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Dynamic model and experimental validation for the control of emersion manoeuvers of devices for marine currents harnessing

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ABSTRACT

Finding solutions for fully automated performing emersion and immersion manoeuvers of submerged hydrokinetic devices with which to harness renewable energies requires the study of simple and reliable dynamic models. This paper presents a simple dynamic model for an approximately cylindrical body when it performs open loop emersion motions. It includes free surface motion with a single degree of freedom.

The proposed method allows a dynamic model to be obtained that can be used to both evaluate the dynamics of a submerged/semi-submerged body and design control systems for closed loop depth control purposes. This model is fully parameterized and requires a minimal computational effort. It is based on the computation of a hydrodynamic and a hydrostatic effect, namely: i) the added mass of the body in motion and ii) the buoyancy force. A simple new interpolated method is developed to compute the variation of the added mass when the body is partially submerged and the device velocities with regard to fluid are not constant. The inherent instability of any submerged compressible body is proved by using Lyapunov/Chetaev functions.

The appropriateness of the proposed model has been validated by comparing simulation results with real-time experimental-laboratory prototype measured signals, resulting in excellent agreement.

1. Introduction

The growing interest in the use of renewable energy in general and in marine renewable energy in particular has become increasingly evident over the last few years. From the point of view of the type of resource to be harnessed, different devices with which to obtain energy from offshore wind, waves, tides and marine currents are being conceived or developed [1–3].

The sea is a huge collector, accumulator and transformer of energy, covering more than 70% of the Earth's surface. Until only a few years ago its energy was, however, extracted by means of oil and gas wells, mainly owing to difficulties in the installation and operation of *Marine Renewable Energy* (MRE) plants [4].

Marine currents are, together with waves, one of the most promising sources of MRE. The quantification of the energy that could be extracted from sea waves and currents is estimated to exceed 8000 TWh/year [5]. Most of this huge potential is concentrated at water depths exceeding 40 m. For tidal devices or offshore wave energy converters it is compulsory to use a mooring system. For the underwater operations of their submerged bodies specific procedures are required.

If we focus exclusively on devices that harness the energy of ocean currents, they can be classified according to various criteria such as: i) type of rotor, ii) type of anchoring, iii) orientation of the device with regard to the stream's flow, among others [6]. The most common configurations of devices for marine current power harnessing [7] are: open rotor perpendicular and main axis oriented along the flow, nozzle type devices, devices with horizontal or vertical axis perpendicular to the current flow and oscillating flap devices.

The development of MRE devices and farms, is like any other offshore device, ranked into different types or generations according to sea depth. The industry's effort is currently focused on *First Generation devices* fixed to the sea bottom. They are suitable for sites with depths less than 40 m. Increasing numbers of *Second Generation devices*, required to be moored to the sea bottom, are suitable for depths greater than 40 m. These devices will be able to

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Nomenclature

$z(t)$	Depth of the geometric centre of the cylinder. It is time-dependant.
$f_1(t)$	Weight force. Constant.
$f_2(t)$	Buoyancy force. It is time-dependant.
m	Mass of the body. Constant.
m_{Add}	Added mass of the body. It is proposed that this be considered as only a function of depth z by ignoring its dependence on speed, unlike that which usually occurs.
ν	Viscous friction coefficient. Viscous friction is considered proportional to the square of the speed and motion opposite.
g	Gravity constant.
$V(t)$	Submerged volume. Because actuators will produce volume variations, it is considered time-dependant.
V_0	Nominal volume of the body outside the sea.[1] Constant.
L	Length of the nominal cylinder outside the sea.[1] Constant.
R	External ratio of the cylinder outside the sea.[1]
γ	Cylinder compressibility coefficient. It is constant and positive, and is considered only for negative values of depth z (zero when $z \geq R$).
$\Delta V_u(t)$	Control volume. It is actuated from a servo based on motor-reduction gear-spindle and a set of linear pistons.
V_{Buoy}	Non-submerged volume of the cylinder. It depends only on z.
ρ_w	Water density. It is considered to be constant (not as a function of depth z, temperature θ or salinity Sal).

access a wide source of energy but specific challenges must first be confronted [8–10].

If the life cycle cost for an MRE farm [11] is analyzed, it is possible to conclude that the installation and maintenance procedures are of the utmost importance and must be optimized from the technical and economical points of view [12]. Furthermore, because the main purpose of these kinds of devices is energy harnessing, which has the potential to be competitive with regard to conventional generation in the future [13], a principal aim of this study is to reduce maintenance costs. One well known means used to reduce costs is that of successively automating more tasks, which means less human intervention or the possibility of using the cheapest general purpose ships rather than high cost special vessels for maintenance purposes. Some previous papers have studied the fully automatic maneuvering emersion and immersion of devices [14,15]. If closed loop control is considered for depth control [16], the first step required is to obtain dynamic models of submerged bodies, with good correspondence with real responses, which requires minimum computational effort from which control schemes can be developed. Examples of this kind of simple models used to further control design can be seen in Refs. [17–19], in which only a lumped mass was considered for modeling and controlling a three degrees of freedom flexible robot, or [20,21] in which only a simple mass and gravitational effects together with simple transitions among actuators were used to model and control a stair climbing mobility system.

The approach adopted in this paper avoids the complex chaotic dynamic models of [22,23] and the solution of a nonlinear potential theory of surface waves [24] based on underwater landslides an hence the required dynamic computing effort. The simpler approach to be adopted is the well-known Morrison et al. equation [25,26] and the well-established expressions for added mass provided in Ref. [27]. The computation of added mass, viscous drag and buoyancy forces on vertical cylinders under different conditions is addressed in Refs. [26,28], whereas the complex modeling of underwater robotics arms has been investigated in Refs. [29,30]. The simpler dynamics modeling approach proposed will address a horizontally disposed and vertically moving cylindrical body that performs open loop emersion motions. The model will include free surface interaction via a single degree of freedom model. Thus the proposed model requires minimal computational effort and is developed in a manner analogous to [17,20].

The paper is structured as follows: Section 2 provides a brief description of different operations for devices. In Section 3 we illustrate the proposed dynamic model of a submerged body when it performs vertical movements and a nonlinear stability analysis based on Lyapunov/Chetaev functions is also included. Section 4 briefly describes the experimental setup and the prototype built for experimental validation, including the design criteria. Section 5 describes a laboratory experimental setup and presents the results obtained, which show a good fit between their simulated and the corresponding experimental responses. Finally, Section 6 shows the conclusions of this article and our proposals for future work.

2. Operations with vertical motion of submerged bodies

The development of marine renewable energies is clearly linked to the solution of a set of both technological and economic challenges. One of the most important challenges is the development of procedures for the installation, maintenance and dismantling of the devices. These procedures should be designed to provide high reliability and to be performed within an appropriate “weather window”, with reduced associated costs. Several aspects are considered: the transportation of each of the devices from the earth hub to its installation site, the preparation of the sea bottom, the placement and installation of anchor systems and/or the mooring system deployment, and the positioning, connection and disconnection of the main units of the devices.

In the case of devices with a floating support it is not necessary to separate the power generation unit from their support to undertake maintenance subject to their structures withstanding operational forces and external wave or wind forces. For a fully submerged device it must be possible to extract the main element from the water (including Power Take-Off (PTO) unit) for maintenance without any difficulty. The design of the entire device is significantly influenced by the need to facilitate the distinct operations of engage, emersion and immersion. For such procedures the following principal alternatives exist:

- The use of a servoactuated crabbing based system to move the main element from the support structure [31,32].
- The use of elevation and placement by means of floating cranes [33–37].
- The use of a ballast management system to generate vertical forces, thus enabling the main element's emersion and immersion movements to be controlled [14,38–40].

By providing instrumentation and a control system that performs emersion and immersion manoeuvers in a teleoperated or fully automatic mode, human operator involvement can be

[1] Without compression effects.