Technical Notes

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Propulsive Vortical Signature of Plunging and Pitching Airfoils

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Introduction

VISUALIZATIONS of flows relevant to the unsteady propulsive systems of birds, insects, and fishes are rare and inconclusive. The wings of traveling birds and insects execute complex motions whose most obvious component is flapping, while for a fishtail it is pitching. While animal propulsion is complex,[1] some understanding may be gained by considering simplified systems of unsteady propulsion. The aim of this note is to elucidate the propulsive vortical signature of two-dimensional airfoils in pure periodic plunging and pitching motions.

Once the basic propulsive signature has been found, gradual buildup of complexity, which includes combined pitching and plunging motions and three-dimensional effects, can be pursued later in a more rational manner.

An explanation of what constitutes a propulsive vortical signature seems in order. As for any fluid dynamic propulsive system, generation of a jet-like flow in the downstream direction is required by the momentum theorem. Vortex streets with a placement of the vortices so that they induce on each other a downstream motion (Biot-Savart law) would provide the requisite propulsive signature. This principle is best illustrated by examples in which signatures of drag and thrust are contrasted to each other. The top of Fig. 1 shows the well-known Kármán vortex street generated behind a circular cylinder immersed in a steady flow at Reynolds number $Re = 120$ and visualized by a smoke tracer. Flow is from left to right. Clearly, the top row of vortices rotate clockwise and the bottom row counterclockwise, thus inducing on each other a velocity component in the upstream direction. Therefore, this vortex street is indicative of the drag associated with the cylinder wake. In contrast, the bottom of Fig. 1 shows the vortex street generated behind the trailing edge of a periodically pitching airfoil, immersed into the same flow. Clearly, the sense of rotation of the vortices is reversed compared to Fig. 1 top, i.e., the two rows of vortices induce on each other a downstream, jet-like velocity component indicative of propulsive thrust. Some hints of such propulsive signatures can already be gleaned from previous work,[2,3] but entire time sequences are shown in this Note for the first time.

Classical theories, as reviewed by Bublitz,[4] also support the notion of thrust generation by plunging and pitching airfoils. These theories are linear and inviscid, and therefore, their connections to the large-amplitude, low-Reynolds number configurations envisioned by us seem tenuous.

Apparatus and Procedures

Plunging and pitching was done in a horizontal wind tunnel with a 91-by-91-cm test section of 2-m length. Airfoils had a NACA 0015 profile. Periodic plunging and pitching was done manually by an appropriate plunge or pitch mechanism from outside the tunnel, and the airfoil profile was observed in side view. At the midspan of the airfoil, a narrow strip of liquid titanium tetrachloride ($TiCl_4$) was deposited from the leading to the trailing edge. The fumes given off by this liquid tagged the vorticity in the boundary layer and made separation and vortex development visible.[5] The vortex development was photographed with a Bolex 16-mm movie camera at a rate of 64 frames/s. For best photographic results, the tunnel was kept at a low speed, $U_o = 61$ cm/s.

Limited Objective and Flow Parameters

In the interest of brevity, only one sequence each for a plunging and a pitching airfoil will be presented, clearly exhibiting the sought-after propulsive vortical signatures and their generation. Parametric trends will only be touched upon. The flow parameters are the reduced frequency $k = \pi fc/U_o$ (where f is the frequency of plunging or pitching, c is the airfoil chord length, and U_o is the freestream velocity), the mean angle of attack $\bar{\alpha}$, the dimensionless plunge amplitude h/c (where h is the plunge amplitude) or the pitch angle amplitude α_p, and the Reynolds number $Re = U_o c/\nu$ (where ν is the kinematic viscosity in air).

Experimental Results

Figure 2 shows a time sequence of movie frames visualizing vortex generation and development for a periodically plunging NACA 0015 airfoil immersed in steady flow $U_o = 61$ cm/s from left to right. Frames are ordered into columns from top to bottom and then across columns from left to right; the time between consecutive frames is $\Delta t = 1/32$ s. The airfoil has a

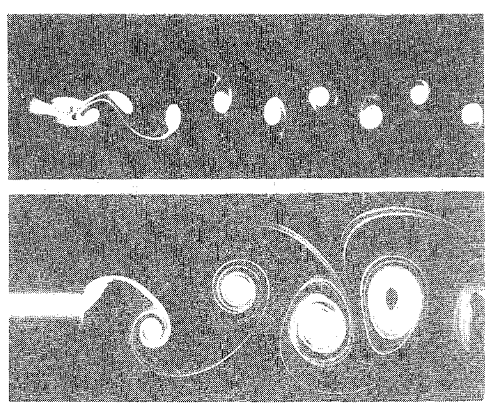

Fig. 1 Top: vortex street shed from a circular cylinder at $Re = 120$ (cylinder diameters 0.63 cm, flow speed $U_o = 30.5$ cm/s). Bottom: vortex street generated behind the trailing edge of an airfoil pitching periodically around the quarter-chord axis (chord length $c = 35.6$ cm, $U_o = 61$ cm/s, frequency $f = 2$ Hz, pitch amplitude $\alpha_p = 10$ deg).

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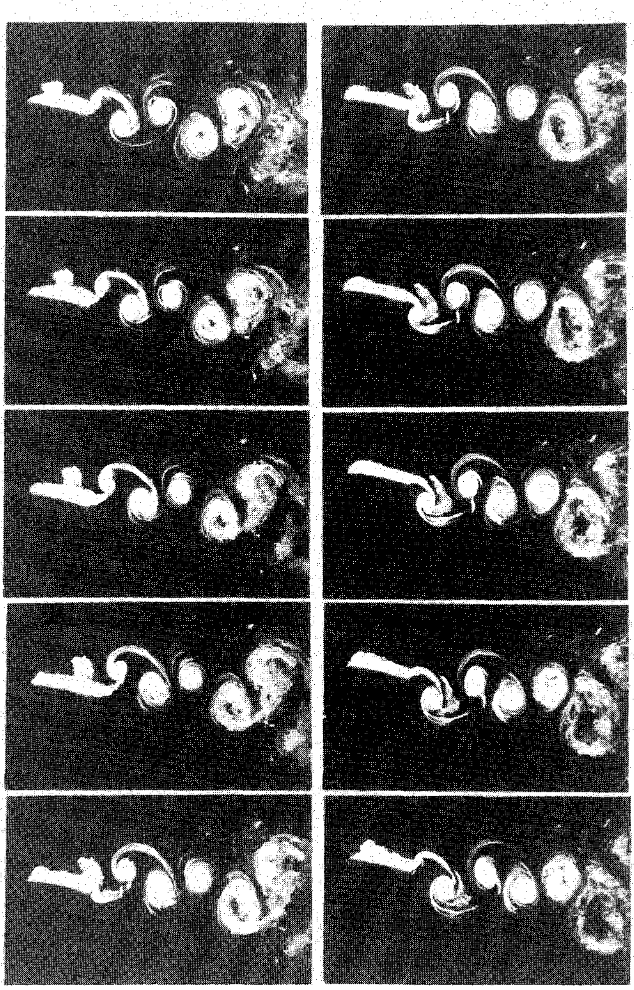

Fig. 2 Sequence for airfoil in pure plunging motion; $k = 2.7$, $Re = 5200$, $h/c = 0.2$, $\bar{\alpha} = 5$ deg.

chord length $c = 15$ cm and was plunged up and down with an amplitude $h = 3$ cm at a frequency $f = 3.5$ Hz. The resulting dimensionless parameters are listed in the figure caption.

Just as in Fig. 1 bottom, we recognize in all frames the thrust type of vortex street, where the top row of counterclockwise rotating vortices induces for the bottom row of vortices a downstream component of velocity and where the bottom row of clockwise vortices does likewise for the top row. In other words, the vortex street represents the signature of unsteady jet propulsion. Let us consider how this thrust type of vortex street is generated. The first four frames of the left column show the airfoil in downward plunge, during which time a counterclockwise rotating vortex forms from vorticity, leaving the trailing edge of the airfoil. The subsequent upward motion then causes formation of a clockwise vortex, which is deposited below and to the left of the previously formed counterclockwise vortex. It is of interest to note that in addition to the separation from the trailing edge, weak separation also occurs over the leading edge. This clockwise vorticity is merging with the clockwise vorticity shed from the trailing edge, thus reinforcing this vortex. For an average angle of attack considerably larger than 5 deg, the leading-edge vortex was not incorporated any more into the appropriate trailing-edge vortex and seemed to weaken the generation of thrust. It should be noted from the diffuseness of the smoke that the vortex street of Fig. 2 is not entirely laminar.

The situation turned out quite similar for NACA 0015 airfoil in periodic pitch around the $c/4$ axis, as is shown in Fig. 3. In this case, we have $U_o = 61$ cm/s, $c = 35.6$ cm, $f = 1.6$ Hz, $\bar{\alpha} = 5$ deg, $\alpha_p = 20$ deg, and $\Delta t = 1/16$ s. Pitchup in the first column deposits a counterclockwise vortex into the flow. During

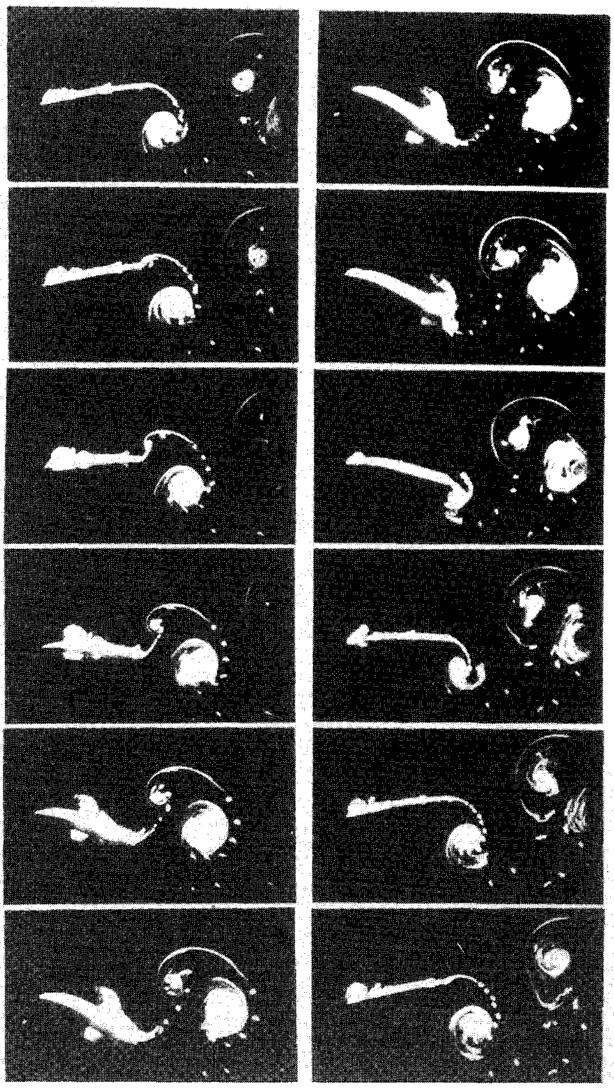

Fig. 3 Sequence for airfoil in pure pitching motion around the $c/4$ chord axis; $k = 2.9$, $Re = 12{,}000$, $\bar{\alpha} = 5$ deg, $\alpha_p = 20$ deg.

pitchdown in column 2, a clockwise vortex is deposited to the left and below the counterclockwise vortex. Actually, the vortex filaments leaving the trailing edge break up into small vortices due to the Helmholtz instability before these small vortices merge into the main vortices. Once again, weak leading-edge separation occurs, reinforcing the appropriate trailing-edge vortex.

It should be mentioned that increases in mean angle and in pitch or plunge amplitude tend to cause severe leading-edge separation with an associated erosion in the propulsive signature of the vortex array. A decrease in reduced frequency increases the distance between vortices, whose rollup gets more sluggish. At very low frequencies, propulsive tendencies get overwhelmed by the drag of the airfoil profile, and a drag indicating Kármán vortex street emerges.

Conclusion

Propulsive vortical signatures and their generation have been documented for airfoils in pure plunging and in pure pitching motions. It is hoped that these visualizations contribute to an understanding of animal propulsion.

Acknowledgments

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On Nonlinear Aspects of Hypersonic Boundary-Layer Stability

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Introduction

LINEAR boundary-layer stability theory was slow to be accepted by the scientific community. This was primarily because the wind-tunnel experiments of that time could find no evidence of the instability waves predicted by theory, and there seemed to be no connection between linear stability theory and transition.[1] The classic experiments of Schubauer and Skramstad[2] completely changed the opinions. Previous wind tunnels had high freestream turbulence levels, which completely obscured the existence of small boundary-layer disturbances. The low-turbulence wind tunnel of Schubauer and Skramstad provided the first demonstration of the existence of instability waves in a laminar boundary layer, their connection with transition, and the quantitative description of their behavior by the theory of Tollmien and Schlichting. These experiments, as well as subsequent experiments, provided verification that linear stability theory adequately decribed the onset of small disturbance growth and the growth characteristics of the disturbances in a subsonic laminar boundary layer. In the following years, linear stability theory found wide applications in the description of instability parameters and in the prediction of transition for subsonic flows. When hypersonic wind-tunnel stability experiments were contemplated, there was concern whether the freestream disturbances would be low enough to permit the detection and study of the second-mode instability disturbances predicted by the linear stability theory of Mack.[3-5] Second-mode disturbances are high-frequency, acoustical-type disturbances that are unique to high Mach number boundary layers. First-mode disturbances are lower-frequency disturbances similar to the Tollmien-Schlichting disturbances of incompressible flow. Linear stability theory predicts the existence of both first- and second-mode disturbances in a hypersonic boundary layer, with the second-mode disturbances being the major instability. Kendall's pioneering stability experiments[6] provided some important answers. Stability experiments at a Mach number of 4.5 indicated that disturbances of all frequencies grew monotonically larger in a region of the boundary layer extending from the flat plate leading edge to the predicted location of instability, i.e., in a region where linear stability theory indicated that the boundary layer should be stable for all disturbance frequencies. This early growth of disturbances was attributed to the forcing mechanism of the strong freestream sound field generated by the turbulent boundary layer on the nozzle wall. Additional experiments at a freestream Mach number of 8.5 found a different situation. In this case, the initial disturbance growth was as described by linear theory. The second-mode disturbances of linear stability theory were clearly observed, and they were the dominant instability. Subsequently, stability experiments[7-11] at $M_\infty = 8$ in a different wind tunnel provided additional confirmation of second-mode disturbances. In addition to the first- and second-mode disturbances identified by linear stability theory, all of the above-mentioned hypersonic stability experiments observed disturbance growth at higher frequencies. The identity of the higher frequency disturbances is not certain; however, there is strong evidence to indicate that they are nonlinear disturbances. The dominant frequencies of these disturbances were two and three times the most unstable second-mode frequencies, suggesting that they were harmonics of the second mode. They were not observed until significant second-mode growth had occurred. Also, Mack[5] has stated that unstable frequencies in the frequency range in question do not exist in linear stability theory.

It cannot be assumed, on the basis of its verification for low-speed flows, that linear stability theory will adequately describe the instabilities in a hypersonic laminar boundary layer. Even though stability experiments have verified the existence and dominance of second-mode disturbances in a hypersonic boundary layer, this is only the first step in the evaluation process of determining how well linear stability theory describes hypersonic boundary-layer instabilities. It must also be verified that linear stability theory can adequately handle important second-mode characteristics, such as identifying the most unstable frequencies, obtaining their growth rates, and locating the neutral branches. Furthermore, the experiments have indicated that nonlinear disturbances were a significant factor. An evaluation of nonlinear effects must be a prerequisite to the application of linear stability theory to hypersonic problems.

Some hypersonic experimental results, obtained through the use of hot-wire anemometry, are shown to illustrate the scope of the problems involved. These data demonstrate that the rapidly growing second-mode disturbances obtain relatively large amplitudes (which could possibly exceed the limits of a small-disturbance assumption), that high-frequency disturbances (presumably nonlinear disturbances) were present, and that linear stability theory was not able to predict the measured disturbance growth rates.

Results and Discussion

Figure 1 (from Ref. 8) shows the fluctuation spectra at the location of peak energy in the boundary layer in a pictorial format to illustrate the growth of the disturbances in a hypersonic laminar boundary layer (A = disturbance rms amplitude in arbitrary units). The hypersonic boundary layer was very selective in the frequency of the most amplified disturbances. There was evidence of a tuning effect of the boundary layer, and the most amplified disturbances had a wavelength of approximately twice the boundary-layer thickness. The "tuned" disturbances (in the frequency range from about 70 to 150 kHz) were identified as second-mode disturbances. These rap-

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