Extremum Seeking Adaptive Separation Control on a Wing with Plasma Synthetic Jet Actuator*

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Abstract
Plasma synthetic jet actuator (PSJA) is a flow control device which has structure that insulator is tucked with electrode pair. It generates electrohydrodynamic (EHD) effect and induces a flow. The experiment was held to investigate the effect of flow control using extremum seeking with PSJA placed on the surface of NACA0012 wing installed in the wind tunnel. Frequency of the input signal to PSJA is modulated to maximize the effect of PSJA in flow control. The wake velocity fluctuation is one of indexes on separation control effect. The seeking algorithm calculates the correlation of the modulation frequency and wake velocity fluctuation. The modulation signal frequency where the correlation changes from negative to positive minimizes the wake velocity fluctuation. To detect a local minimum of the wake velocity fluctuation by extremum seeking, it is necessary to change the modulation signal frequency with time. Sine and square waves change the modulation signal frequency to PSJA. The wind tunnel speed was changed as an external factor. The experimental results show that the modulation signal frequency can track the optimum value when the wind tunnel speed is changed. This paper shows that adaptive flow control to optimize the modulation signal frequency with PSJA using extremum seeking enables to suppress turbulence on the flow field of wings.

Key words: Plasma Synthetic Jet Actuator, Extremum Seeking, Separation Control, Modulation Signal Frequency, Correlation Coefficient

1. Introduction
The studies on energy saving are focused because of fuel resource depletion and global warming. The countermeasures for energy effect are taken in each field. In the field of fluid dynamics, studies on drag reduction by fluid control are continued. Various methods of fluid control exist. On separation control, for example, there are vortex generator and flap on the wing. Other than these devices which are installed on wing, there are active control devices which are driven by supplied energy. For example, stall control on wing by sound wave. In order that sound wave makes vortex from the lower part of wing efficiently around leading edge, it is shown that separation control is possible using inflectional instability(1). Also, there is the method using jet flow. In the case that the angle of attack (A.O.A) excess 20deg,
separation control is possible by supplying momentum by jet flow from leading edge\(^{(2)}\). As the example of jet flow generator, there is synthetic jet actuator (SJA). SJA is an actuator which mass flow equals zero as the result that SJA iterates absorption and blowing alternately by continuous jet flow. This device is effective for separation control \(^{(3)(4)}\). SJA has mechanical structure. On the other hand, there is electric plasma actuator as similar jet flow generator. Recently, studies are proceeding with flow control with plasma actuator.

We see this plasma actuator as an extension of SJA and call it plasma synthetic jet actuator (PSJA). PSJA is a device which generates jet flow by glow discharge which occurs by applying high voltage between two electrodes which are anode and cathode. High frequency square wave is used for input signal. SJA is mechanical devices. While, PSJA is light and is easily miniaturized because PSJA does not have moving parts. The experiment that PSJA installed on NACA0012 wing showed PSJA effect approximately 29\(^{(5)(6)(7)}\) in drag reduction effect.

We provide adaptive closed loop flow control\(^{(8)}\) around NACA0012 wing with PSJA driven by pulse weighted modulation (PWM) signal when the main velocity changes in flow field. NACA0012 wing is installed in the wind tunnel. Stationary signal shown in Fig. 1(a) is used as the signal to PSJA. In this paper, the modulation signal shown in Fig. 1(b) is used to maximize the effect of PSJA in flow control under the wind tunnel speed change. Separation control effect depends on the modulation signal frequency. Therefore, it is necessary to optimize the modulation signal frequency. On the investigation of PSJA effect, the wake velocity fluctuation is one of important elements on flow control. The optimum value of frequency minimizes the wake velocity fluctuation. The modulation signal frequency is controlled to track the optimum value in real time when the wind tunnel speed changes as external factor.

It is necessary to change the modulation signal frequency with time to detect the optimum value by extremum seeking. We investigate the effect using sine and square waves to change the modulation signal frequency with time.

![Fig. 1 Input signal to PSJA](image)

2. Experimental Equipments

2.1 Plasma Synthetic Jet Actuator

There are many shapes of PSJA, strip-strip type (S-S type) PSJA is used in this paper. S-S type PSJA is constructed with electrode pair as metallic strip. Insulator is tucked with electrode pair at Fig. 2. The distance between electrode pair is 0mm. Electrode is capper
thickness 20µm, insulator is polyimide film thickness 50µm. Considering durability, we lay 3 sheets of polyimide film on top of another. Glow discharge with plasma is generated by supplying A.C. voltage to electrode pair. Jet flow is induced by creating vortex to inhale ambient fluid from anode side to cathode side through electrohydrodynamic (EHD) effect.

2.2 Wind Tunnel and NACA0012 Wing with PSJA

The suction type wind tunnel shown in Fig. 3 is used for the experiments. Maximum wind tunnel speed is 20m/s, and the tunnel test section has a cross-section of 250 mm × 150mm. NACA0012 wing of leading edge stall type is chosen for the experiments. PSJA is placed on the surface of the wing as shown in Fig. 4. We placed PSJA at 5mm from leading edge of the wing because Ref. (9) shows separation control effect by the experiment for PSJA placed at the same place. Maximum wing thickness is 7.2mm at 18mm from the leading edge. The wake velocity is measured by hot-wire airflow meter (Kanomax Japan, Inc. System7000). It is installed at 38mm backward from trailing edge of the wing and 75mm height from bottom of the test section. Figure 5 shows the schematic diagram of the tunnel test section.
2.3 PSJA Control Theory and Measurement Method

Figure 6 shows the schematic diagram of experimental devices. Digital Signal Processor (DSP) on PC generates square wave through the function generator and this signal is inputted to PSJA drive circuit. Electric power is amplified by the power amplifier. Glow discharge occurs between electrode pair to amplify the voltage by set-up transformer. At this time, the current carrying on actuator is tens mA. This discharge is recognized as glow discharge, because the current of glow discharge is below tens mA at atmospheric pressure.

![Figure 6 Experimental devices](image)

3. Detection of Optimum Modulation Signal Frequency

3.1 Extremum Seeking Method for Modulation Signal Frequency

We use extremum seeking method to detect the modulation signal frequency which minimizes the wake velocity fluctuation. This algorithm seeks the frequency that a local minimum of the wake velocity fluctuation. The frequency where the correlation coefficient changes from negative to positive is regarded as the optimum value. This frequency minimizes the wake velocity fluctuation, and the wake velocity is a local minimum. The correlation coefficient is calculated from the modulation signal frequency and the wake velocity fluctuation. Correlation coefficient $r$ of two sequences $x = (x_1, \ldots, x_n)$ and $y = (y_1, \ldots, y_n)$ is

$$r = \frac{\sum_{i=1}^{n} (x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^{n} (x_i - \bar{x})^2 \sum_{i=1}^{n} (y_i - \bar{y})^2}} ,$$

$$\bar{x} = \frac{x_1 + \cdots + x_n}{n}, \quad \bar{y} = \frac{y_1 + \cdots + y_n}{n} .$$

Where $x = (x_1, \ldots, x_n)$ is wake velocity fluctuation, $y = (y_1, \ldots, y_n)$ is modulation signal frequency.

Extremum seeking method proceeds along the following.

**Input Signal Generation** : Apply a modulation signal to PSJA. Sine or square wave of the period $T = 5s$ and the amplitude $A = 10Hz$ changes the modulation signal frequency around the center frequency $f_c$ in measurement time $T_d = 15s$. The center frequency $f_c$ is increased by
20Hz after the seeking in one frequency range. Figure 7 shows the schematic figure of it. For example, a modulation signal (\( f_m = 30Hz \)) is shown in Fig. 8. This modulation signal frequency is changed accordance with Fig. 7. In this paper, the duty ratio of the modulation signal is 50\%. The input voltage to PSJA is 6000V and the frequency is 20kHz.

**Calculation Method of Correlation**; Calculate the correlation and correlation coefficient in each frequency range with sequences of modulation signal frequency and wake velocity fluctuation measured by hot-wire airflow meter.

**Optimum Value Judgment**; The correlation changes are of two types. One is the change from positive to negative. The other is the change from negative to positive. Reference (10) shows that RMS became small when PSJA produced a great drag reduce effect. We regard the optimum value as the frequency where the wake velocity takes a local minimum. The optimum frequency is determined as the value when the correlation changes from negative to positive because the optimum frequency is where the wake velocity fluctuation is a local minimum.

![Fig. 7 Time variable of the modulation signal (square wave signal)](image)

![Fig. 8 Example of modulation signal to PSJA (\( f_m = 30Hz \))](image)
The optimum value of the modulation signal frequency is determined in real time measurement. For example, if the wake velocity fluctuation is a local minimum when the modulation signal frequency is 50Hz, then the wake velocity fluctuation increases in the case that modulation signal frequencies are 40, 60Hz. Considering that in correlation calculation, the correlation is negative at 40Hz and positive at 60Hz. Therefore, the correlation change from negative to positive is a local minimum in extremum seeking. On the other hand, the correlation change from negative to positive is a local maximum. Since the optimum value is the frequency such that the wake velocity fluctuation is a local minimum, this method regards 50Hz as the optimum modulation signal frequency.

3.2 Experimental Method for Optimizing Modulation Signal Frequency

The experiment is conducted for PSJA placed on the surface of NACA0012 wing as shown in Fig.4. NACA0012 wing of the A.O.A 10-13deg is installed in the wind tunnel. Separation control effect of PSJA appears significantly in this A.O.A. range. The wind tunnel speed is selected in 5-10m/s, and PSJA is driven by a modulation signal. In this time, a modulation signal frequency changes in time. The sampling time of wake velocity is 0.02s. The measurement time $T_d$ is 15s per one frequency range. Mean values are needed to calculate the correlations and correlation coefficients. To promote accuracy of the optimum value detection, 0-5s of the measuring time 15s is the time to calculate the mean wake velocity and correlation coefficients are calculated in remaining 5-15s. Between sine wave and square wave are made a comparison. Also, two types are tested as calculation method of the correlation. One calculates on all frequency range. The other calculates on each frequency range.

4. Experimental Results and Discussion

Figures 9 and 10 show correlation coefficients in the frequency range from 20 to 100Hz when the wind tunnel speed 5m/s, $Re \approx 2.0 \times 10^4$ and the A.O.A 13deg. Figure 9 shows the result of sine wave. Figure 10 shows the result of square wave.

![Fig.9 Correlation coefficient (sine wave signal)](image1)

![Fig.10 Correlation coefficient (square wave signal)](image2)

Wake is turbulence. It read velocity fluctuation, hence, correlation coefficient were different each run. Variation of correlation coefficient in the case of square wave signal is smaller than that in the case of sine wave signal. Since then, square wave signal is used to change the modulation signal frequency.

In this experiment, the correlation coefficients were calculated for all frequency range as Table 1 because all frequency ranges of a modulation signal was 100Hz with calculation method of correlation coefficients. The correlation changes appear in the constant range in this method. It is difficult to detect the accurate optimum value because the initial correlation coefficient affects the correlation coefficients in each frequency range in time if
measuring time becomes long. Therefore, correlation coefficients are calculated when measuring range of the modulation signal changes as Table 2.

Table 1 Correlation coefficient compute method (all area)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Modulation signal frequency $f_m$ [Hz]</td>
<td>10-30 30-50 50-70 70-90 90-110</td>
</tr>
<tr>
<td>Correlation coefficient compute time[s]</td>
<td>0-10 0-20 0-30 0-40 0-50</td>
</tr>
</tbody>
</table>

Table 2 Correlation coefficient compute method (each area)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Modulation signal frequency $f_m$ [Hz]</td>
<td>30-50 50-70 70-90 90-110 110-130</td>
</tr>
<tr>
<td>Correlation coefficient compute time[s]</td>
<td>5-15 20-30 35-45 45-55 60-70</td>
</tr>
</tbody>
</table>

The experiment that a modulation signal frequency was changed between 30-210Hz (the center frequency was changed from 40 to 200Hz) was conducted. In the views of results of Fig. 9 and 10, square wave changed the modulation signal frequency in time. To promote accuracy, the experiment was repeated until the detected the optimum modulation signal frequency is in agreement 3 times. To investigate whether the modulation signal frequency can track the optimum value, the wind tunnel speed was changed from 5 to 10m/s. Figures 11-16 show correlation coefficients for each the wind tunnel speed 5-10m/s. Figures 17 and 18 show example of positive and negative correlation. Figures 19 and 20 show detection ranges where the optimum frequency was detected.

The optimum values were detected when modulation signal frequencies $f_m$ were 60-80, 140-160Hz in Fig. 11 (the wind tunnel speed 5m/s). The correlation coefficient was negative and -0.00465 quit near 0 at 140Hz. When $f_m=160$Hz, the correlation coefficient was 0.12515 and changed to positive. Therefore, this frequency was regarded as the optimum value. Similarly, the optimum values were detected when the wind tunnel speed was changed from 6 to 10m/s. In Fig. 19, $f_m=130$, 150Hz made the wake velocity fluctuation small. Additionally, the correlation became positive when $f_m=150$Hz and negative when $f_m=130$Hz. Clearly, about 140Hz is the boundary of correlation change.

The correlation change was detected around 180Hz on the first and the second run in Fig. 20. However, this frequency was excepted from optimum values because these values were not detected in all 3 runs.

If the optimum values are detected at two frequencies such that the result when the wind tunnel speed 5m/s in Fig. 11, it is difficult to determine which is better frequency. It is necessary to determine the optimum value with consideration for standard deviation of the wake velocity fluctuation.
Fig. 11 Correlation coefficient for wind tunnel speed 5m/s \((Re \approx 2.0 \times 10^4)\)

Fig. 12 Correlation coefficient for wind tunnel speed 6m/s \((Re \approx 2.4 \times 10^4)\)

Fig. 13 Correlation coefficient for wind tunnel speed 7m/s \((Re \approx 2.8 \times 10^4)\)

Fig. 14 Correlation coefficient for wind tunnel speed 8m/s \((Re \approx 3.2 \times 10^4)\)

Fig. 15 Correlation coefficient for wind tunnel speed 9m/s \((Re \approx 3.6 \times 10^4)\)

Fig. 16 Correlation coefficient for wind tunnel speed 10m/s \((Re \approx 4.0 \times 10^4)\)
Fig. 17 An example of positive correlation
(wind tunnel speed 10m/s, Re $\approx 4.0 \times 10^4$, second run)

Fig. 18 An example of negative correlation
(wind tunnel speed 5m/s, Re $\approx 2.0 \times 10^4$, first run)

Fig. 19 Optimum point (wind tunnel speed 5m/s, Re $\approx 2.0 \times 10^4$, third run)
5. Conclusion

We have presented adoptive separation control method using extremum seeking. The experiment that extremum seeking detected the modulation signal frequency to minimize the wake velocity fluctuation in real time was conducted. PSJA was placed on the surface of NACA0012 wing in the wind tunnel. Square wave changed the modulation signal frequency from 30 to 210Hz. The frequency where the correlation coefficient changes negative to positive was regarded as the optimum value. The optimum value was detected when the wind tunnel speed changed from 5 to 10m/s. The experiment results showed the modulation frequency adopted the optimum value when the wind tunnel speed and uncertainty of the wake velocity fluctuation changed. The optimum values were detected on two ranges when the wind tunnel speed was 5m/s. We regarded the lower frequency as the optimum value. However, it is necessary to establish how to choose it logically. This paper shows that separation control around wing is possible by optimized tracking with extremum seeking to control the modulation signal frequency inputted to PSJA.

References
