論 文 の 内 容 の 要 旨

論文題目 Computational Analysis of the Flow Fields Induced by a DBD Plasma Actuator toward Separated-Flow Control
（プラズマアクチュエータによる剥離流れ制御の数値解析に関する研究）

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For aircrafts, flow separation is a critical phenomenon that leads to an increase in drag and a decrease in lift. In the current aircraft design, shapes of wing surface are changed using devices, e.g. vortex generators and flaps, and the flow separation is passively avoided. However this approach is effective only for the design points and encompasses limitation in a range of aerodynamic body design. In this context, active flow control using micro-scale devices are getting much attention in various fields. Especially in the aerospace engineering field, a "dielectric barrier discharge (DBD) plasma actuator" is well investigated in several devices for separated-flow control around airfoils. This device can control the global flow fields by adding the fluctuation to the local flow field with inducing weak flow (of a few meters per second). When a DBD plasma actuator is installed near the leading edge of an airfoil at a stall angle, and is operated, the separated flow is suppressed. Dielectric barrier discharge plasma actuators have a lot of advantages such as simplicity, active control capability and low energy consumption compared to conventional flow control devices (e.g. steady jets). Although the availability of a DBD plasma actuator for separated-flow control is mainly verified by experimental studies, there are no clear guides for operation of the DBD plasma actuator because most of these studies are conducted by trial and error approaches, and understanding the mechanism of separated-flow control is insufficient. On the other hand, some studies in recent years show that use of unsteady input voltage which is called a "duty cycle" or a "burst wave" gives higher capability of separated-flow control with less input energy. The burst wave is the unsteady alternative current switched on and off periodically. The separated-flow control by the DBD plasma actuator operated with this bust wave might have the key phenomena for separated-flow control. (In the present study, the operating condition when the DBD actuator operated with a burst wave, is called as a "bust mode" while the operating condition when the DBD actuator operated with a basic sinusoidal wave, is called as a "normal mode".)

Therefore, the objectives of this study are to clarify the mechanism of separated-flow control and to show guides for use of DBD plasma actuators, toward the practical use of DBD plasma actuators for separated-flow control. In this study, flow fields controlled by a DBD plasma actuator around NACA0015 at a low Reynolds number (Re_c = 63,000 based on chord length and free stream velocity) are analyzed with computational fluid dynamics (CFD). Large-eddy simulations (LES) using compact difference scheme are conducted to resolve small fluctuations induced by DBD plasma actuators and unsteady phenomena like flow separation and turbulent transition.

This thesis comprises seven chapters. In chapter 1, backgrounds and previous studies are introduced. In chapter 2, problem settings are described. In chapter 3, governing equations, numerical methods, and the numerical modeling of a DBD plasma actuator utilized in the present study are explained. In chapter 4, validation and verification of the numerical methods and the modeling explained in chapter 3 are described.

In chapter 5, we analyze seven cases in which the operating conditions (normal and burst modes), the locations of the actuator, and the power of DBD plasma actuators, are changed. In the first half of this chapter, the relations between aerodynamic characteristics and the effectiveness of separated-flow control with a DBD plasma actuator over the airfoil are discussed. The results show that even if lift coefficients are comparable values on two different controlled-flow fields, lift-drag ratios could be different. Thus, the appropriate criteria should be chosen for any purpose. In the second half of this chapter, first, differences between the burst mode and the normal mode cases are discussed. For the normal mode, direct momentum addition into separated boundary layer plays an important role in separated-flow control. On the other hand, for the burst mode, vortices generated by the DBD plasma actuator enhance fluid mixing, and free stream momentum is induced into the separated flow. This indirect momentum induction plays an important role for the burst mode.

Second, the burst frequency effect of the DBD plasma actuator on the control of separated flow over the airfoil is discussed. For the burst mode, non-dimensional burst frequency F^+ based on a chord length and a free stream velocity is often discussed as an important parameter when the effectiveness of burst waves is considered. In this study, F^+ is set to one and six. In the conditions of the present analysis, F^+ = 6 achieves better aerodynamic characteristics and robustness against the installed locations than F^+ = 1. This is because the dominant mechanism of the separated-flow control is different between the F^+ = 1 and F^+ = 6. The F^+ = 1 enhances the vortex shedding from the separated shear layer, and the flow field has the unsteady large separated region near the leading edge although the massive separation from the leading edge is avoided. In addition, this mechanism associated with the large fluctuation of lift. The $F^+ = 6$ suppresses the separated flow mainly by promoting the turbulent mixing.

In chapter 6, transient states in which separated flows are controlled and separated regions are gradually suppressed, are discussed. The results show the transient states consist of following three stages: 1) the large lift and drag decreasing temporally occur. 2) the peak of negative pressure near the leading edge gradually recovers. 3) the fluid mixing region moves upstream gradually, and the flow goes to the quasi-steady state. In particular, on the stage 1), the large lift and drag decreasing which are temporary observed, are caused by advections of the spanwise vortices which involve the free stream to the airfoil surface. This vortex advection plays an important role in the initial stage of separated-flow control.

Finally, in chapter 7, the results of the present analysis are concluded, and guides for the practical use of the DBD plasma actuator are proposed. the conclusions gathered from this study are as follows: There are three mechanisms of separated flow control. The first one is a direct momentum addition into the separated boundary layer (Normal mode), the second one is a spanwise vortex advection to downstream ($F^+ = 1$) and the third one is a mixing enhancement ($F^+ = 6$). At low Reynolds number like this study, the third mechanism is most preferable for separated-flow control because the robustness to the location of the DBD plasma actuators and stable aerodynamic characteristics.