Closed-loop Control of Laminar Separation Bubbles

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Abstract

Laminar separation bubbles induced by adverse pressure gradients generate in many engineering applications severe losses caused by premature laminar-turbulent transition, pressure drag increase and flow unsteadiness. The mitigation of laminar separation bubbles by flow control remains a highly promising approach. Non-adaptive control, for example by vortex generators, has been used for decades to delay flow separation. Recently Pastoor et al. (2008), Parezanvić et al. (2015) among others, showed the superiority of closed-loop control for drag reduction and increase of mixing. In particular such control systems can adapt to changing flow conditions and external perturbations thus improving the robustness of control. The goal of this study is to apply such closed-loop control to laminar separation bubbles in order to analyse the complex bubble dynamics composed of an intriguing interaction between the Kelvin-Helmholtz instability of the separated shear layer and the flapping motion of the recirculation zone.

Due to real-time constraints most closed-loop systems employ local sensor based feedback with restricted information on the actual flow state. In this study we propose a new global sensor technique based on Lagrangian tracers obtained with the help of the controlled release of hydrogen bubbles in combination with real-time image processing. The experiments are carried out in a low-speed water tunnel with a smooth ramp configuration to generate canonical separation conditions. A vertically movable wire of 0.13 mm thickness (Kaiser et al. 2013) spans over the whole test section upstream of flow separation. This wire works as actuator which is operated by the controller. The actual flow state is evaluated by instantaneous pictures of the tracer distribution. These pictures are analysed by SVD (Singular Value Decomposition) and the corresponding Eigenvalues are supplied to the controller. In this way the actual spatio-temporal scales inside the flow are permanently compared to the control objective function, which targets to minimize the separated flow region. We found that closed-loop control with SVD produces, like the best open-loop reference control, quasi-periodic actuation around the natural frequency of the Kelvin-Helmholtz instability. Similar optimal closed-loop control by quasi-periodic excitation has been found recently for mixing layers and wake flows (Parezanvić et al. 2016). While the separated flow region can be reduced up to 60 %, the increase of pressure recovery remains restricted to several per cent. Flow visualisations strongly point to a predicament: while regularly spaced vortices avoid flow separation, they also limit the pressure recovery.

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