Embedded System Design in Closed-loop Active Flow Control

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Abstract. Closed-loop active flow control in this paper is applied in S-shaped inlet to enhance engine intake quality for the sake of the inlet's special structure. The pressure coefficient gradient is used to reflect the degree of controlling flow reattachment on the S-shaped inlet. A transfer function is established using input/output model identification, input and output data are respectively the oscillatory excitation magnitude of the vortex generator and pressure coefficient gradient. Different control algorithms have been designed by Simulink based on the identified transfer function. By means of model based control, Simulink model could be automatically transformed to C codes, which could be directly downloaded into embedded system.

Introduction

The S-shaped inlet is significant to the stealth aircraft, but the special structure brings about some defects such as boundary layer separation, total pressure distortion, these would cause dangerous situations like engine surge, even flameout. Benefit to the closed-loop active flow control, a subject of using extra excitation stream to change the mainstream characteristics, is an effective solution to the defects[1]. This paper presents a closed-loop embedded system to precisely control the degree of the boundary layer separation. The mathematical model, as the form of transfer function G(s), being used in controller design is established under MATLAB system identification toolbox. For the identified mathematical model, different control algorithms have been designed and simulated under MATLAB/Simulink. Then model-based design, provides a solution to meet the requirement of increasing systematics development, supplies a convenient medium translates Simulink language to C code. The use of automatic code generation with proven tools makes it possible to automate code verification and move the focus of reviews from code to models[2]. The C code from translation combines with the hardware interface program could be directly downloaded to the DSP (Digital Signal Process) processor for the next embedded system's development. The complete system design procedure could be seen from Fig. 1.

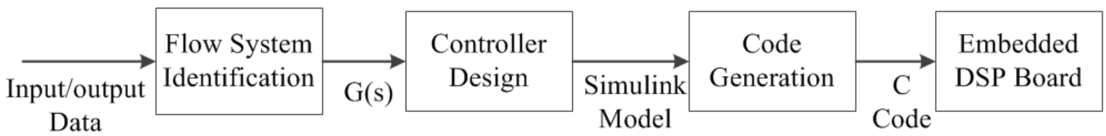


Fig. 1 The complete design procedure of the system

Model Construction

Model construction is based on the experiment data, the mach number of mainstream in the test is 0.42. The pressure coefficient gradient, a nondimensionalized pressure difference representation $\frac{d_{Cp}}{d_x}$ is measured by two dynamic pressure sensors. It can directly reflect the degree of the boundary layer separation. Two points are chose at the position from the inlet entrance of 246mm and 530mm, respectively nondimensionalization at 0.367 and 0.791. In the experiment, the frequency of vortex generator fixed to 200Hz, the variant is the oscillatory excitation magnitude P_s. Fig. 2 shows the S-shaped inlet model inferior wall pressure distributions with different excitation intensity, P_s. The P_s is set to 0Mpa, 0.5Mpa, 0.6Mpa, 0.7Mpa, the pressure coefficient gradient $\frac{d_{Cp}}{d_x}$ is correspondingly equal to 0.9581, 1.0563, 1.1238 and 1.2039. It represents a further size reduction of the boundary layer separation with the increasing excitation intensity. Therefore, from input data, oscillatory excitation magnitude of the vortex generator, to output data, pressure coefficient gradient, using MATLAB identification toolbox's Autoregressive exogenous model, a third-order system is established. The system identification data comprison is shown in Fig. 3. Apparently, there are four period during the whole time domain under different excitation intensity. The blue line represents the acquired data, and the red line is the fitting result corresponding to it. Overall, the linear model does a fair job of predicting the system. The transfer function of the inlet flow system shows in Eq.1.

$$G(s) = \frac{79.16s+24880}{s^3+47.58s^2+27880s+648300} \tag{1}$$

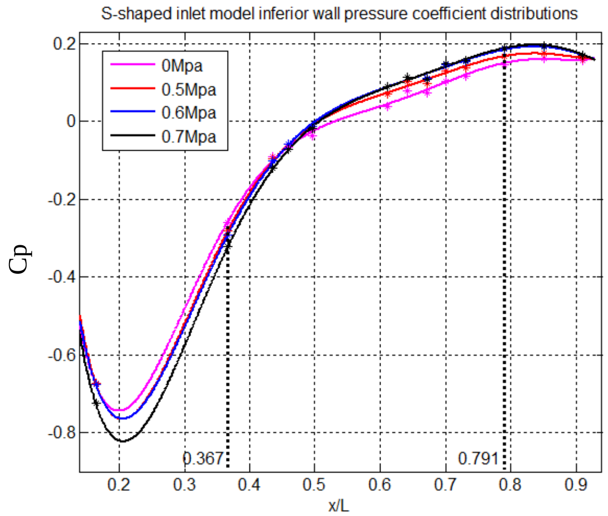


Fig. 2 The pressure coefficient distributions

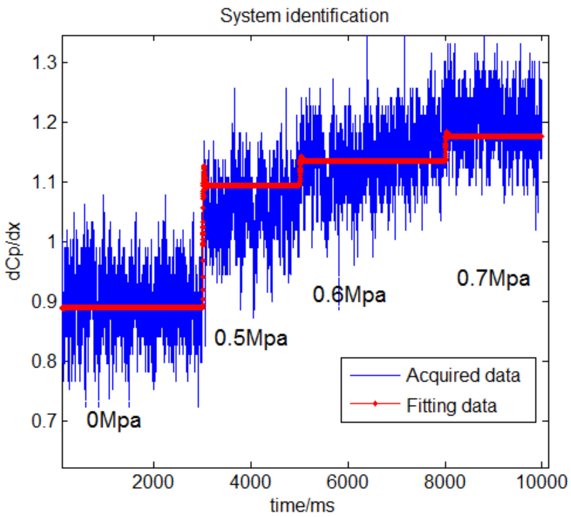


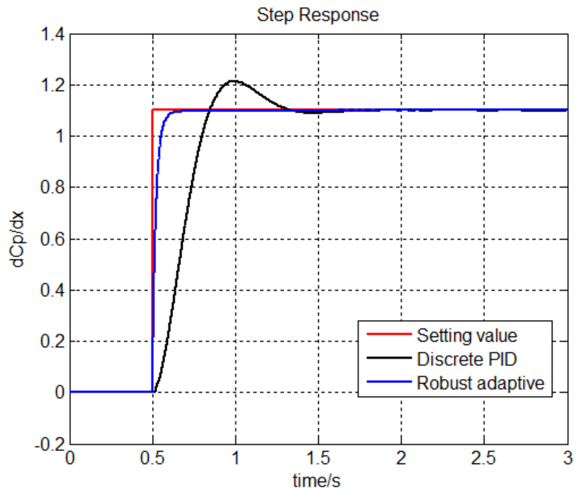
Fig. 3 The system identification data comprison

Feedback Control Design

Two different controller are designed in this control system: discret PID（Proportional -Integral-Derivative) control and robust adaptive control. PID control have been widely used in engineering, it has simple principle, high reliability and strong versatility, but the regulating of Kp, Ki and Kd is time consuming, once the model is changed, the controller parameters will no longer be valid. Robust adaptive controll can regulate itsself along with the state change, specifically against modeling parameter perturbation and external disturbance.

The objective of the control system is to get a desired flow control effect, which is reflected by $\frac{d_{Cp}}{d_x}$, and the controller's characteristic, namely stability, speed and accuracy must be satisfactory. In this paper, we set the designed value of $\frac{d_{Cp}}{d_x}$ to be 1.1, which is in the expected control effect scope. Based on the basic requirement of controller, we built the two control models above in

Simulink environment and get the step response results of two controllers. Fig. 4 and Fig. 5 show the step response of the closed-loop system and traking error under two controllers.



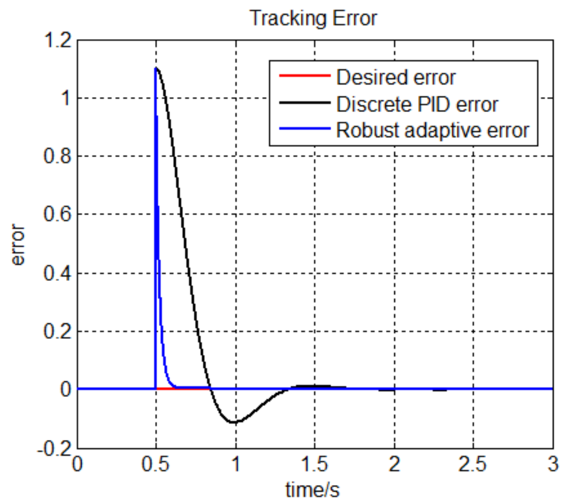


Fig. 4 Step response of two controllers   Fig. 5 Traking error of two controllers

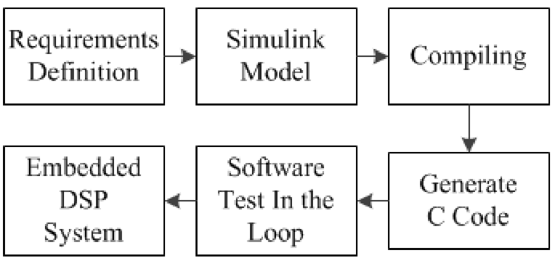
From the figure above we can see, two control algorithms both can track the desired objective, their steady performance are similarly well, steady error can be restricted in a slight scope. However, when compared the dynamic performance, it could be easily found that the discret PID control has a overshoot about 9%, which may cause dangerous problems, even so, it takes longer rise time and more than one second enter the steady state. By comparison, the robust adaptive control rises much faster and more smoothly than discrete PID control. Therefore, the robust controller performs a better transient response.

Code Generation and SIL

There are several steps in the development of embedded system software: requirements definition, function design, code and test. Generally, test, find and resolve vulnerabilities spend a lot of energy and enormous cost. Using the model based design, we can guarantee the correctness of the model in the early stage of design, avoid unnecessary waste of resources, especially when designing complex systems. Fig.6 shows the flow chart of model-based design.

The model has been built under the Simulink environment in the previous steps. Simulink verification & validation toolbox could help examine modeling standardization to make sure the requirment satification. After being approved by the embedded coder toolbox, the model is able to be generated C codes. Fig.7 shows the generated codes from Simulink model.

Software in the loop test (SIL) is in the model environment, a non-real-time co-simulation to the code which is automatically generated code or handwritten code to assess the merits of these codes, complete early validation of the generated code. Compiling SIL module for be tested subsystems, compare the output between original module and SIL module, in order to confirm the correctness of the algorithm.



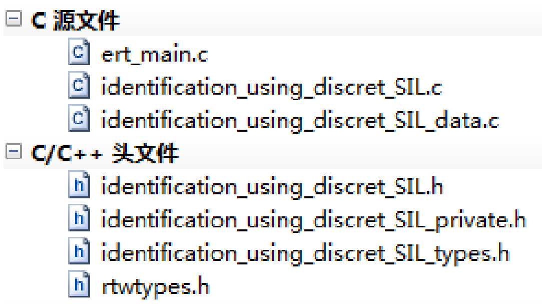


Fig. 6 Flow chart of model-based design   Fig. 7 Generated codes

Discrete PID algorithm model was chosen to generat C codes. In oder to certificate the correctness of the generated codes, we used software in the loop test. Fig. 8 compares the result between the two outputs, from the picture, the generated C codes realized control purpose, and its effect is very same as the Simulink model. The absolute error, showing in Fig. 9, is small enough to be accepted, so the codes are reliable. Combine with the hardware interface program, it can be downloaded into the DSP embedded system for the actual application.

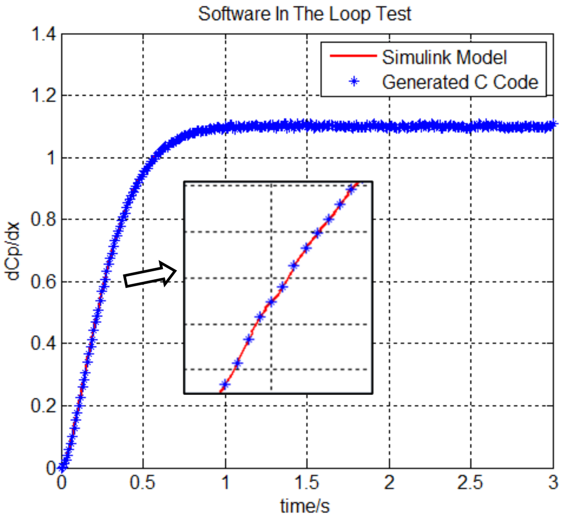


Fig. 8 Software in the loop test

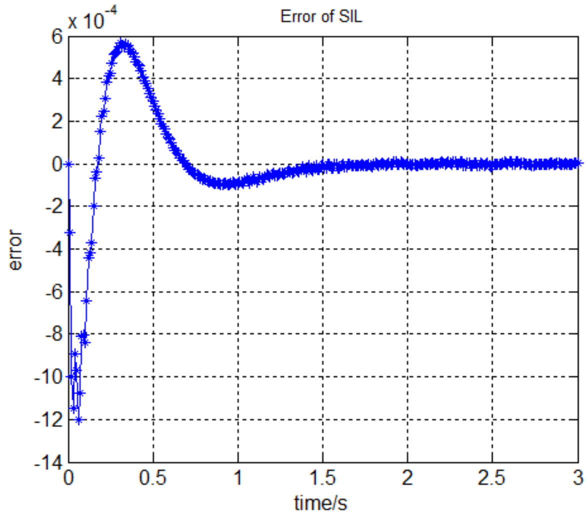


Fig. 9 The error of SIL

Conclusions

In this paper, a design of closed-loop active flow control embedded system for a S-shaped inlet is presented. A transfer function, which reflected the transfer relationship between the degree of flow separation and the magnitude of the oscillatory excitation, is obtained from the experiment input/output data. The transfer function could be used in the control algorithm design. Two different control algorithms, discrete PID control and robust adaptive control, are applied in the system, and both got the expected result with good performance, by comparison the robust adaptive control enjoys a better effect. Moreover, rather than hand-written codes, C codes are generated automatically, which, saves a lot of time and expenditure. It is Important in embedded designs and will be widely applicated in the engineering field.

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