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Analytical linear modelization of a buckled undulating membrane tidal energy converter

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ABSTRACT

This paper presents an analytical linear model developed to study the behaviour of a buckled membrane tidal energy converter. The Euler beam theory and the elongated body theory are used for the fluid structure interaction formulation. The effect of electromechanical converters used to convert the undulating motion into electrical energy is reproduced by adding a term equivalent to viscous material damping.

The influence of compression force, flaps and hanging conditions is studied, as well as the effects of simulated power take-off through internal damping. The system's behaviour is characterized by undulating mode, critical flow velocity, motion frequency and amplitude.

The model shows good agreement in terms of frequency and satisfactory results for the amplitude compared to experimental data. The linear assumptions were validated on fluid and structure models as a good start for a first analytical model describing the system's physic. The obtained results confirmed the benefits of initial stress and optimized damping to the tidal converter for energy harnessing.

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1. Introduction

In these times of energy transition, the idea of using the tidal power of oceans as a renewable energy source arises again. This source has many advantages (Tecnomare [1]) and a lot of research has been done to find the best way to gather it (Boye et al. [2]). The corresponding field of research is mainly aimed on turbine-based technologies (Day et al. [3]) but several other systems have been suggested, based on flow-induced flutter. Various tactics are being adopted to capture energy from fluid through undulating motion, based on vortex-induced vibration in cables (Grouthier et al. [4]; Lee and Bernitsas [5]), oscillating foils (Kinsey et al. [6]; Xiao and Zhu [7]) or flexible membranes either distorted by vortex shedding downstream bluff bodies (Shi et al. [8]; Taylor et al. [9]) or set in motion by axial flow (Doare and Michelin [10]).

The analytical model presented in this paper is developed to model the behaviour of the undulating tidal energy converter (Fig. 1, Deporte et al. [11]; Träsch et al. [44]). It is equivalent to a compressed membrane undulating in axial flow. The membrane is hung by three semi-rigid arms that allow small motion freedom at its upstream extremity. Initial stress is applied to the membrane by cables linking both extremities. They are shorter than the membrane and buckle it. This enables to give an initial shape presenting a larger frontal area to the fluid and enabling the system to be put in motion at a slow flow speed. When operating, the membrane undulates, activating the electromechanical converters distributed along the main center line of the structure. We can observe a propagating wave in the current direction which has a lower celerity than the fluid velocity. This technology is in development and proposes an alternative for classical tidal turbines at low current speed (1–3 m/s).

Many publications propose analytical model to deal with an elastic plate immersed in an axial uniform flow. We can class these analytical models according to the way they express the fluid loads. Among all formulations, (Huang [13]; Kornecki et al. [14] and Watanabe et al. [15]) use the Theodorsen formulation to take into account the vortex circulation around the plate. In continuity, the structure boundaries can be divided into small panels by the use of

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Nomenclature

A	Dimensional maximum amplitude
$[\tilde{A}]$	Eigenvector of the equation system
a	Non-dimensional amplitude calibration
$a_{1..4}$	Coefficient for shape function
$\tilde{a}_i$	Modal relative amplitude
$[C]$	Damping matrix
C_d	Drag coefficient
D	Damping coefficient for material viscosity
D'	Damping coefficient for Power Take-Off
d	Cable length
E	Young's modulus
$\mathscr{F}_{flap}$	Flap localized load
F_d	Drag force
F_{flap}	Flap force coefficient
F_l	Lift force
f_d	Non-dimensional drag force
f_{flap}	Non-dimensional flap force coefficient
f_l	Non-dimensional lift force
I	Quadratic moment
$[\mathscr{I}]$	Identity matrix
i	Imaginary number
$()_i, ()_j$	Modal indices
$[K]$	Stiffness matrix
L	Total length
L_0	Membrane length
L_a	Membrane width
$[M]$	Mass matrix
m_f	Fluid linear added mass
m_s	Solid linear mass
N	Number of modes used in calculation
P	Harvested power
p	Non-dimensional collected power
Q	Linear external load
q_j	Non-dimensional time function
$[R]$	Calculus matrix
S	Frontal area
s	Curvilinear coordinate along the beam
T	Cable compression force
$\mathscr{T}$	Period
t	Time
U	Upstream flow speed
U_c	Critical velocity
u	Non-dimensional flow speed
x	Horizontal position
y	Vertical position
w	Fluid velocity orthogonal to the body
β	Mass ratio
Γ	Non-dimensional cable compression force
γ_i	Eigenvalue of the system
ΔP	Pressure difference along the beam
δ_j^i	Kronecker delta
η	Non-dimensional beam deflection
θ	Local angle with horizon
ι	Non-dimensional cable length
λ	Wave number
ξ	Non-dimensional curvilinear coordinate
ρ_f	Fluid volumic mass
ρ_s	Solid volumic mass
σ_i	Coefficient for shape function
τ	Non-dimensional time
ϕ_i	Non-dimensional shape function
ω_i	Non-dimensional complex frequency

the panel method (Tang [16]) to estimate more precisely lift and pressure loads. Another approach consists of imposing continuity of the pressure everywhere except across the plate and of solving the pressure distribution into the Fourier space (Eloy et al. [17]; Guo and Paidoussis [18]). When the elongated body theory is used, like in (Coene [19]; Lighthill [20]; Païdoussis [21] and Yadakin et al. [22]), the potential flow is regarded as the sum of the flow around the structure at rest and the flow disturbed by the displacement of a small body section. The solid motion is in most cases described by a Euler-Bernoulli beam theory.

These models are validated by several experiments on flexible plate or filament in axial flow with various materials (in term of mass and rigidity), characteristic lengths and fluid velocities (Lemaitre et al. [23]; Watanabe et al. [24]; Watanabe et al. [15]). Most of the cited models are 2D according to the experimental behaviour, but some of them have shown the influence of the aspect ratio (Doare et al. [25]; Eloy et al. [17]). These models also highlight the influence of mass ratio, rigidity, flow speed and induced tension into the beam. However, the range of parameters used in the works described above are different from our prototype characteristics due to differences in application (paper flutter, swimming fish, pipe conveyed fluid).

The power take-off impact on flexible plate is studied in (Doare and Michelin [10]; Pineirua et al. [26]; Singh et al. [27]; and Tang [16]) with piezoelectric devices. They investigate the intensity and the location of piezoelectric energy converters, but applied to smaller scale devices in comparison.

A special feature of this structure is pre-stress imposed by cables. Many authors take into account an induced tension due to bending (Argentina and Mahadevan [28]; Eloy et al. [29]; Moretti

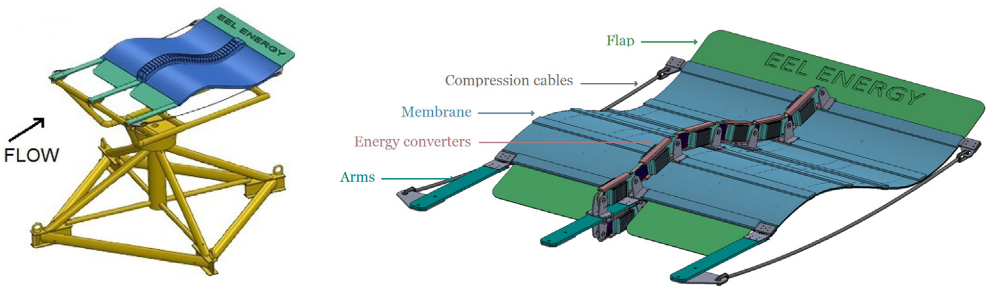

Fig. 1. CAD representations of an undulating tidal energy converter.

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