A condenser microphone, which is set at a location 300mm above the center of the cavity, is used for the sound measurements. It was checked that the microphone was far enough not to generate any additional sound by its own existence.

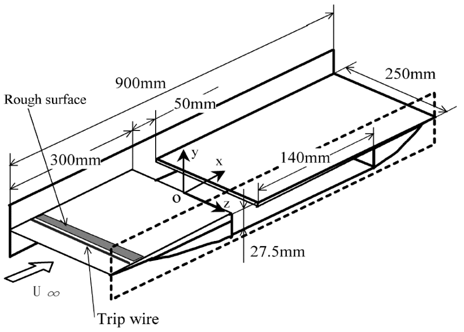
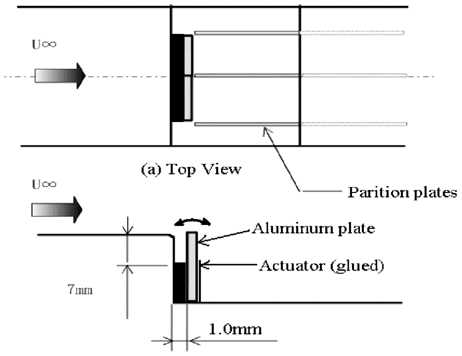


*Figure 1.* Test piece with a cavity.



(a) Top View

(b) Cross sectional View

*Figure 2.* Aluminum plates with actuators.

## Results

The velocity fluctuation $U'$ inside the cavity when the freestream velocity $U_\infty$ is 35 m/s is shown in Fig. 3. This profile is obtained by applying the ensemble averaging technique using the sound measured by the condenser microphone as the reference signal. The clear patterns of velocity fluctuations generated from the upstream edge of the cavity can be found. With a help of the resonator, the flow generates a strong aerodynamic noise.

The piezo-electric actuators are placed near the upstream wall of the cavity. The purpose of the control is to change the phases of velocity fluctuations along the spanwise direction by active forcing. The control signals with 180 degree phase difference are supplied to the actuators. The voltage is 60 $V_{rms}$ and the frequency is set to the dominant frequency(540 Hz). The free stream velocity $U_\infty$ is set to 31 m/s. The results are shown in Fig. 4, Fig. 5, and Fig. 5.

In Fig. 4 the contour map of velocity fluctuation in the $x-z$ plane at $y$= -5 mm is shown. These figures are obtained by taking the ensemble-average using the control signal as the reference. It can

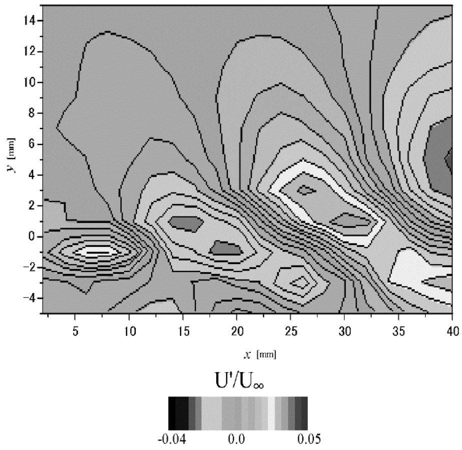


*Figure 3.* Velocity fluctuation pattern at the cavity. ($U_\infty$ 35.0 m/s, $L_c$=50mm)

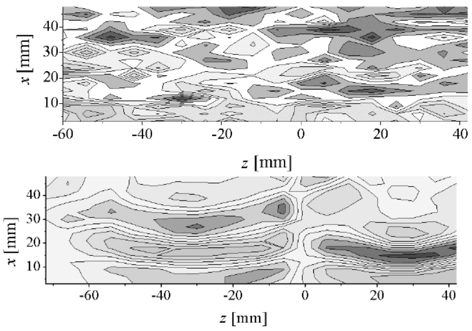


*Figure 4.* Contour maps of velocity fluctuations in $x$-$z$ plane. (Interval of the contour lines are $0.01U_\infty$)

be found that a clear phase difference of velocity fluctuation along the spanwise direction exists in the controlled case. Fig. 5 shows one of the sound wave spectrum samples under control. Supplied voltage is 100V, and the space between upstream edge and the actuator is 1.5mm. It can be found that the dominant peak of the spectrum clearly decreases. In Fig. 5 the height of the peaks on the spectra of FFT analyses against various supply voltages are shown. This result shows that the actuators are effectively suppressing the aerodynamic noise. It can be found the noise reduction effect appears to saturate when the supplied voltage is over 60 V. It also shows that a noise reduction up to 30 dB is achieved by the active control.

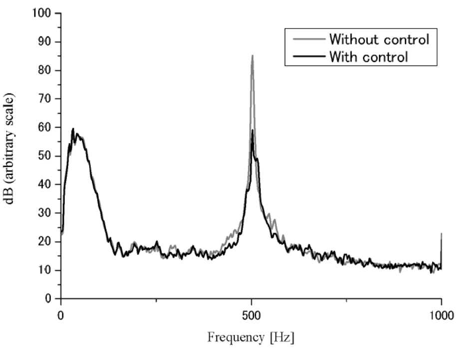


*Figure 5.* FFT spectrum of the sound wave. (100V)

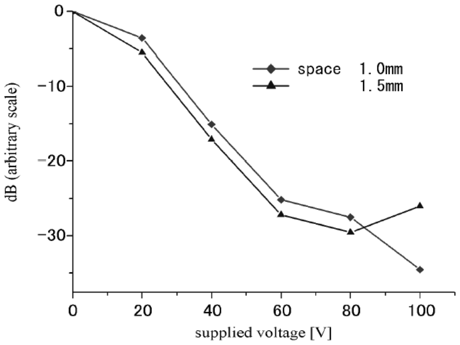


*Figure 6.* Peak sound power vs. supplied voltage.

## Conclusion of Part 1

An experiment to control of cavity noise using bimorph-type piezo-ceramic actuators attached on the upstream wall of the cavity was carried out[8]. It was found that a flow field with a velocity fluctuation pattern as was designed could be generated by the active control. As a result, the noise could be reduced as much as 30 dB by the active control. The relation between the noise reduction and the supplied voltage was shown.

## 3. Part 2. Control of a Transitional Boundary Layer

## Introduction and Experimental Setup

The primary objective of this study is to develop a system that can automatically control T-S waves or oblique waves in a flat-plate boundary layer. These instability waves are cancelled in their linear stages of transition by superimposing the counter waves. Many attempts to generate a wave in a boundary layer have been proposed for the last several decades. A vibrating ribbon attached on a surface [9], periodic heating of thin Nichrome films [10], and suction/blowing system[11] are examples of activators for generating the waves in the boundary layer. In the flow controlling attempts, Sturzebecher & Nitsche [12] used the slot system which is all-in-one device including a speaker and a sensor. An open-loop control using an array of PZT actuators was attempted by Sakai et al.[13] and Fukunishi et al.[14].

On the other hand, in this experiment small and thin piezo-ceramic (PZT) actuators are used as the control device to generate the counter waves against the incoming waves. The actuators aligned in the spanwise direction attached on a flat-plate surface were designed so that they could be operated independently with different amplitudes and phases, allowing the device to generate two dimensional or oblique waves of various angles. The actuator's operating signals are successively updated using the velocity fluctuations monitored downstream by a rake of hotwires. A simple feedback system is applied to the semi-automatic and active control of T-S waves and oblique waves.

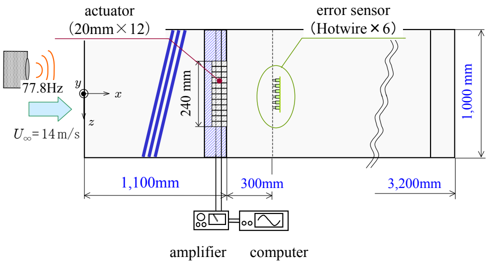
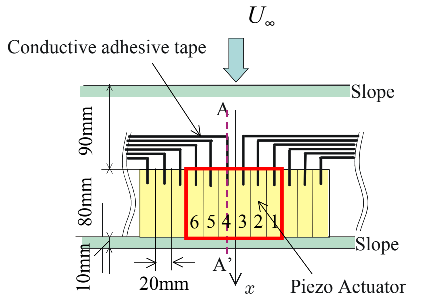
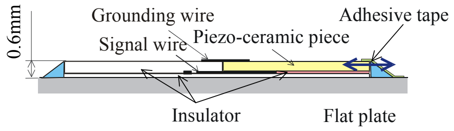


*Figure 7.* Experimental setup.



(a) Plane view from underside



(b) A-A' cross section view

*Figure 8.* Piezo-ceramic actuators.

**Flat Plate, Actuators and the Control System.** The experiments are conducted in the low turbulence wind tunnel at the Institute of Fluid Science of Tohoku University. The wind tunnel is a Göttingen type with an octagonal test section, which is 3,200mm long and 1,010mm from wall-to-wall The contraction ratio between a settling chamber and a test section is 12:1.

The schematic view of the experimental setup is shown in Fig. 7. A smooth flat plate made of Aluminum alloy, which is 3,200mm long, 1,000mm wide and 10mm thick, is mounted vertically in the middle of the test section. From the leading edge of the plate, Scotch tapes, actuators, and error sensors are attached to its surface. Target waves, either T-S waves or oblique waves, are excited upstream by a combination of Scotch tapes on the surface and an acoustic forcing using a loudspeaker set upstream of the settling chamber. The operating frequency of loudspeaker is 77.8Hz. The sweep angle of generated waves is changed by inclining the tapes. The axes $x$, $y$, and $z$ are in the streamwise, wall-normal, and spanwise directions, respectively.

Fig. 8 shows the details of the piezo-ceramic actuators. Each actuator is wired separately so that they can be manipulated independently using a computer. The tip of an actuator must be adjusted very carefully, because if the tips are even slightly tilted up or down, that can cause a large difference in the amplitude of the introduced velocity fluctuations. Both the upstream and downstream ends of the actuators are sloped to prevent separations and the high-receptivity at the edges. In the current experiment, six middle pieces (channel 1though 6) among the twelve pieces of the actuator array are used. A hotwire sensor is installed straight downstream of the center of each activated actuator, about 2mm away from the wall. Reynolds number $Re_x$ at the actuators' position, $x$ = 1,000mm, is $9.9 \times 10^5$. The total thickness of each actuator is approximately 0.6mm, which is 13% of the boundary layer thickness at the location. The freestream velocity $U_\infty$ is 14.0m/s and the velocity fluctuation within the freestream is 0.07%.

The details of the controlling system are described in this section. A feedback loop system for an active flow control using actuators and error sensors is constructed. First, the sensors capture the velocity fluctuations of the waves generated upstream. Each signal is filtered and stored for three cycles and then, based on the ensemble averaged property of the signal, the operating amplitude and the phase of each actuator is determined and successively updated. The adjustment is performed for only one actuator piece at a time, and the actuators are adjusted in turn. This adjustment process is repeated until the waves are damped to a level lower than a certain criterion. Each adjustment is limited to below 5% of the previous value. Because the influence of one actuator spreads in the spanwise downstream, it is difficult to satisfy the control criteria at the sensors of the spanwise ends. So, six actuators (channel 1 through 6) are adjusted to satisfy the criteria at four inner sensors (channel 2 though 5).

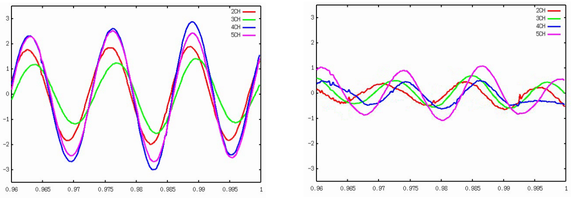


*Figure 9.* Control effect on velocity fluctuation waves (T-S waves), (a) before and (b) after the 97th adjustment.

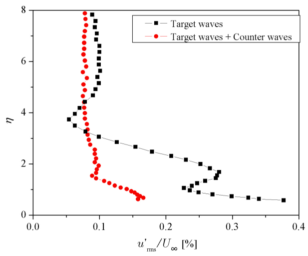


*Figure 10.* RMS profile of the velocity fluctuation at $x$ = 1,350mm, $z$ = 0mm (T-S waves).

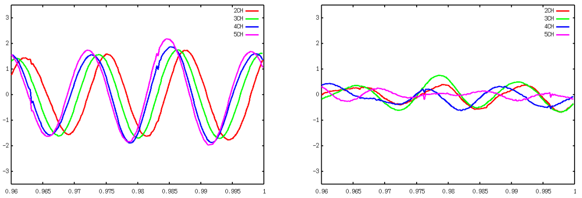


*Figure 11.* Control effect on velocity fluctuation waves (15 degree oblique waves.), (a) before and (b) after the 44th adjustment.

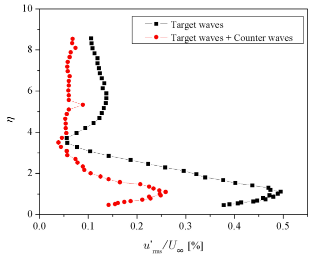


*Figure 12.* RMS profile of the velocity fluctuation at $x$ = 1,350mm, $z$ = 0mm (15 degree oblique waves).

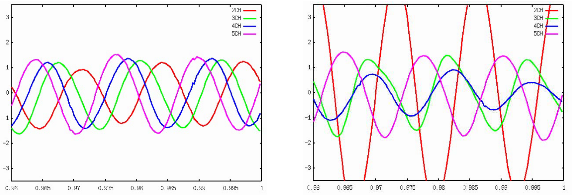


*Figure 13.* Control effect on velocity fluctuation waves (30 deg. oblique waves.), (a) before, (b) after the 67th adjustment.

## Results and Discussion

Velocity fluctuation waves captured by the downstream sensors before and after the controlling the T-S wave are shown in Fig. 9. In this case, after 97 adjustments the system regarded the control to be successful and stopped. In Fig. 9, it can be found that the velocity fluctuation became much weaker for all sensors. It should be noticed that the amplitudes of the waves does not monotonously decrease as the adjustment progresses.

In Fig. 10, the RMS profiles of fluctuating velocity components, measured 250mm downstream from the actuator array is presented. The weakening effect reaches approximately 66% after the 97th adjustment. In the figure, a very high value of RMS can be found near the wall. This comes from a minute and local unevenness of the downstream slope behind the actuator, $x$ = 1,000mm and $z \simeq$ 0mm. It is found that this particular slope, although very slightly, moves up and down accompanying the generated waves, amplifying the waves..

Fig. 11 shows the effect of the active control when the target waves are inclining 15 degrees. The target for this weakening control is set at 6dB, instead of 10dB, because the flow control is more difficult. As well as the T-S wave case, the amplitude of each velocity fluctuation is well suppressed as the result of the control. The weakening effect reached 6dB after the 44th adjustment. The RMS value of the velocity fluctuation at the peak around $\eta = 1.5$, decreased to nearly half as the result of the control, which is shown in Fig. 12.

The control becomes more difficult with the increase in the sweep angle. Fig. 13 shows the control attempt against the oblique waves with a 30 degree sweep angle. The target for weakening is set at 6dB as in the 15 degrees case. Unfortunately, the amplitude of the velocity fluctuation does not show any sign of decreasing even after more than 70 adjustments. The reason for the difficulty, comes from the effect that the wave front of waves generated by a single actuator tends to form an arch and possibly some unknown effects. It may require more actuators along the spanwise direction for the more accurate generation of the waves with large sweep angles. More improvement in the control algorithm may be also needed.

## Conclusion of Part 2

A semi-automatic active control of the T-S waves and the oblique waves was attempted using an array of piezo-ceramic actuators attached on a flat-plate surface[15]. It was shown that the system could reduce the two-dimensional T-S waves and the oblique waves if their sweep angles were not large. However, it was found that the system was not effective against oblique waves of a large sweep angle.

## 4. Summary

Two examples of active flow control using piezo-ceramic actuators were shown. The effectiveness of the piezo-ceramic actuators as a flow controlling device appears to be promising. However, what are shown are only the successful cases. There are numbers of subtle techniques needed in using these devices, which cannot be presented because of the page limitations. The effort for the further improvement of the flow controlling technique is still needed.

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