C. R. Mecanique 342 (2014) 532–538

Contents lists available at ScienceDirect

Comptes Rendus Mecanique

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Experimental study of the response of a flexible plate to a harmonic forcing in a flow

Étude expérimentale de la réponse d'une plaque flexible à un forçage harmonique dans un écoulement

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A R T I C L E   I N F O

Article history:
Received 14 April 2014
Accepted 10 June 2014
Available online 16 July 2014

Keywords:
Fluid–structure interaction
Flexible plate
Harmonic forcing
Resonance
Non-linearity
Propulsion

Mots-clés :
Interaction fluide–structure
Plaque flexible
Forçage harmonique
Résonance
Non-linéarité
Propulsion

A B S T R A C T

Most aquatic animals propel themselves by flapping flexible appendages. To gain insight into the effect of flexibility on the swimming performance, we have studied experimentally an idealized system. It consists of a flexible plate whose leading edge is forced into a harmonic heave motion, and which is immersed in a uniform flow. As the forcing frequency is gradually increased, resonance peaks are evidenced on the plate's response. In addition to the forcing frequency, the Reynolds number, the plate rigidity and the forcing amplitude have also been varied. In the range of parameters studied, the main effect on the resonance is due to the forcing amplitude, which reveals that non-linearities are essential in this problem.

R É S U M É

La plupart des animaux aquatiques se propulsent grâce au battement d'appendices flexibles. Afin d'avoir une meilleure compréhension de l'effet de la flexibilité sur la performance de la nage, nous avons étudié expérimentalement un système idéalisé. Il consiste en une plaque flexible, immergée dans un écoulement uniforme, dont le bord d'attaque est forcé en un mouvement harmonique transverse à l'écoulement. En augmentant graduellement la fréquence de forçage, des pics de résonance ont été mis en évidence. Outre la fréquence de forçage, on a également fait varier le nombre de Reynolds, la rigidité de la plaque et l'amplitude du forçage. Dans le domaine de paramètres étudié, le principal effet sur la résonance est dû à l'amplitude du forçage, ce qui révèle que les non-linéarités sont essentielles dans ce problème.

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http://dx.doi.org/10.1016/j.crme.2014.06.004
1631-0721/

1. Introduction

Animal swimming has attracted a lot of attention from hydrodynamicists in the last decades. This interest was partly motivated by the design of bioinspired aquatic propulsion devices. Numerous reviews can be found on the different aquatic propulsion modes, such as the monographs of Lighthill [1] and Childress [2] or the articles of Lighthill [3], Sfakiotakis et al. [4] and Triantafyllou et al. [5]. Propulsion using flapping appendages is common for large aquatic animals and, in particular, most of the fast swimmers such as sharks, tuna and dolphins flap their caudal fins to propel themselves. An observation of these appendages shows that they are generally flexible along the chord. It has often been argued (e.g. [6] and [7]), that this flexibility enhances the swimming performance. However, the origin of this performance enhancement has proved elusive so far.

Inspired by this caudal-fin swimming mode, different studies have been carried out to quantify the propulsion efficiency of a flapping foil. Propulsion by rigid foils has been first studied theoretically by Lighthill [8] and Wu [9]. It has also been the object of experiments by Triantafyllou et al. [10], Anderson et al. [11], Schouveiler et al. [12], and Buchholz and Smits [13], among others. These experimental studies have all reported that propulsion performance is maximized for a flapping frequency f corresponding to a Strouhal number $St \approx 0.3$, where $St = 2fA_{TE}/U$, with A_{TE} the amplitude of the trailing edge motion and U the swimming speed. The same value of $St \approx 0.3$ can be observed in nature for swimmers with moderate aspect ratios (cetaceans, sharks, salmons, trouts and scombrids) as seen in the data recently compiled in [14].

The numerical simulations of Katz and Weihs [15] have shown that, using a flapping foil flexible along its chord rather than a rigid one, yields an increase of the propulsive efficiency. In this case, because of the foil flexibility, its natural structural frequencies are introduced in the system, in addition to the flapping frequency. These structural frequencies depend not only on the geometry and the material of the foil but also on the surrounding flow because of added-mass effects. Two-dimensional numerical simulations of Alben [16] and Michelin and Llewellyn Smith [17] have later revealed peaks in the amplitude of the plate response, when the flapping and structural frequencies are resonant. They showed that efficiency can be maximized at these resonance peaks.

Gain in propulsive performance through the chordwise flexibility has been confirmed by the experimental works of Prempraneerach et al. [18], Heathcote and Gursul [19], or Marais et al. [20]. Moreover, Dewey et al. [21] for a pitching flexible plate, Alben et al. [22] and Quinn et al. [23] for a heaving flexible plate have clearly evidenced the phenomenon of resonance experimentally, as the forcing frequency is varied, and considered its link with propulsive performance, but none of these studies has considered the effect of changing the forcing amplitude.

In this study, to have a better understanding of the dynamics of a flexible fin, we have examined the response of an elastic plate immersed in a uniform flow and forced into a harmonic heave motion at its leading edge. The objective has been to quantify the influence of the different experimental parameters: the amplitude and frequency of forcing, the flow velocity, and the plate bending rigidity. This problem involves complex fluid–structure interactions since the flow load deforms the plate, whose motion in turn affects the flow. We believe that the full complexity of these interactions can only be addressed with experimental studies because, at the present time, accurate numerical simulations are limited to moderate Reynolds numbers and theoretical models usually assume linear problems, i.e. small-amplitude propulsion.

This paper is organized as follows: first the experimental set-up and methods are presented. Then the response of flexible plates to harmonic heave forcing is analyzed and effects of the different experimental parameters are discussed. Finally, some conclusions are drawn and discussed in the context of swimming.

2. Experimental set-up

Experiments have been conducted with the set-up schematically illustrated in Fig. 1(a). It consists of a horizontal flexible plate molded out of polysiloxane with a rounded leading edge and a tapered trailing edge (Fig. 1(b)). The plates used have a thickness $e = 0.004$ m, span $s = 0.12$ m, and chord $c = 0.12$ m, giving an aspect ratio $s/c = 1$. During molding, a rigid axis is inserted inside the plate at the leading edge; this axis has some roughness to prevent the rotation of the plate around it. This set-up reduces the flexible length of the chord to about 0.115 m. The plate is then immersed in a uniform flow, of velocity U, of a free surface water channel. The test section is 0.38 m wide, with a depth of water at rest of 0.45 m.

As shown in Fig. 1(a), the axis is attached to an inverted U-frame such that the plate, at the leading edge, is maintained parallel to channel flow. This inverted U-frame is set into vertical motion by a computer-controlled linear actuator, which allows to impose an arbitrary heave motion to the leading edge. In the present experiments, the leading edge has been forced into a harmonic heave motion: $A_{LE}\cos(2\pi ft)$. The plate is confined between two vertical walls separated from the plate by less than 1 mm. The role of these confinement walls is, first, to minimize the flow around the side edges of the plate and, second, the inverted U-frame being outside of these walls, to avoid the perturbations from the wake of the frame. In addition, free surface effects have been prevented by a rigid horizontal wall placed above the experiment. Channel and confinement walls have been made of transparent material to facilitate visualizations.

To investigate the response of the plate when forced into heave motion, visualizations have been carried out through the side wall of the water channel and recorded with a video camera. The successive shapes and positions of the plate centerline have then been extracted by image analysis of the recordings. A quantitative characterization of the plate response is achieved by measuring the simultaneous displacements of the leading and trailing edges as a function of time by means of two high-accuracy laser sensors (Fig. 1(a)).