Applied Ocean Research 69 (2017) 27–37

Contents lists available at ScienceDirect

Applied Ocean Research

journal homepage: www.elsevier.com/locate/apor

Review

Forces on a pitching plate: An experimental and numerical study

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ARTICLE INFO

Article history:
Received 10 February 2017
Received in revised form 5 September 2017
Accepted 6 September 2017

Keywords:
Pitching plate
Thrust
Experiment
Numerical simulation

ABSTRACT

A flat plate in pitching motion is considered as a fundamental source of locomotion in the general context of marine propulsion. The experimental as well as numerical investigation is carried out at a relatively small Reynold number of 2000 based on the plate length c and the inflow velocity U_∞. The plate oscillates sinusoidally in pitch about its $1/3-c$ axis and the peak to peak amplitude of motion is 20°. The reduced frequency of oscillation $k=\pi fc/U_\infty$ is considered as a key parameter and it may vary between 1 and 5. The underlying fluid-structure problem is numerically solved using a compact finite-differences Navier–Stokes solution procedure and the numerical solution is compared with Particle Image Velocimetry (PIV) measurements of the flow field around the pitching foil experimental device mounted in a water-channel. A good agreement is found between the numerical and experimental results and the threshold oscillation frequency beyond which the wake exhibits a reverse von Kármán street pattern is determined. Above threshold, the mean velocity in the wake exhibits jet-like profiles with velocity excess, which is generally considered as the footprint of thrust production. The forces exerted on the plate are extracted from the numerical simulation results and it is shown, that reliable predictions for possible thrust production can be inferred from a conventional experimental control volume analysis, only when besides the wake's mean flow the contributions from the velocity fluctuation and the pressure term are taken into account.

Contents

1. Introduction

Unsteady flows around oscillating foils or plates have been the subject of numerous studies for decades, since early investigations on airfoil theory (cf. [1]) and also motivated, among other issues, by biological applications on the propulsion of flying and aquatic species [2,3]. For example, flapping wings propulsion has been both the subject of numerical studies, in the context of non-viscous flows [4,5] or viscous flows [6,7], and experimental investigations [8–10], just to cite a few. Many of these investigations focused on the wake structure of flapping foils, emphasizing in particular that when the structure starts to generate thrust, the classical Kármán vortex street (representative for drag) is reversed such that the mean velocity profile is jet-like, exhibiting a velocity excess [8]. An important aspect in these studies was the prediction, from experimental measurements, of the propulsive performance resulting from the flapping motion of wings, foils or plates. A way to do this is to estimate the mean thrust force experimentally from the measure of a mean longitudinal velocity profile somewhere in the wake, using the integral momentum theorem applied to a control volume surrounding the body as illustrated in Fig. 1.

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http://dx.doi.org/10.1016/j.apor.2017.09.003

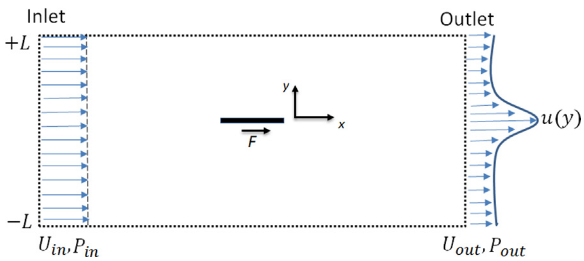

Fig. 1. Definition of the control volume surrounding a plate for the momentum theorem analysis.

Traditionally, only the mean streamwise velocity profile is considered, neglecting the contributions from the velocity fluctuation and the pressure which gives rise to the formula, in a two-dimensional setting and by taking into account mass conservation, for the mean force (per unit span) in the streamwise x direction

$$F = \rho \int_{-L}^{+L} \langle U(x_0, y)\rangle(\langle U(x_0, y)\rangle - \langle U_{\mathrm{in}}\rangle)dy, \tag{1}$$

ρ being the fluid density, $\langle U_{\mathrm{in}}\rangle$ the mean velocity at the control volume inlet, which is generally equal to the incoming uniform free stream velocity U_∞, and $\langle U(x_0, y)\rangle$ the mean longitudinal velocity profile inside the wake at a chosen position x_0 from the foil's trailing edge. A negative value of F corresponds to drag and a positive value to thrust.

In the above formula it is understood, that upper and lower limits of integration are taken far enough from the moving foil such that uniform flow is recovered and that the integrand approaches zero at $y = \pm L$. This expression has been widely used to estimate the mean thrust force [8,11,12] and very recently for example in [13]. As shown for instance in [14] or [15], since the wake behind a pitching foil is highly unsteady, velocity fluctuations are likely to be not negligible anymore. Also, depending on the experimental device there is no general guarantee that the far field velocity in the wake remains equal to the free stream velocity U_∞ for a given measurement window. Also, an optimal distance x_0 from the trailing edge has to be chosen, such that x_0 is large enough to minimize pressure variations across the wake and small enough such that three-dimensional effects have not been established [16].

The aim of the present investigation is precisely to reexamine the forces exerted on a structure in pitching motion, by considering an idealized configuration of a very thin plate in a quasi-two-dimensional configuration, both in an experimental set-up and by performing numerical simulations for an identical flow regime. We focus in particular on the importance of the traditionally neglected contributions in the momentum balance, in order to predict the transition to a propulsive regime, the numerical simulation results allowing in particular of recovering the precise forces acting on the plate.

The paper is organized as follows. In Section 2, an overview of the experimental device used to perform the PIV measurements is presented. The numerical method, which was used for instance in [17] for the flow around a flat plate in uniform flapping normal motion, is summarized in Section 3. The numerical simulations and experiments results are presented and compared in Section 4 and some conclusions are drawn in Section 5.

2. Experimental setup

The experimental investigation was conducted in the water-channel at the French Naval Academy Research Institute – IRENav. This device has a test section of dimensions 1000 mm (length) × 192 mm (width) × 192 mm (depth). The flow velocity can be controlled between 0.05 m/s and 15 m/s and the pressure from 30 mbar to 3 bar. A rigid thin carbon flat plate of length c = 40 mm and width s = 191 mm was placed in the middle of the test section as shown in Fig. 2. The plate's thickness is 3 mm, that is the plate is expected to be sufficiently thin in order to minimize particular body-shape effect on the forces during the pitching motion, the model in the numerical solution procedure (outlined in the next section) being that of a plate with vanishing thickness. Also, the aspect ratio width to length is high enough to ensure, that the flow along the center region of the plate is likely to be quasi-two-dimensional. Note that the plate's width is almost equal to that of the water channel. The leading edge of the plate was rounded with a diameter of 3 mm, and the center of rotation was located at $x_c/c = 1/3$, where x_c is the distance from the leading edge to the pivot point.

The flow velocity considered is that of the minimum possible velocity $U_\infty = 0.05$ m/s in the water-channel and the corresponding Reynolds number based on the plate length is hence $Re = 2000$, which corresponds to a flow regime which is also achievable in the numerical simulation. The sinusoidal pitching plate motion is generated by an oscillatory electrical drive through an interface aimed at controlling the signal frequency and amplitude with the angle of incidence defined as

$$\alpha(t) = \alpha_0 \sin(2\pi f t). \tag{2}$$

The values of oscillation frequency f range from 0.6 Hz to 2 Hz, corresponding to reduced frequency defined as $k = \pi f c/U_\infty$ in the range of 1.5–5, and the peak to peak amplitude of the pitching motion was fixed to 20° about a mean angle of attack of 0°, which means that in (2) the pitch amplitude of $\alpha_0 = 10°$ has been chosen. Signals for each angular position of the plate were recorded during all the measurement campaigns and a simple Fourier transform of the plate motion allowed to control the imposed oscillation frequencies.

The Particle Image Velocimetry (PIV) system was used to measure and visualize experimentally the flow around the pitching plate. The PIV measurement plane was positioned at mid-span and was set to capture the whole height of the channel test section.

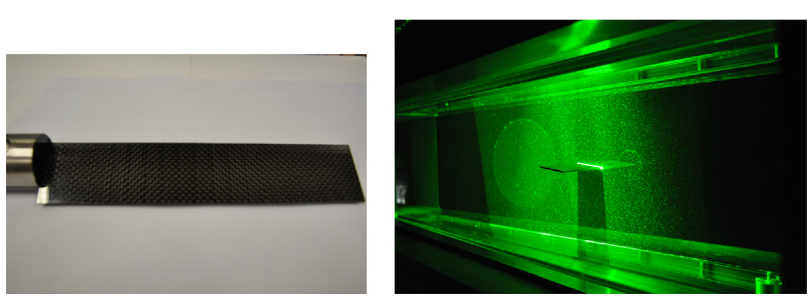

Fig. 2. Left: Rigid thin carbon flat plate of dimensions 3 mm (thickness) × 191 mm (width) × 40 mm (length). Right: PIV field of view at mid-span of the pitching plate inside the water-channel.