論 文 の 内 容 の 要 旨

論文題目　Flow Control Mechanism of a DBD Plasma Actuator for Airfoils in Low Speed Free-streams
（低速流中の翼に対するDBDプラズマアクチュエータによる流れ制御のメカニズム）

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Once separation occurs, they have negative impacts on performance of applications in aeronautical and mechanical engineering, such as decrease of lift, increase of drag and aerodynamic noise. In the viewpoint of safety, environment and economy, control of separation is important and has been intensively researched in many years. For control of separation, passive-control devices, such as improvement of wing shape and a vortex generator, have limitations of performance in terms of the fact that they are effective in conditions near design points. On the other hand, active-control devices are more favorable because they can be driven when required. Because of increase of demands to micro-air-vehicle (MAV) and such small machines, active flow control with micro-scale devices is getting much attention. In this study, a "dielectric-barrier-discharge (DBD) plasma actuator" of micro-scale devices is especially featured. When alternate current (AC) high voltage is applied to this device, plasma is generated and relatively small flow of about $1m/s$ is induced. Utilizing this small induced flow, many researches for flow control from basic one to practical one have been reported. Especially, unsteady (called "burst mode" in this study) actuation is getting attention because it is more effective than steady (called "normal mode" in this study) one in spite of less energy consumption. Concerning burst actuation, burst frequency is considered as an important parameter for control of separation and the optimum non-dimensional frequency of burst frequency F^+ has been intensively discussed. However, the consensus has not been achieved in spite of long-time discussion. Because induced momentum from a plasma actuator is not so large, innovative method such as burst actuation is important for controlling flows with sever condition, therefore, detailed investigation for burst mode actuation is so important.

The final goal of this study is to find much better control guideline of burst actuation. For this purpose, experiments are conducted with two types of airfoil, NACA0015 and NACA0012, in two types of Reynolds number, 63,000 and 189,000. And two locations for actuation, x/c = 0% and 5%, are applied in each case. In each experiment, control capability of a plasma actuator is investigated with three different angles of attack, pre-stall angle, post-stall angle and deep-stall angle.

In chapter 3, before applying a plasma actuator to control of separated flow, induced flow from a plasma actuator in static air is investigated. The actuator is applied on a flat plate and induced flow field with different input voltage and base frequency is evaluated with PIV visualization. From the results, it is verified that induced U-velocity is up to about 1m/s and gets faster with increasing input voltage and base frequency. Considering these results, burst frequency in this study is adjusted only by changing wave number with fixed base frequency to eliminate the base-frequency effect.

First, in chapter 4, a plasma actuator is applied to a NACA0015 airfoil in Re = 63,000 flow to investigate basic characteristics of separation control. In pre-stall angle cases, burst actuations with high frequency more than $F^+ = 6$ and normal actuation have the smallest separation bubble and separation bubble gets larger with decreasing burst frequency. In post-stall angle cases, in terms of minimum voltage for enough suppression of separation, some burst actuations are more effective than normal actuation as reported in past researches. Among the burst actuations, $F^+ = 6$ to 10 is the most effective and the range of burst frequency in which the trailing edge C_p is the highest gets wider with increasing input voltage. In deep-stall angle cases, only some burst actuations can suppress separation enough. As post-stall angle cases, $F^+ = 6$ to 10 is the most effective. From the results, it is concluded that actuation with a plasma actuator includes following four factors; direct momentum addition, enhancement of transition by normal actuation, enhancement of transition by burst actuation and generation of vortex structure.

Then, in chapter 5, co-flow and counter-flow blowing actuators are applied to a NACA0015 airfoil in Re = 63,000 to investigate directionality of burst actuation. Results indicate that both normal and burst counter-flow blowing actuations can affect flow. In pre-stall angle cases, cases with x/c = 5% actuation have almost the same trend as co-flow blowing actuations, where actuation at x/c = 0% has less effect. In post-stall angle cases, both normal and burst actuation can suppress separation with high input voltage and actuation at x/c = 5% is more effective than that at x/c =0% in terms of minimum voltage for enough suppression of separation. In deep-stall angle cases, only some burst actuations can suppress separation enough and clear difference is not observed between actuations at x/c = 0% and 5%. Comparing co-flow and counter-flow blowing actuators, co-flow blowing actuation is generally more effective than counter-flow blowing actuation. From the results, it appears that counter-flow blowing actuation also have the four factors as mentioned above. Transition enhancement by burst actuation is robust for actuator direction and position. On the other hand, factor of vortex generation seems to be sensitive for these parameters.

In chapter 6, a plasma actuator is applied to a NACA0012 airfoil in Re = 63,000 flow and a NACA0015 airfoil in $Re= 189,000$ flow for further analysis. In NACA0012 cases, diminishment of separation bubble is observed as NACA0015 cases in pre-stall cases. In post-stall and deep-stall angle cases, on the other hand, actuations at x/c = 5% is clearly less effective than that at x/c = 0%. This is because a NACA0012 airfoil is thinner than a NACA0015 airfoil and the distance between separated shear layer and actuation point x/c = 5% of NACA0012 cases is farther than that of NACA0015 cases. In Re = 189,000 cases, only actuation at x/c = 0% has control capability and that at x/c = 5% has no control capability. This seems to be caused by the same reason explained above. In x/c = 0 cases, trailing-edge C_p is the highest in the range of F^+ = 0.1 to 1. In α = 15deg (α_{stall} + 1deg) cases, all the burst actuations have almost the same steep leading-edge peak with any input voltage. This indicate all burst actuations in this experiment can enhance turbulent transition. In α = 17deg (α_{stall} + 3deg) cases, leading-edge peak is the largest at F^+ = 6 and this implies that there is limitation of burst frequency for enhancement of turbulent transition in this angle of attack. In α = 19deg (α_{stall} + 5deg) cases, any actuation does not have steep leading-edge peak and leading-edge peak is the largest at F^+ = 2. Considering these results, effect of large vortex is more dominant in Re= 189,000 cases than Re = 63,000 cases. In terms of aerodynamic coefficients, however, enhancement of turbulent transition is still important in α = 15deg and 17deg cases.

From above results, burst actuation should be focused because burst actuation is generally more effective than normal actuation as reported. There are two dominant factors in burst actuation, ″generation of large vortex ($F^+ \fallingdotseq 1$)″ and ″enhancement of turbulent transition ($F^+ \fallingdotseq 5$)″.

In conclusion, toward practical use of a DBD plasma actuator for separation control, I propose following guideline: Two-dimensional span-wise actuator attached at the location which is near and before separation point should be driven with voltage as high as possible, and better one out of $F^+ = 1$ or $F^+ = 6$ should be chosen as burst frequency.