모델 기반 관측기를 이용한 폐루프 박리 제어 시스템 설계

Closed-loop separation control system design using model-based observer

최병훈[1]*, 이병현[1], 김종암[1], 김현진[1]
서울대학교[1]

초 록

본 연구는 유동 박리 상에서의 synthetic jet의 효과를 파악하고 synthetic jet을 이용한 유동 박리 폐루프 제어 시스템을 설계한다. 유동 박리 폐루프 제어 시스템의 설계는 본 연구에서 제안하는 유동 모델을 이용한다. synthetic jet의 물리적 현상을 기반으로 하는 유동 모델이 유도되며, 풍동 실험 데이터를 바탕으로 유동 모델의 변수들을 추정한다. 본 연구에서는 박리의 효과적인 추정을 위한 모델 기반 관측기를 사용한다. 모델 기반 관측기를 이용한 결과로부터, 효과적인 유동 제어 시스템 설계의 가능성을 파악한다.

ABSTRACT

The objective of this research is to assess the effect of synthetic jets on flow separation and provide a feedback control strategy for flow separation using synthetic jets. A feedback control loop is crucial for the efficient operation of synthetic jets. Constructing the flow model with synthetic jet actuators is important to accomplish such feedback control. The mathematical model whose structures are based on physical knowledge of synthetic jets is derived to estimate the model coefficients from experimental data. In order to estimate the separation, this research employs an observer. The results performed with an observer, it showed the possibility of reliable flow control system design using model-based observer.

Key Words : Closed-loop Separation Control (폐루프 박리 제어), Synthetic Jet Actuator Model-based Observer (모델 기반 관측기)

1. INTRODUCTION

To date, a large number of research literatures have appeared on flow separation control of lifting surfaces using synthetic jets. Reported research includes dynamic stall control as well as static stall control. The characteristics of synthetic jets, such as actuation frequency, slot width and jet momentum coefficient, have been widely examined[1~3].

Implementation of a feedback loop is essential for flow separation control using synthetic jets. Supposing that a synthetic jet actuator is applied on an aircraft in flight, it should cope with large uncertainties associated with the flow around a wing. In addition, the available power to operate the actuator is limited during flight. Therefore, robustness and efficiency of the controller are crucial to ensure the performance of the actuator. However, results on feedback control flow separation using synthetic jets are not readily available, since it is challenging to develop a flow model to facilitate the synthesis of control algorithms that can guarantee the required performance. The difficulty in modeling is mainly due to the highly nonlinear mechanisms associated with the synthetic jets.

From a control standpoint, a synthetic jet model should be of sufficiently low order to be applicable in realistic control applications, while capturing the key dynamics of the original physical system. The approach is to employ mathematical models, such as ordinary differential equations, whose structures are based on physical knowledge of synthetic jets, and estimate the model coefficients from experimental data. This study attempts to build the reasonable linear model that captures the flow response for synthetic jets[4~6].

The outline of the paper is as follows. The experimental apparatus is described in section 2 which also includes a discussion of the synthetic jet actuators and the parameters that affect their performance. Section 3 summarizes the mathematical model for flow dynamics, while section 4 describes the feedback control algorithm and observer. Section 5 presents the simulation results, and section 6 offers conclusions and discussed future work.

2. EXPERIMENTAL SETUP & ANALYSIS

As shown in Figure 1, synthetic jet actuator is embedded in the flat plate, which has a chord length of 150 mm and a span of 200 mm. The surface pressures were measured at nine locations by a data acquisition system. Then, lift coefficients were computed from a trapezoidal-rule integral of the measured pressures. The jet exit slot is located at 5.3 % of the chord. Experiments were conducted in a low-speed wind tunnel under the free stream velocity 20 m/s.

Figure 1. Experimental setup for flow control

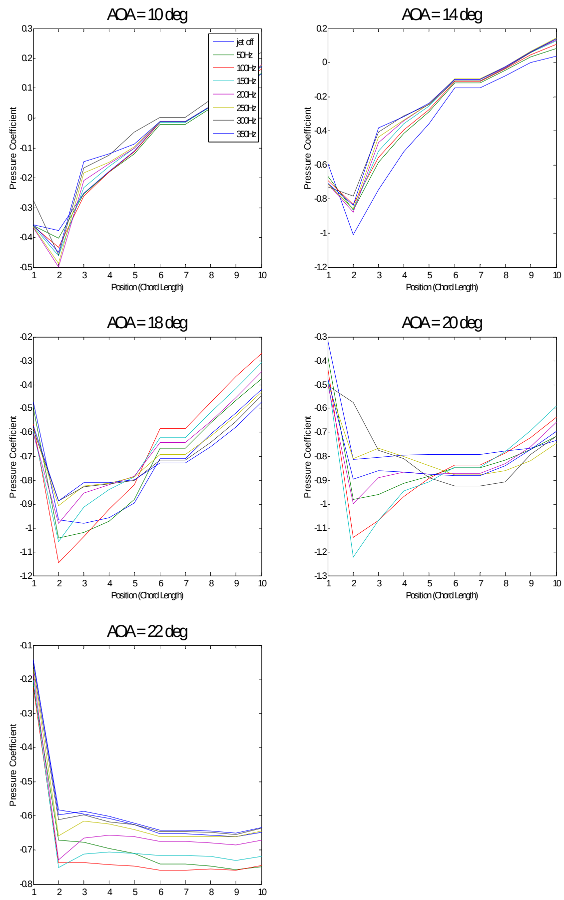

Figure 2. Measured pressure data for each AOA with synthetic jet actuator

As shown in Figure 2, the synthetic jets have little effect on the pressure profile at low angles of attack, even though the synthetic jet actuator frequency increases.

However, as the angle of attack increases higher, the synthetic jets show the reverse pressure gradient on the upper surface. In the absence of jet actuation, the reverse pressure gradient on the upper surface begins to decrease from $\alpha = 20^\circ$, and it becomes nearly flat except in a small area close to the leading edge. The flatness of the overall pressure gradient indicates the flow separation on the flat plate. With actuation, the rapid pressure recovery occurs for leading edge region and thereafter the pressure varies gradually towards the trailing edge. Consequently, the resulting lift force on the plate is improved. Figure 3 shows the fitting of the experimental data.

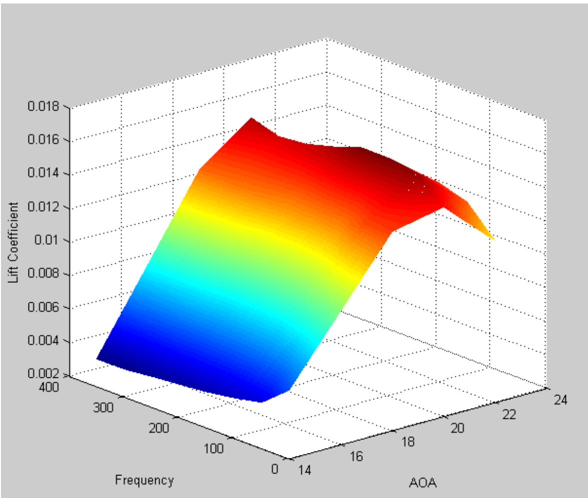

Figure 3. Fitting of Lift Coefficient

2. MATHEMATICAL MODEL

The closed-loop control system used in this research employs an observer that detects imminent separation using feedback from a single upper surface pressure sensor and a measurement of the pitch angle of the airfoil. The observer is based on a mathematical model of the unsteady aerodynamics of the wing(7).

The model can be applied to predict pressure at a specified location given the pitch time history. The total lift produced by an airfoil is closely related to the strength of the upper surface pressure field, making this interchange possible. Because the greatest changes in pressure occur in the leading edge suction peak, the pressure at the second chordwise tap from the leading edge has been determined to be the best control metric for flat plate. Hence the model will be applied to the modeling of pressure.

Although the details of the flow physics were not used to derive the model, three mechanisms involved in the flow dynamics were given consideration.

The separation dynamics consisted of a second-order relaxation to the steady separation condition :

$$\ddot{B} = K_B(B_s(\alpha) - B) - K_{\dot{B}}\dot{B}$$

where K_B is a constant, $B_s(\alpha)$ is the steady separation function, and $K_{\dot{B}}$ is the damping parameter. The second order model of separation dynamics was chosen as a means of producing the peak in both lift and suction observed when the dynamic stall vortex (DSV) is shed. By adding a proportional term to $\dot{B}$, the DSV shedding effect can be included. In order to cause the DSV to appear at only higher angles of attack, $B_s(\alpha)$ can be forced to remain zero at low angles of attack so that no separation occurs at all in that region.

The pressure dynamics are first-order and the state equation consist of two terms:

$$\dot{Z} = K_Z(Z_s(\alpha) - Z) + K_{Z/B}\ddot{B}$$

The first term, wherein K_Z is a constant parameter defining the speed of the lift dynamics and $Z_s(\alpha)$ is the steady pressure curve, produces the relaxation to the steady condition. The second term produces the bump in Z resulting from the separation dynamics. Since $\dot{Z}$, not Z, appears on the left-hand side, $\ddot{B}$ is added on the right. Although $\ddot{B}$ is not a state, it can be written in terms of the state variables as shown above. $K_{Z/B}$ is a constant relating B to Z.

3. CONTROLLER DESIGN

The decision of the controller is based on the B state variable in a model of the unsteady aerodynamics operating in real time on the control microprocessor. At each sampling time, the separation is projected ahead to the next sampling instant using the current values of B and its derivatives. If B is predicted to cross a preset threshold (B=0.5 in this case), the jets are turned on. The jets are turned off once the airfoil begins the pitch down.

Since B cannot be measured, it must be determined from other measurements. For a suitable linear model with known inputs and a measurable output, the internal states can be determined using a Luenberger observer. We assume for the present research that the angle-of-attack is known.

4. LUENBERGER OBSERVER

The observer employs a model of the system operating in parallel with the controlled system. The output of the model is computed from the model states and compared with a measured system output. The model states, which are the estimates of the system states used by the controller, are updated based on the error between the actual and model outputs. Stability properties for the Luenberger observer and constraints on the gain matrix may be found in most control system textbooks.

To implement the observer, the state equations must be written in the form :

$$\dot{X}= AX+BU, \quad Y=CX$$

where X is the state vector, U is the input, and Y is the output.

$$A=\begin{bmatrix} -K_z & -K_{Z/B}K_B & -K_{Z/B}K_{\dot{B}} \\ 0 & 0 & 1 \\ 0 & -K_B & -K_{\dot{B}} \end{bmatrix}$$

$$B=\begin{bmatrix} K_Z & K_{Z/B}K_B \\ 0 & 0 \\ 0 & K_B \end{bmatrix}$$

$$C=[1\,0\,0]$$

$$\dot{\hat{X}}= A\hat{X}+BU+L(y-\hat{y})$$

Here "^" indicated estimated values. The matrix L is a gain matrix whose values govern the convergence properties for the observer. Finally, the model output is computed :

$$\hat{y}=C\hat{x}$$

The estimates of B and $\dot{B}$ may then be used by the control decision algorithm.

5. SIMULATION RESULTS

Figure 4 compares the observer output to the measured system outputs. The observer continues to track the actual output

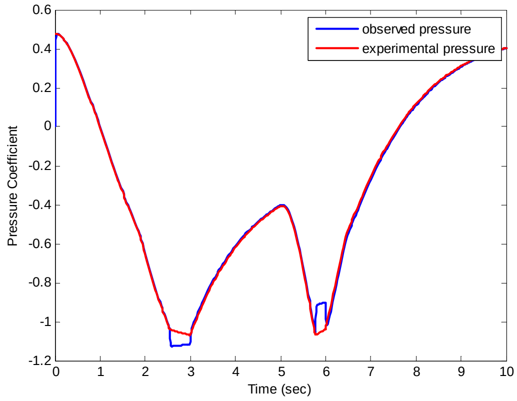

Figure 4. Comparison of measured pressure to observe estimates

Figure 5 shows the estimated separation during the simulation. The angle-of-attack is shown for reference in Figure 6.

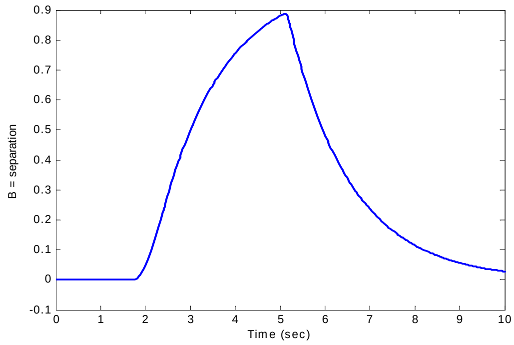

Figure 5. Estimated separation

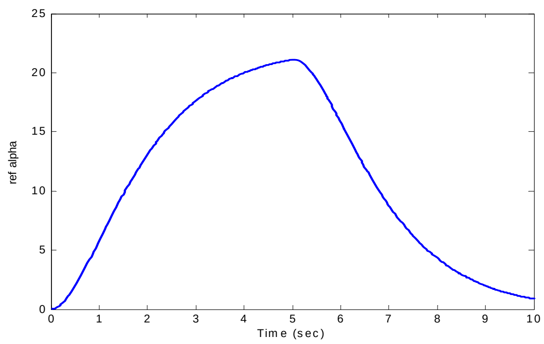

Figure 6. Angle-of-attack shown for reference

In Figure 7, the performances of the on/off controller are compared. If the observer detects the separation, the synthetic jet turns on. The result shows the enhancement of the lift coefficient.

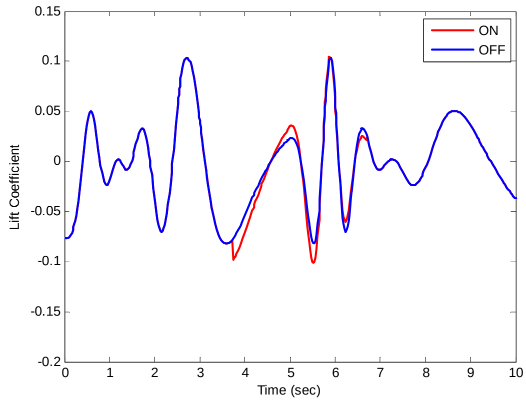

Figure 7. Lift coefficient comparison between jet on and off

6. SUMMARY AND CONCLUSIONS

This research investigated a feedback control approach for flow separation control using synthetic jets. A differential equation model was derived and a Luenberger observer based on the mathematical model detected incipient separation. The wind tunnel experiments using the synthetic jet actuator showed that synthetic jet actuation can be a good tool for flow separation control. The limitation of synthetic jets is that they have little effect on aerodynamic coefficients at low angles of attack where the flow is attached even without the jet actuation. Synthetic jets are effective only for the condition of flow separation.

후 기

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참고문헌

(1) Donovan, J., Kral. L. and Cary. A, 1998, "Active Flow Control Applied to an Airfoil," *AIAA Paper*, No. 98-0210, pp. 1~17.

(2) Greenblatt, D., Nishiri. B., Darabi. A. and Wygnaski. I, 2001, "Dynamic Stall Control by Periodic Excitation, Part2 : Mechanisms," *Journal of Aircraft*, Vol. 38, No. 3, pp. 430~438.

(3) Seifert, A. and Pack. L, 1999, "Active Control of Separated Flows on Generic Configurations at High Reynolds Numbers," *AIAA Paper*, No. 99-3403, pp. 1~19.

(4) Gallas, Q., Holman. R., Nishida. T., Carroll. B., Shelpak. M., and CAttafesta. L, 2003, "Lumped Element Modeling of Piezoelectric-Driven Synthetic Jet Actuators," *AIAA Journal,* Vol. 41, No. 2, pp. 240~247.

(5) Allan, B., Juang. J., Raney. D., Seifert. A., Pack. L., and Brown. D, 2000, "Closed-loop Separation Control Using Oscillatory Flow Excitation," *NASA Langley Research Center, Tech. Rep. NASA/CR-2000-210324*.

(6) He, Y., Cary. A. W., and Peter. D. A., 2001, "Parametric and Dynamic Modeling for Synthetic Jet Control of a Post-Stall Airfoil," *AIAA Paper, 2001-0733*, pp. 1~11.

(7) Magill, J., Bachmann. M., Rixon. G. and McManus. K, 2003, "Dynamic Stall Control Using a Model-Based Observer," *Journal of Aircraft*, Vol. 40, pp. 355~362.