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► **To cite this version:**

Florine Paraz, Christophe Eloy, Lionel Schouveiler. Dynamique d'une plaque flexible en oscillation forcée. CFM 2013 - 21ème Congrès Français de Mécanique, Aug 2013, Bordeaux, France. hal-03439729

**HAL Id: hal-03439729**

**<https://hal.science/hal-03439729>**

Submitted on 22 Nov 2021

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# Response of a flexible plate heaving in a flow

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## Résumé :

*La plupart des animaux marins utilisent une nageoire caudale flexible pour nager. Afin de comprendre l'effet de cette flexibilité sur les performances propulsives, nous avons étudié expérimentalement un système idéalisé. Il consiste en une plaque flexible dont le bord d'attaque est forcé par un mouvement harmonique et qui est immergée dans un écoulement uniforme. Lorsque la fréquence de forçage augmente, deux pics de résonance sont observés sur la réponse de la plaque. Les effets du nombre de Reynolds, de la rigidité de la plaque et de l'amplitude de forçage ont été considérés. Dans la gamme des paramètres étudiés, la résonance est principalement affectée par l'amplitude de forçage, ce qui révèle le caractère essentiel des non-linéarités dans ce problème.*

## Abstract :

*Most swimming animals use a flexible caudal fin to propel themselves. To gain insight into the effect of flexibility on the propulsion performance, we study experimentally an idealized system. It consists of a flexible plate whose leading edge is forced into an harmonic heave motion, and which is immersed in a uniform flow. As the forcing frequency is changed, two resonances peaks are evidenced on the plate response. Effects of the Reynolds number, plate rigidity and forcing amplitude are considered. 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.*

**Mots clefs :** Resonance ; Plaque flexible ; Forçage harmonique

## Nomenclature

$c$	Chord	m
$s$	Span	m
$e$	Thickness	m
$f$	Frequency	Hz
$f_0$	Natural frequency	Hz
$A_{LE}$	Leading edge amplitude	m
$A_{TE}$	Trailing edge amplitude	m
$U$	Flow velocity	$\text{m}\cdot\text{s}^{-1}$
$\nu$	Fluid viscosity	$\text{m}^2\cdot\text{s}^{-1}$
$B$	Bending rigidity	Nm
$Re$	Reynolds number	-

## 1 Introduction

Large aquatic animals can be divided into three main classes depending on their modes of locomotion. Some of them create a pulsating jet (e.g. jellyfish, squids), others use their paired fins or appendages (e.g. seahorses, clown fish, rays, boxfish), but most good swimmers use their caudal fins (e.g. sharks,

tuna, dolphins) [1, 2, 3, 4]. An observation of these caudal fins shows that most of them are flexible along the chord. It has often been argued that this flexibility likely enhances the swimming performance [5, 6, 7].

Inspired from this caudal-fin swimming mode, different studies have been performed to quantify the propulsion efficiency of a flapping foil. Rigid foils have been first studied theoretically [8, 9], as well as experimentally [10, 11, 12]. These latter studies have shown that performance is maximized for a flapping frequency  $f$  corresponding to a Strouhal number  $St \approx 0.3$ , where  $St = fA_{TE}/U$ , with  $A_{TE}$  the peak-to-peak trailing-edge amplitude and  $U$  the swimming speed. When the flapping foil is flexible, other frequencies enter the problem : the structural frequencies, which are the natural frequencies of the foil. These structural frequencies highly depend on the geometry and the material of the foil. Numerical studies have indicated that maximum efficiency is achieved when the flapping frequency is close to the smallest structural frequency [13, 14]. However, this resonant phenomenon has not clearly been evidenced in the experiments [15, 16, 17].

In this study, to have a better understanding of the dynamics of a flexible fin, we have examined the response of a heaving flexible plate in a uniform flow, with the objective of quantifying the influence of the different experimental parameters when they vary on wide ranges. 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, numerics is limited to moderate Reynolds numbers and theoretical models usually assume two-dimensional linear problems.

This paper is organized as follows : first the experimental set-up and methods are presented. Then the response curves of the flexible plates as a function of the different experimental parameters are given and discussed. Finally, we draw some conclusions and consider them in the context of swimming.

## 2 Experimental set-up

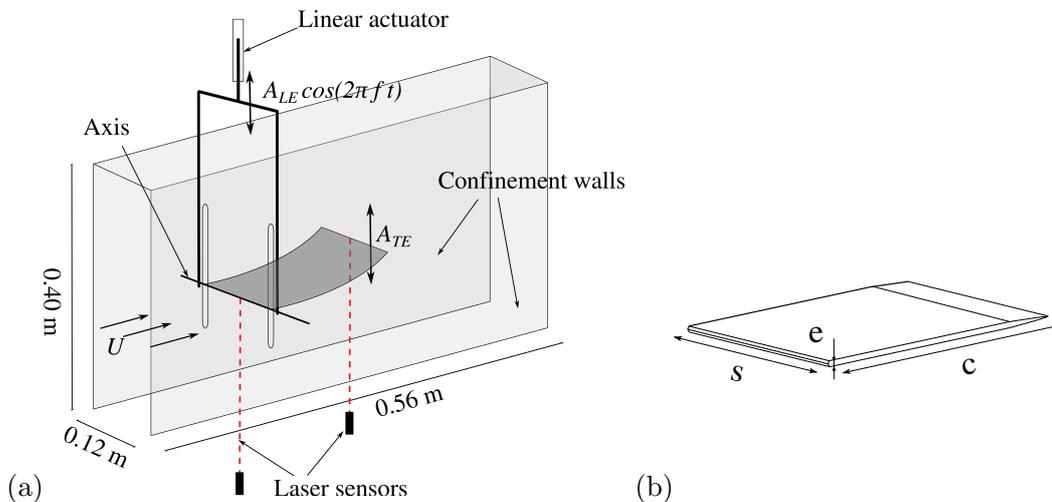


FIGURE 1 – (a) Drawing of the experimental set-up; (b) shape of the flexible plate.

The experimental set-up is illustrated in Figure 1. It consists of flexible plates made of silicon with a rounded leading edge and a tapered trailing edge. The plate dimensions are : thickness  $e = 0.004$  m, span  $s = 0.12$  m and chord  $c = 0.12$  m, which gives an aspect ratio  $c/s = 1$ . In the present experiments, a plate is immersed in the uniform flow of a free surface water channel of section  $0.38$  m (height)  $\times$   $0.45$  m (depth). A rigid axis is inserted inside the plate, at the leading edge, and attached to an inverted U-frame. This frame is set in motion by a linear actuator, which imposes a harmonic heave motion expressed by  $A_{LE} \cos(2\pi ft)$ . In order to minimize the flow around its side edges, the plate is confined between two vertical walls separated from the plate by less than 1 mm. In addition, free surface effects are prevented by a rigid horizontal wall placed above the experiment (Fig. 1(a)).

Because we are interested by the response of the plate to heave forcing, we measure as a function of time the displacements of both the leading and trailing edges with two high-accuracy CCD lasers sensors. During the experiment, the shape of the plate is recorded through a side wall with a video camera. The successive positions of the plate centerline are then extracted by image analysis.

In the present study, we considered the variation of four experimental parameters. First, the frequency and amplitude of the forcing have been varied in the ranges  $f = 0.2 - 8$  Hz and  $A_{LE} = 0.004 - 0.014$  m respectively. Then, the flow velocity has been changed up to  $U = 0.1$  m.s<sup>-1</sup>. Finally, three plates of bending rigidity  $B = 0.018, 0.028, 0.053$  Nm have been tested.

For each plate, the response of the trailing edge to an impulse forcing is recorded in the water at rest as illustrated in Figure 2. From such recordings, we can extract the damping ratio and the lowest natural frequency. These frequencies, which take the values  $f_0 = 0.75, 0.99, 1.3$  Hz for inscreasing bending rigidity, will serve as reference frequencies for each plate. In addition, the flow velocity is made dimensionless by using the Reynolds number  $Re = Uc/\nu$  to characterize the flow.

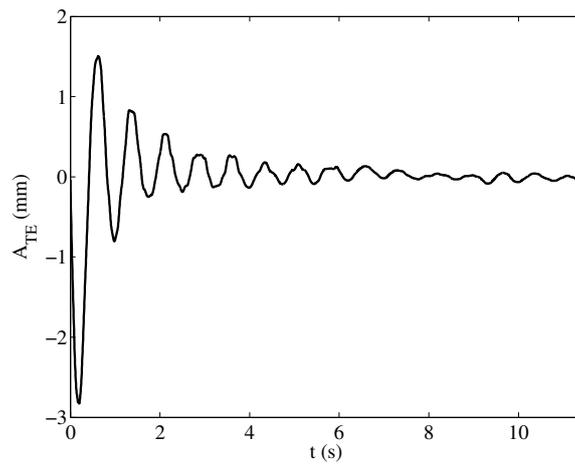


FIGURE 2 – Impulse response of a flexible plate of bending rigidity  $B = 0.053$  Nm in water at rest.

### 3 Results

In this study, we characterize the response of a flexible plate to a harmonic heave forcing. In an experiment, for a given Reynolds number, forcing amplitude and plate bending rigidity, the trailing edge motion is recorded as the frequency of the forcing is varied. We first note that the trailing edge displacement is always harmonic of the form  $A_{TE} \cos(2\pi ft + \phi)$ , where  $\phi$  is the phase relative to the leading edge position.

For Reynolds number  $Re = 6000$ , forcing amplitude  $A_{LE} = 0.004$  m, and bending rigidity  $B = 0.018$  Nm, the variations of the relative response  $A_{TE}/A_{LE}$  and phase  $\phi$  with the forcing frequency are shown in Figure 3. The amplitude curve exhibits two distinct peaks : a first sharp peak at a frequency close to the natural frequency (i.e.  $f \approx f_0$ ), and a second peak, flatter and lower in amplitude, at a larger frequency ( $f \approx 6f_0$ ). Far from these peaks, the phase shift is around 0 while, at the first peak, it is close to  $\pi$ . Note that at the second peak, there is no clear trend of this phase shift. The envelopes of the plate deflection for  $f/f_0 = 1$  and  $f/f_0 = 6.5$ , corresponding respectively to the first and second resonant modes, are shown in Figure 4(a) and (b). Contrary to the first mode, the second mode exhibits a neck close to its trailing edge showing that higher structural modes are involved at high frequencies. Note that, because the plate is slightly denser than water, the envelopes are slightly asymmetric. These characteristics of the response, in particular the presence of two peaks and the shape of the mode envelopes, have been observed for all of the explored values of the parameters :  $Re$ ,  $A_{LE}$  and  $B$ .

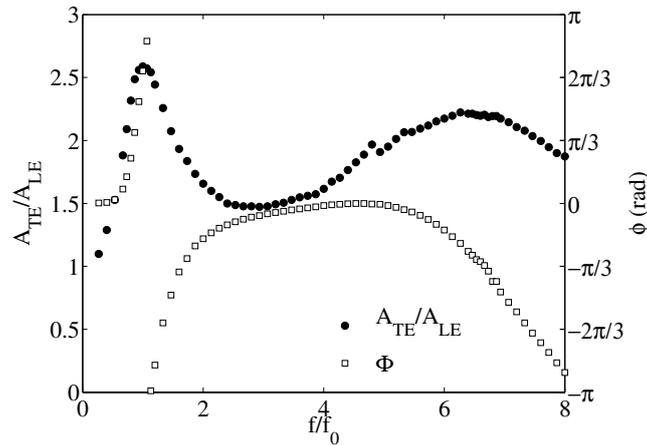


FIGURE 3 – Typical response of the amplitude of the trailing edge to the forcing amplitude  $A_{TE}/A_{LE}$  and the corresponding phase shift for  $A_{LE} = 0.004$  m,  $Re = 6000$  and  $B = 0.018$  Nm.



FIGURE 4 – Envelope of the mode at (a) the first ( $f/f_0 = 1$ ) and (b) the second peaks ( $f/f_0 = 6.5$ ) of resonant for  $A_{LE} = 0.004$  m,  $Re = 6000$  and  $B = 0.018$  Nm.

**Effect of the plate rigidity.** The effect of the flexibility can be seen in Figure 5(a). In dimensional units, the frequencies of the resonant peaks increase with the plate rigidity. However, the natural frequencies  $f_0$  also increase with the rigidity and when the response curves are plotted using the dimensionless frequency  $f/f_0$ , the curves collapse (Fig. 5(b)). This shows that there is no significant effect of the flexibility as long as the frequency is properly normalized.

**Effect of the Reynolds number.** Figure 5(c) illustrates the effect of the Reynolds number on the dynamics of the response. For the first resonance, as  $Re$  increases, the peak frequency increases while the response amplitude decreases. For the second peak, the picture is less clear. However, these variations in the response are only minor, meaning that the Reynolds number affects only slightly the plate response in the range of flow speeds explored. In other words, whether there is a flow or not, the response is similar.

**Effect of the forcing amplitude.** In Figure 5(d) the influence of the forcing amplitude is presented, around the first resonant peak. Contrary to the variation of the plate rigidity and Reynolds number, which have almost no effect on the plate dynamics, varying the forcing amplitude changes drastically the response. As the forcing amplitude  $A_{LE}$  is increased, the relative response  $A_{TE}/A_{LE}$  and the peak frequency decrease. This clearly indicates non-linear effects. These non-linearities likely originates from the large-amplitude plate deformations, which introduce non-linear terms in both the plate and flow dynamical equations. However, we believe that there are no structural non-linearities, i.e. the plate strains remain in the linear elastic regime.

## 4 Conclusion

Experiments have been conducted to investigate the response of a flexible plate in a uniform flow when its leading edge is forced into a harmonic heave motion. In this study, the response amplitude

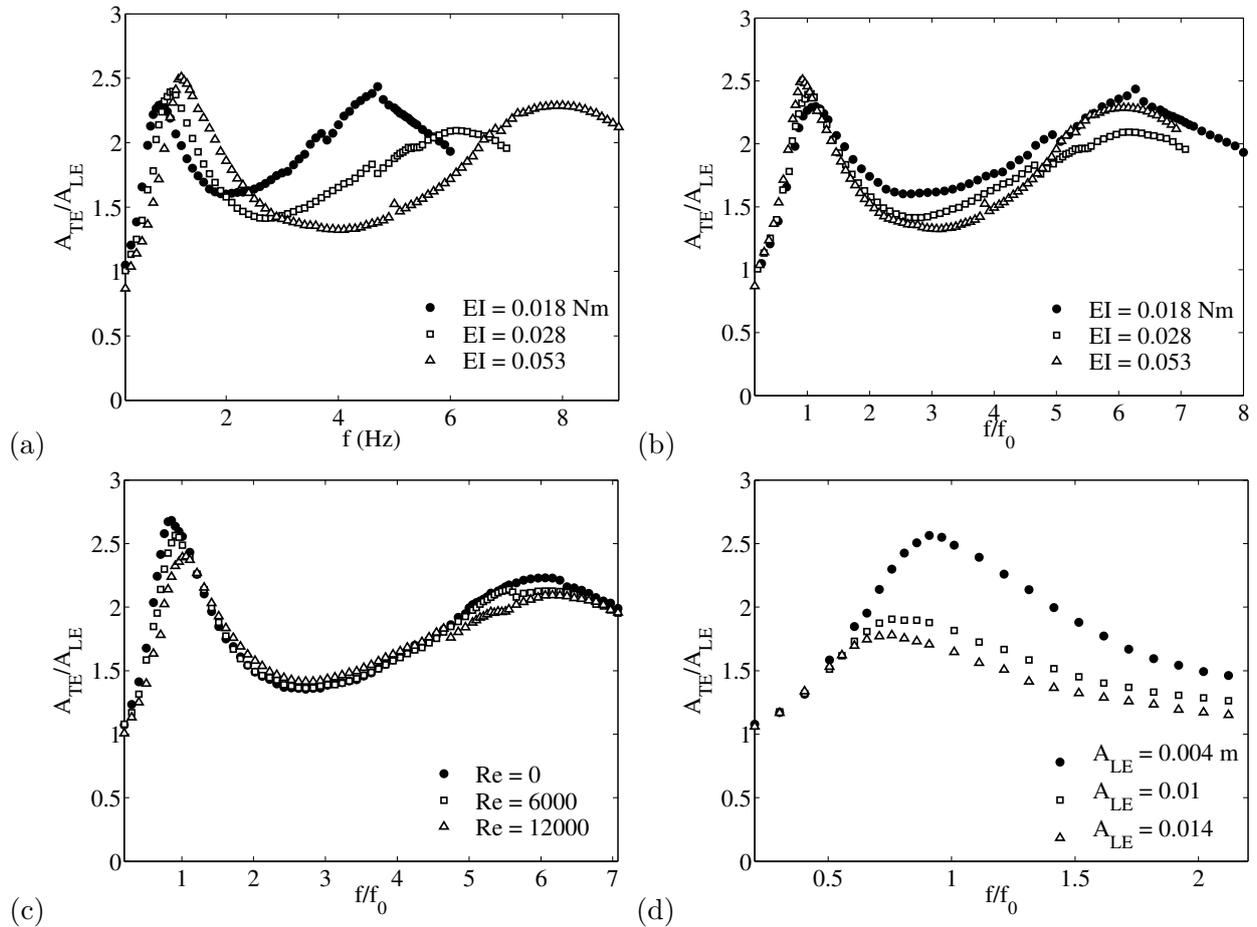


FIGURE 5 – Effect of the experimental parameters on the response of the amplitude of the trailing edge to forcing. (a) Effect of the flexibility on the amplitude of response  $A_{TE}$  for  $Re = 12000$  and  $A_{LE} = 0.004$  m; (b) Same effect than in (a) as a function of normalized frequencies; (c) Effect of the Reynolds number for the flexible plate  $B = 0.028$  Nm and  $A_{LE} = 0.004$  m; (d) Effect of the forcing amplitude on the first resonant peak  $A_{LE}$  for the plate of flexibility  $B = 0.028$  Nm at  $Re = 6000$ .

has been measured as the forcing frequency was varied. We have focused on the effects of variation of the different experimental parameters : the bending rigidity of the plate, the Reynolds number and the forcing amplitude. We have shown that the plate rigidity and the Reynolds number have only minor effects as long as the frequency is properly normalized. In contrast, the forcing amplitude affects strongly the plate dynamics, indicating the importance of non-linearities in the system.

The present experiment with an idealized geometry has helped to gain insight into the physical mechanisms of thrust production by flexible appendages. It is known, from the seminal work of Lighthill [1], that the thrust scales as the square of the trailing edge deflection amplitude in the linear limit. This study not only shows that this amplitude can be maximized when the flapping frequency is close to the natural structured frequency, as expected from previous studies [13, 14]; but it also shows that non-linear effects are important and probably affects Lighthill's scaling of thrust production.

### Acknowledgments

C. E. acknowledges the support of the European Union (fellowship PIOF-GA-2009-252542).

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