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Vortex Dynamics in Flow Instabilities and Biomimetic Flows

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Flow patterns around bodies undergoing flow-induced vibrations and biomimetic flows have intriguing similarities, and similar flow mechanisms can be used to understand their principal properties and find ways to alter their behavior. The long history and extensive study of flow-structure interaction allowed the rapid development of the new field of biomimetic fluid mechanics. In return, the properties that were revealed and the discoveries that were made through the study of the swimming of fish and cetaceans and of bird flight are now entering the engineering domain, suggesting new ways to control the flow and how to devise new technology as well as invigorating our profession.

INTRODUCTION

Flow-structure interaction is a problem of great importance to ocean and offshore engineering, coastal engineering, and mechanical engineering. Flow mechanisms have been explored for the purpose of reducing loads on large and small structures, cables, risers, and hawsers. Theoretical and experimental results derived from studies around structures have found application to a totally new field of study, biomimetic fluid mechanics, i.e., the mechanisms employed by swimming and flying animals for propulsion and maneuvering. For example, intriguing similarities between the flow patterns behind swimming animals and in the wake of structures placed in cross-flow have led to the identification of similar flow mechanisms that can be used to understand the principal properties of both classes of systems. In return, the discoveries made through the study of the swimming of aquatic animals and of bird flight can now be used in engineering to better control the flow and to devise novel technologies such as novel sensors and actuators. The proliferation of articles in engineering journals on biomimetics and the plethora of new biomimetic journals promise that this exchange will continue in the years to come.

EXPLORING FLOW INSTABILITY MECHANISMS

One of the most extensively studied topics in flow-structure interaction is the spontaneous formation of the Karman street behind bluff bodies in cross-flow that results in vortex-induced oscillations of flexible or flexibly mounted structures (Bearman, 1984; Williamson, 1996; Williamson and Govardhan, 2004; Zdravkovich, 1997; Triantafyllou, Bourguet, et al., 2016). For fixed bodies and despite the fact that the oncoming cross-flow is steady, the wake flow becomes unstable, generating streets of vortices of alternating-sign vorticity that induce oscillatory loads at the Strouhal frequency. The instability is attributed to the doubly inflected time-averaged velocity profile that causes an absolute instability (Bers, 1983; Triantafyllou et al., 1986; Huerre and Monkewitz, 1990), i.e., a flow instability with a preferred frequency that propagates both upstream and downstream, overwhelming the entire flow. The frequency of maximum growth dominates the response, and its value is related to the average velocity profile. This is the Strouhal frequency that is related to the width h of the average velocity profile: $f = St \cdot U/h$, where St is the Strouhal number with a nearly universal value of around 0.16 when it is related to the width of the wake rather than the diameter of the cylinder. This flow instability constitutes the mechanism through which kinetic energy is extracted from the oncoming flow and then transferred to the body in the form of oscillations.

In the case of a harmonically oscillating foil mimicking the action of the caudal fin of a fish, the role is reversed. Energy supplied by the oscillating foil generates arrays of vortices similar to the Karman street but with a reverse rotation direction and different from the case of a bluff body, hence actuating a jet flow rather than a drag wake. Through the use of the same tools as instability analysis, it can be found that a jet flow is accompanied by a convective instability, i.e., an instability that responds at the frequency of excitation with a wavenumber governed by the dispersion relation of the waves and provided by the average velocity profile. At a specific frequency f, the spatial growth rate of the waves is maximized; this is the frequency at which the useful energy, in the form of developing thrust, is maximized and can be used to define a new Strouhal number that is also based on the width of the average velocity profile h and takes values in a relatively narrow range around $St = fh/U = 0.3$. When the excursion of the foil A is used rather than the width of the average velocity profile h, a more practically useful approximate Strouhal number is obtained, $St = fA/U$, with values in the range of 0.2 to 0.4 (Triantafyllou et al., 1991, 1993, 2000; Anderson et al., 1998).

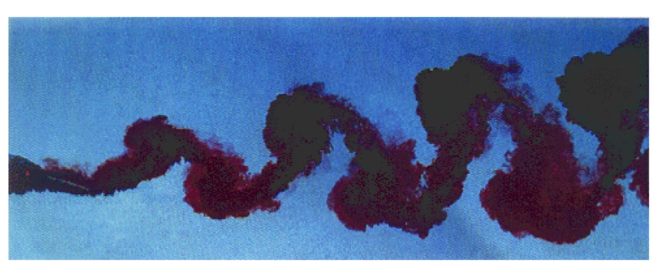

Fig. 1 Jet flow and reverse Karman street visualized through dye behind a tuna-shaped swimming robot (Triantafyllou and Triantafyllou, 1995)

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