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Vortex Buffeting of Aircraft Tail: Interpretation via Proper Orthogonal Decomposition

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The proper-orthogonal-decomposition method is applied to particle-image-velocimetry (PIV) data to extract the most energetic flow structures of vortex-tail interaction. The reconstructed flowfields, in conjunction with patterns of vorticity and streamline topology, are compared with the original PIV data on a crossflow plane. The reconstructed flowfields using 5 and 10 eigenfunctions can predict the largest-scale features of the original flowfield. However, the smaller-scale flow structures, which are evident in the original PIV image, are lost. In other words, the flow features of smaller scale can be filtered out by employing the first few eigenmodes. By employing 40 eigenmodes, the reconstructed flowfield can reproduce most of the smaller-scale flow structures of the original flowfield. In terms of the kinetic energy of the fluctuations, about 80% of the total flow energy can be accounted for using 40 eigenmodes.

I. Introduction

THE interaction of a broken-down vortex with various types of physical configurations is generally recognized as a major source of the unsteady loading. Of particular interest for buffet loading of an aerodynamic surface is characterization of the frequency and amplitude of velocity and pressure fluctuations. Gursul and Xie[1] provided representations of the dimensionless frequency of vortex breakdown on delta wings. Detailed consideration of the power spectra of velocity fluctuations within the region of vortex breakdown has been assessed by Garg and Liebovich[2] and Gursul and Yang.[3] Moreover, Gursul and Yang[3] investigated the local pressure fluctuations at specified locations on a delta wing. The classification of pressure fluctuations in terms of dimensionless frequencies, which represent various features of the unsteady flow including vortex breakdown, was provided by Menke et al.[4] The helical mode of instability of vortex breakdown was viewed to play an important role in determining the unsteady surface loading. The unsteady features of this mode were described by Garg and Leibovich[2] and Gursul.[5] Reviews and assessments of the flow phenomena of the vortex breakdown include those of Sarpkaya,[6–8] Escudier,[9] Brown and Lopez,[10] and Delery.[11]

As reviewed by Rockwell,[12] a number of investigations have assessed the unsteady loading of an aircraft tail as a result of incident unsteadiness, typically arising from vortex breakdown. Representative investigations include those of Triplett,[13] Brown et al.,[14] and Komerath et al.,[15,16] Lee et al.[17] observed the vortical flow above an F/A-18 aircraft. In addition, results for a model F/A-18 with forebody and leading-edge extension configurations in water tunnel were found to be in accord with the wind tunnel and flight tests.[18] It is expected, however, that the detailed structure of the vortical flowfield after burst, or vortex breakdown, will generally be a function of both Reynolds number and Mach number. As a consequence, certain details of the flow structure characterized herein can be altered as one approaches values of parameters characteristic of full scale. The eventual objectives of any of the foregoing types of investigation are to gain an insight into the physical phenomena of the unsteady flowfield, in relation to the vortex breakdown and the corresponding loading induced at the aerodynamic surfaces. Numerical investigations of the unsteady loading on tail/fin include those of Kandil et al.,[19] Gordnier and Visbal,[20] and Kandil and Sheta.[21] Recent development of quantitative imaging techniques has provided instantaneous global patterns of the flow to allow rational interpretations of the unsteady loading caused by the vortex-plate and the vortex-tail configurations.[22] These approaches, which are based on a laser-scanning version of high-image-density particle image velocimetry (PIV), are addressed by Adrian,[23] Rockwell et al.,[24] and Westerweel.[25] More recently, Rockwell[26] assessed case studies of vortex-dominated flows using the technique of PIV.

II. Experimental System and Techniques

Experiments were conducted in a large-scale free-surface water channel having a cross section 927 mm wide, 610 mm high, and approximately 5000 mm long. It is located in the Fluid Mechanics Laboratory of Lehigh University. This recirculating water channel was constructed of optically transparent Plexiglas® with water reservoirs at the inlet and outlet ends. In this study, the flow velocity was maintained at 152 mm/s at a water depth of 559 mm. The corresponding Reynolds number based on the chord length of the delta wing was $Re_c = 5.2 \times 10^4$.

The plan and side views of the delta-wing-tail system are shown in Fig. 1. The laser sheet orientation is indicated. The tail is aligned with, or parallel to, the axis of the leading-edge vortex. The sweep angle of the wing is $\Lambda = 75$ deg, and the effective sweep angle of the leading-edge vortex is $\lambda_L = 79$ deg. The chord length of the wing is $C = 342$ mm. Moreover, the distance between the trailing edge of the wing and the leading edge of tail is $L_T = 5$ mm or $0.0146C$, and the angle of attack of the delta wing is $\alpha = 21$ deg for the experiment. The distance between the leading edge of the tail, at the root of the tail/delta-wing junction, and the plane of the laser sheet is indicated by $X_L = 0.965C_T$, where C_T (=105 mm) denotes the root chord length of the tail. Figure 2 shows the dimensions of the rigid tail. The tail had a root chord length of $C_T = 105$ mm, and the ratio of its thickness-to-chord ratio was $t_T/C_T = 0.12$. The span of the swept leading-edge of the tail was $S_T = 136$ mm. The length of the support

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