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The optimization for the backward-facing step flow control with synthetic jet based on experiment

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ABSTRACT

Active flow control, which has great application prospects in aerodynamic design, can restrain flow separation and reduce drag. In this paper, a newly developed synthetic jet device with non-linear oscillation of the reciprocating piston actuator into the pipe is introduced and applied to control flow field of backward-facing step. An in-looped design optimization system based on experimental data adopting hybrid searching algorithm is constructed and applied to optimize parameters of this synthetic jet device. The optimum state based on experiment restrains separation dramatically, which validates the efficiency of the design optimization strategy and the excellent performance of synthetic jet device. The optimum jet slot angle is 127.5° and the optimum frequency is 35 Hz. Then, power consumed in driving reciprocator is considered to derive a multi-objective optimum scheme. With theoretical analysis and experimental data of velocity profiles and Reynolds stress distributions, flow control mechanism of synthetic jet device is preliminarily revealed. The optimization process and the analysis of optimum state provide guidance to the design of active flow control devices.

1. Introduction

Though traditional aerodynamic design tends to avoid separation on aircraft surface, separated flows still commonly occur in engineering practices. Rear separation of cargo-transport aircraft and detached flow of landing/takeoff configurations are typical examples of separated flows. Separation leads to dramatic increase in drag and changes in moment. The complex flow structures of separation induce non-linear variation of aerodynamic forces, which has negative effects on maneuverability and stability of the aircraft. Thus, it is of engineering significance to take measures to restrain flow separation. In the aspect of modern aircraft design, passive flow control devices (vortex generator for instance) can weaken separation at the designation state while leading to massive separation and additional drag at the non-designed states. Active flow control technique introduces inputs which corresponding to instability of separated flow and obtains distinct effects with less energy consumption, thus restrains flow separation in broader flight envelope with acceptable of energy input. On the other hand, by controlling the effective aerodynamic shape of an aircraft using active flow control technique, like synthetic jets, a fighter can maneuver without deflecting a control surface, thus retaining its minimum radar cross section (RCS), as revealed by Donovan et al. [1].

Backward-facing step flow is a typical kind of separated flow, representing the flow around a blunt body with sudden expansion of cross-section. Shear layer structure is observed between the free stream and the main vortex, with generation of complex vortices and pressure loss. The length of recirculation zone and the wall shear stress are important parameters for analysis of the flow field. The baseline flow of backward-facing step is a generic example for understanding separated internal flow. Sagaut [2] provides general features of flow field of backward-facing step. The boundary layer which develops upstream of the step separates at the step corner, becoming a free shear layer. Shear layer expands in the recirculation region, thereby entraining turbulent fluid volumes. This entrainment phenomenon influences the development of the shear layer, which curves inward toward the wall in the reattachment region and impacts on it. After the reattachment, the boundary layer re-develops while relaxing toward a profile in equilibrium. Eaton and Johnston [3] provided a comprehensive review of the experimental investigation on the time-averaged characteristics of the flow field. Extensive experimental efforts on flow field structure have been conducted by Troutt et al. [4], Driver et al. [5], Heenan and Morrison [6], Scarano et al. [7] and Lee and Sung [8], among others. Armaly et al. [9] reported the influence of Reynolds number on separation length and structure of flow regimes and

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revealed inability to predict the flow field over relatively high Reynolds numbers.

Jet flow, having complex spatial and temporal characteristics, has been widely applied in areas of active flow control, for instance separation control over finite wing by Amitay and Jansen [10], and throat shifting technique by Anders et al. [11]. Considering flow dynamics and spatial evolution, pulse jet is entirely different from continuous jet even with the same aperture and momentum flux, as revealed experimentally by Smith and Swift [12]. Synthetic jet (zero mass jet) works similarly to pulse jet, but its working medium is the fluid of external flow field and its momentum transportation is conducted with zero net mass flux, as reported by Smith and Glezer [13]. Interaction with the external flow field by synthetic jet can distort the local streamlines, resulting in changes of the wall boundary shape, and affecting structure of the flow field with length scales one to two orders of magnitude higher than the characteristic length scale of synthetic jet, according to investigation by Glezer and Amitay [14]. Jet formation, or rather the appearance of a time-averaged outward velocity excited by the generation and subsequent convection or escape of a vortex ring is experimentally investigated and revealed by Holman et al. [15]. It should be highlighted that Ming [16] independently discovered the zero mass jet and clarified the formation mechanism as rectifying effect in later researches [17]. Based on types of vibration source of the actuator [18], synthetic jet can be categorized into piezoelectric diaphragm excitation [19–21], piston vibration excitation [22], acoustic excitation [23], memory alloy excitation [24], and so on. Currently, flow control mechanism of synthetic jet driven by piston vibration remains unsolved and needs further investigation, as compared to mechanism of spanwise instability and interaction of successive vortex pairs of other synthetic jet devices [13].

Separation control cases of backward-facing step using synthetic jet with various parameters are extensively reported, both adopting experiment by Marrot et al. [25], Abu-Mulaweh et al. [26] and applying numerical simulations by Okada et al. [27], Kanchi et al. [28] and Jain et al. [29], among others. Researches on separated flow control of backward-facing step mainly focus on experimental works or sophisticated numerical simulations separately. However, since angle, velocity and frequency are coupled due to inherent nonlinear characteristics of synthetic jet, selection of the optimum control parameters is often tough and time-consuming. Design of wind tunnel experiments generally uses orthogonal design method, as experimentally applied by Guan et al. [30] and theoretically analyzed by Dong et al. [31], and optimization method is less adopted. To date, literature considering synthetic jet flow control of backward-facing step in the experimental aspect utilizing optimization method is not yet available. In this paper, hybrid particle swarm pattern search algorithm based on in-looped update surrogate model is developed to address this issue. Due to the fast convergence and accurate prediction characteristics of this algorithm, design optimization and experimental work can be effectively combined. This paper introduces the newly developed synthetic jet apparatus and measuring techniques, and describes design optimization system based on in-looped update surrogate model. A multi-objective optimum scheme is derived considering power consumption in driving reciprocator. Further theoretical and experimental analysis of the optimum state preliminarily reveals flow control mechanism of synthetic jet and provides guidance to the design of active flow control devices with the utilization of synthetic jet.

2. Experiment system

2.1. Experimental apparatus

This experiment was conducted in the subsonic suction wind tunnel of Nanjing University of Aeronautics and Astronautics. Parameters of the wind tunnel are: 1998 mm from entrance to test section, 2035 mm from test section to the exit. Cross section of test section is 500 mm(H) $\times$ 300 mm(W). The height of backward-facing step is 30 mm with expansion ratio of 1.06. Aluminum honeycombs at wind tunnel entrance reduce the intensity of free-stream turbulence, and nominal turbulence intensity of test section is approximately 0.3%. The newly developed synthetic jet actuator was designed by Professor Ming of Nanjing University of Aeronautics and Astronautics. The reciprocator section is composed of controller, servo motor and cylinder, as shown in Fig. 1. Controller is responsible for controlling the servo motor via digital signal and then driving the reciprocating piston actuator in the cylinder. Piston actuator cycles up and down in the cylinder with the amplitude of 25 mm, causing velocity variation and pressure fluctuation at the bottom of the pipe. Configuration of the synthetic jet slot and connecting section is shown in Fig. 2. Jet flow is transmitted to the wind tunnel test section by a long inflected pipe connecting reciprocator and jet slot. Synthetic jet is ejected and sucked through a jet slot of 200 mm width and the operating frequency is between 0 Hz and 35 Hz. The distance from centerline of the vertical jet slot to the step is 3.5 mm, as is indicated in Fig. 2. Considering the non-linear oscillation of the reciprocating piston actuator and the long pipe, expansion and convergence of pressure waves play a significant role in this new synthetic jet device. This new synthetic jet differs dramatically from common ones with excellent control effects, which will be certified in the following wind tunnel testing.

Wall shear stress (skin friction), velocity profile and Reynolds stress were measured. Wall shear stress was collected by measuring the static pressure difference across a small fence mounted within the viscous sublayer, first introduced as classical sublayer (Stanton) fence by Konstantinov and Dragnysh [32], and then further developed by von Papen et al. [33], Schiffer et al. [34] and Savelsberg et al. [35]. Arrangements of the sublayer fences and silk threads are shown in Fig. 3. Silk threads, with their middle sections stuck on the wall, visually indicated length of the recirculation zone and stability characteristic of the reattachment point. Sublayer fences, as shown in Fig. 4, were connected to high-resolution pressure transmitter to obtain mean static pressure difference and corresponding wall shear stress. The accuracy of sublayer fences was first calibrated by channel flow with altering height and constant pressure drop to achieve conversion factors between pressure difference and corresponding wall shear stress. The conversion factor between wall shear stress and skin friction coefficient is 4.165×10^{-3}/pa. Time series of velocity were measured by constant temperature hot-wire anemometer *TSI IFA-300* with sampling frequency of 10 kHz. Instantaneous velocities were then decomposed into time-averaged and fluctuating components and Reynolds stress was calculated by multiplying fluctuating ones.

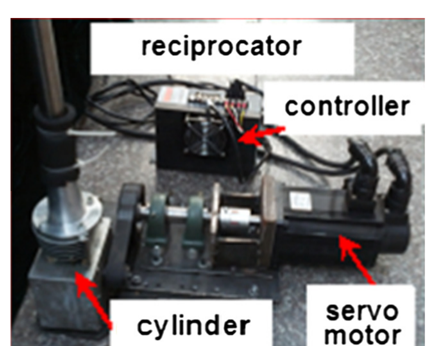

Fig. 1. Newly developed synthetic jet actuator (reciprocator section).