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Unsteady shear layer flow under excited local body-force for flow-separation control in downstream of a two-dimensional hump

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ABSTRACT

We present a detailed numerical investigation of unsteady shear layer dynamics in downstream under an excited local body force, based on the assumption that a plasma actuator is positioned near the top of a two-dimensional hump for flow-separation control. A local body force works in temporal burst mode, which is homogeneous in the spanwise direction. In our previous report (Yakeno et al., 2015), the most effective frequency to cause early reattachment is $f_h = 0.2$, which corresponds to what Hasan (1992) and many other past studies referred to as the step mode. A periodic excitation generates two-dimensional roll vortices and other three-dimensional turbulence between downstream rolls, such as rib structures. These vortex characteristics significantly depend on the excitation frequency. In the study, we discuss these multi-scale turbulence motion separately by considering decomposition of temporal phase-locked periodic statistics of the excitation frequency and non-periodic turbulence fluctuation. At first, we found that non-periodic turbulence kinetic energy due to three-dimensional rib structure increases the most at the optimal frequency $f_h = 0.2$, although that frequency corresponds to the time scale that a hump-height vortex grows. It seems that non-periodic turbulence energy growth near separation point correlates with the control performance more than two-dimensional roll vortex increase. We operated linear hydrodynamic stability analysis on a free shear layer and confirmed that periodic phase fluctuation at high frequency grew on the Kelvin-Helmholtz instability. At low-frequency, periodic turbulence fluctuation is not reproduced with the exponential assumption, while its magnitude is large. From those results, we consider that the time and spanwise-averaged non-periodic turbulence energy becomes strong near the separation point the most at $f_h = 0.2$ because a hump-height vortex occurs the most times at this frequency, which is associated with a generation of the rib structure around it. Temporal-periodic momentum balance based on the decomposition is also investigated. A difference of terms contribution at high and low frequencies to the term of a pressure gradient in the wall-normal direction is discussed. Finally, we investigated how excitation position affects a total drag around a hump and found that, in some cases, two recirculation regions separately emerge in the downstream of the hump, and thus the control performance is degraded. At $f_h = 0.2$, one recirculation occurs regardless of the excitation position, while the most effective position is near the inflection point of the mean velocity of the uncontrolled flow near the wall.

1. Introduction

Over the past decades, flow separation around fluidic machines has attracted significant attention (Gad-el Hak and Bushnell, 1991; Greenblatt and Wygnanski, 2000). Some control technologies involving periodic operation in time or space were found to be effective to reduce separation region in the downstream. Underlying flow physics and the mechanism of these controls have been discussed for years. However, the relationship between the frequency of the periodic controls and the hydrodynamic instability was not clarified sufficiently. Such flow dynamics are sensitive. Performance of the periodic controls depends on many factors such as the Reynolds number, geometry, and even on the upstream turbulence intensity, that makes any investigation complicated.

Hasan (1992) experimentally investigated flow over a backward-facing step with laminar flow separation. By introducing flow

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perturbation through a narrow slit at the separation point, they identified two distinct modes of transition routes at $Re_h = 11,000$: (i) the shear layer mode of the Kelvin-Helmholtz instability at $f_\theta \approx 0.012$ ($f_\theta \equiv f^*\theta^*/u^*_\infty$), where θ^* is the momentum thickness at the separation, and (ii) the step mode of instability at $f_h \approx 0.18$ ($f_h \equiv f^*h^*/u^*_\infty$), where h^* is the step height. Such periodic control reduces the flow-separation region at these distinct frequencies. Some studies mentioned the effective frequency in the other words. Chun and Sung (1996, 1998) also made an experimental study of the separated flow over a backward-facing step, where a periodic oscillating jet is induced from a thin slit near the separation position. They said that the most effective frequency to minimize the flow-separation region was comparable to the shedding frequency of the free shear layer $f_\theta \approx 0.01$ at $Re_h = 13,000$–$33,000$ in a wind tunnel. However, they found $f_h \approx 0.477$ to be most effective at $Re_h = 1200$ in a water channel and showed a visualization of detailed evolution of initial rolled-up vortex. They summarized attempts of such periodic forcing methods in the past and their effective frequencies in a table. It said that the effective frequencies were spanning from $f_h \approx 0.06$–0.35 for backward-facing step flow. Sigurdson (1995) and Kiya et al. (1997) also invoked the shedding-mode instability for flow over a square-shaped leading edge, which was similar to periodic vortex shedding from two-dimensional bluff bodies. To reduce pressure drag, the most effective actuation frequency when the actuator is implemented to the front side of a cylinder is two to five times larger than the shedding frequency, $f_h = 0.16$ to 0.40. Saric et al. (2005) numerically investigated such a perturbed backward-facing step flow by alternative blowing and suction through a thin slit that was installed at the step edge in $Re_h = 3700$, which was studied experimentally by Yoshioka et al. (2001). They compared three perturbation frequency cases and confirmed $f_h = 0.19$ was the most effective with minimum reattachment length. Dandois et al. (2007) summarized effective frequencies in a table too, and they reported their numerical study of the synthetic jet effect on the flow by using LES. They considered two different effective frequencies, $f_h = 0.14$ and $f_h = 1.1$. Two-dimensional roll vortex was observed in detail to explain the mechanism to reduce separation length at these frequencies. A linear inviscid stability analysis of high-frequency control case was operated to discuss the effect of an amplitude of forcing. Dejoan and Leschziner (2004), Leschziner and Lardeau (2011) and Okada et al. (2012) also simulated flow over a backward-facing step to analyze the effect of actuation frequency. With regard to the downstream flow dynamics, Greenblatt et al. (2005) applied triple-decomposition to the fluctuating velocity and pressure fields for analyzing the experimental data and showed two-dimensional profiles of phase-averaged turbulence statistics in downstream.

Recently, a dielectric-barrier-discharge (DBD) plasma actuator (Moreau, 2007; Corke et al., 2010) has attracted attention as a flow-control device. It works like a local body force to directly induce flow momentum. A plasma actuator is based on a simple concept and has a quick response, which allows it to be operated flexibly according to the flow status. Several methods of using an actuator have been suggested. One of the most successful ways is for the flow-separation control. Numerous studies have investigated around an aerofoil and a general geometry, experimentally and numerically (Post and Corke, 2003; 2004; Visbal et al., 2006; Gaitonde et al., 2006; Visbal, 2010; Rizzetta and Visbal, 2011; Corke et al., 2011; Riherd and Roy, 2013; Vernet et al., 2017). From past findings, the suitable operation condition depends on many factors of the flow, and an overall knowledge is needed. Sato et al. (2015a) simulated over 200 cases of large-eddy laminar-separated flow around a NACA0015 aerofoil by using a plasma actuator at the Reynolds number of 63,000, which was based on the chord length. Their study considered the plasma-actuator position and operating conditions, such as actuator frequency and angle of attack of the aerofoil. They found several effective frequencies to improve the aerofoil performance, with which the lift coefficient, drag coefficient, and their ratio were improved the best. They also discussed the interaction of vortices generated by a flow-separation control in the work of Sato et al. (2015b). These vortices collapse and are merged to form vortex pairs in downstream. Further analysis is necessary to find out how the optimal frequency is determined for general geometries, by removing the effect of angle of attack and the shape of the wall surface and find out how the optimal frequency is determined.

In our previous report (Yakeno et al., 2015), we investigated how the frequency of a local body-force of a plasma actuator positioned near the top of a two-dimensional hump affects downstream flow reattachment. Out of all cases tested, the most effective frequency was $f_h = 0.2$, which corresponds to what Hasan (1992) and other studies referred to as the step mode. The conclusion we obtained from the turbulence terms in momentum equations (Yakeno et al., 2015) was consistent with the fact. In the present study, based on well-resolved numerical simulations, we discuss in greater detail how the frequency of a plasma actuator affects flow around a two-dimensional hump. We apply phase-averaged decomposition to the variables and use periodic and non-periodic fluctuation statistics to analyze the unsteady motion of the controlled flow. The turbulence kinetic energy is decomposed into two parts: the former periodic component is compared with the result of two-dimensional instability analysis on a free shear layer flow, and the latter non-periodic turbulence component is also analyzed. Both components increase downstream and modulate the phase-averaged momentum balance to lead early flow reattachment. These characteristics at high and low frequencies are discussed. Finally, we also mention the effect of the excitation position.

2. Problem settings

2.1. Geometry

We consider the flow around a two-dimensional hump geometry mounted on a flat plate. That is in order to analyze the effect of an excitation control more generally, which was mentioned in some papers around thick airfoil geometries. A local body-force excitation is positioned near the top of a hump, that is assumed as a plasma actuation. The present environment is the same as that used in the previous work of Yakeno et al. (2015). The hump geometry, $z_{wall}(=z^*_{wall}/h^*)$, is defined by using the Bessel function as

$$z_{wall} = \begin{cases} -\dfrac{1}{6.04944}\left\{J_0(A)I_0\left(-A\dfrac{x}{a_1}\right) \right. & (-a_1 < x < 0) \\ \left. \quad - I_0(A)J_0\left(-A\dfrac{x}{a_1}\right)\right\} & \\ -\dfrac{1}{6.04944}\left\{J_0(A)I_0\left(A\dfrac{x}{a_2}\right)\right. & (0 < x < a_2), \\ \left. \quad - I_0(A)J_0\left(A\dfrac{x}{a_2}\right)\right\} & \end{cases} \tag{1}$$

where J_0 and I_0 are the zeroth-order Bessel and modified Bessel functions of the first kind with $A = 3.1926$. The upstream diameter is $a_1 = 8.0$ ($x < 0.0$) and the downstream diameter is $a_2 = 4.0$ ($0.0 < x$). The geometry is shown in Fig. 1. All lengths are non-dimensionalized by the hump height, h^*.

2.2. Governing equation

We use well-resolved large eddy simulation (LES) without any subgrid model to investigate the downstream flow characteristics. The governing equations are the three-dimensional, compressible Navier–Stokes equations with the local body-force components S_i in the direction i of a plasma actuator.