INERTIAL BEHAVIOR OF OFFSHORE DEVICES

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Abstract: *In the last years, there has been a continued growth in the number of offshore operations for handling large equipment and objects, with emphasis on installation and maintenance of devices for exploiting marine renewable energy like generators for harnessing wind, waves and currents energy. Considering the behaviour of these devices during manoeuvrings, and due to their size and by the interaction with the surrounding fluid, the effect of inertial forces and torques is very important, which requires a specific modelling.*

This paper especially discusses the masses and moments of inertia modelling problem, with the aim to use it in the simulation of the complex manoeuvres of these devices and in the automatic control systems designed for their offshore operations. Given the importance and complexity of the added mass modelling, a method for its early design identification, developed by the R&D Group on Marine Renewable Energy Technologies of the UPM (GITERM) and its use on special cases like emersion manoeuvres of devices from underwater to the surface will be presented.

Keywords*: Modelling submerged bodies. Added masses. Maritime manoeuvres. Control and Simulation.*

1. INTRODUCTION

The need to find solutions to energy and environmental problems is supporting to consider the Marine Renewable Energies (MREs) as a component of the "energy mix" in the near future. The sea with its large surface area, volume, and heat capacity is the main collector and storage of solar energy (and lunar energy) on our planet [1].

Among the devices for the use of the MREs, at present, the main are the wind, wave and currents types, which show a shift from near-shore to offshore, as it happened in the twentieth century with “oil & gas” platforms.

The devices for the use of the MREs (Fig. 1) usually have large dimensions, requiring complex maritime operations for their installation, maintenance and decommissioning. In many cases it is convenient, and even necessary, the use of big submerged bodies to reduce the lifting capacity required for large cranes, in which the forces and moments of inertia are very significant, making it necessary to control their movements, usually with the help of ballast tanks, as far as they do not usually have own propulsions means, as in the case of submarines or underwater robots [2].

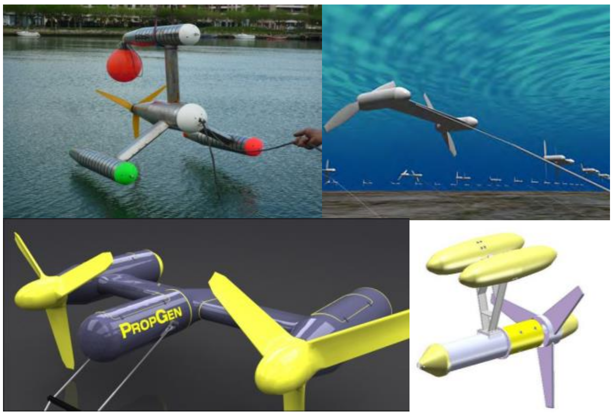

Fig. 1. Marine devices for harnessing sea energy

To design and simulate these manoeuvres it is necessary to develop models and tools to evaluate their behaviour before making the complex, expensive and sometimes dangerous sea trials [3]. Being the modelling their masses and inertias one of their distinguishing aspects, compared to the bodies moving in the air.

2. FORCES OVER A DEVICE IN SEA

Considering the typical shape of devices shown in Figure 1, and in order to study its dynamic behaviour, the device can be decomposed into a series of relatively simple body shapes, overlaying their effects. The types and modelling of the most significant non-inertial types are presented below.

An object at sea is subject to different types of local forces whose integration along its surface gives the resultant force and torque which can be classified into the following types:

– Gravitational Forces. Equal to the sum of the solid and fluid weights inside the object.

- Hydrostatic pressure. Its resultant is the buoyancy force.
- Hydrodynamic forces, which are complex and a function of the relative velocity between the fluid and the object.
- Aerodynamic forces. Due to its minor magnitude, they can be neglected in a first approach.
- Inertial forces. Equal to the product of masses and accelerations, their mass analysis in the case of submerged devices is more complex than in the case of an object moving in the air.
- External forces, mainly the action of mooring ropes, electrical cables, and waves.
- The radiation forces related to the waves generated by the body movements.
- The reaction from the power system that capture the marine energy.
- The actuator elements to control the device motions.

During the manoeuvres of these devices there are two different phases of motion that require a differentiated modelling to represent their dynamic behaviour:

- When the body is fully submerged, gravitational and hydrostatic forces are almost balanced. Wave excitation and reaction forces are negligible and, those of hydrodynamic and inertial character are dominant. The singular problem of partially filled ballast tanks, in which the mass changes in position with the movement [4], can be relevant, but their study is beyond the scope of this work, so these tanks are considered completely full’s or empties.
- When the body floats on the surface, are of major importance the differential immersed volume, linked to areas of flotation, the exciting and reaction forces of waves and the inertial ones that can undergo in major changes. In this case, the typical model is shown in Figure 2 taken from [5].

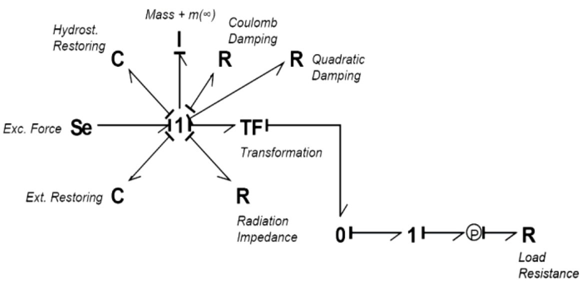

Fig. 2. Classification of forces for a the body on the water surface

Both cases require the consideration of the external reaction forces, mainly those from mooring, because that it is not been captured energy during manoeuvres.

For a submerged body, hydrodynamic forces depend on relative water velocity with respect to the body (*Uw*). They are divided in two components: one of suction or resistance (*Fd*) in the direction of flow, and another of lifting nature (*Fl*) perpendicular to the previous one [6]. Their values can be calculated using (1) and (2):

$$\overline{Fd} = \frac{1}{2} Cd \cdot \rho \cdot A \cdot |Uw| \cdot \overline{Uw} \qquad (1)$$

$$\overline{Fl} = \frac{1}{2} Cl \cdot \rho \cdot A \cdot Uw^2 \cdot \bar{s} \qquad (2)$$

Uw and ρ are respectively the speed and density of water; *Cd* and *Cl*, the drag and lift coefficients. *A* is a significant surface and $\underline{s}$ is a unit vector perpendicular to the current.

When the body is floating, it is also necessary to consider in the model the forces related to waves [7]. In the first approach, a linear model can be used for the radiation forces (*Fr*), in which, as far as they are of a dissipative nature, force is in phase with the velocity. That is (3) can be used as a starting point:

$$\overline{Fr} = [B] \cdot \overline{Uw} \qquad (3)$$

Where the elements of the matrix [*B*] have the dimensions of damping coefficients. Computer applications are commonly used for the identification of such matrices [8].

3. INERTIAL FORCES

In the case of a rigid solid, inertial forces are usually decomposed by its effect on the translation and rotation movements, being their modelling widely studied [9].

The basic equations are shown below for these: forces (4); torques (5); the inertia tensor (6), with examples of volume integrals for the diagonal elements (7) and; other (8).

$$[Fi] = [M][v'] \qquad (4) \qquad\qquad [Ti] = [I][\omega'] \qquad (5)$$

$$[I] = \begin{pmatrix} I_{xx} & I_{xy} & I_{xz} \\ I_{yx} & I_{yy} & I_{yz} \\ I_{zx} & I_{zy} & I_{zz} \end{pmatrix} \qquad (6)$$

$$I_{xx} = \int_V \rho (y^2 + z^2) d^3 r \qquad (7)$$

$$I_{yz} = I_{zy} = \int_M - yz \cdot dn = \int_M - \rho yz \cdot d^3 r \qquad (8)$$

Although normally the mass matrix of (4) can be simplified as a scalar multiplied by the unitary matrix, the existence of added masses, as discussed below, complicates the formulation.

For a solid body included in a floating device, Figure 3 shows the typical breakdown of the masses (and thus the inertial moments) when it is partially submerged. It can be seen that the total mass is equal to the sum of:

- The mass of the solid part of the object (*Mee*), consisting on the mass of the structure and the equipment installed in the device (this group includes the equipment associated fluids).
- The mass of water in ballast tanks *(MwL)*. This mass is a very important part of the set, allowing the draft

control and changing the orientation of the device. Filling and emptying various seawater tanks perform the control of this mass.

- The trapped water mass (*MwT*) in the inner parts of the object, which are in communication with seawater. Usually corresponds to spaces between the hydrodynamic envelope and the structural hull.
- The mass of water added (*MwA*), which is the water mass surrounding the object and which is accelerated as a result of the body movement.

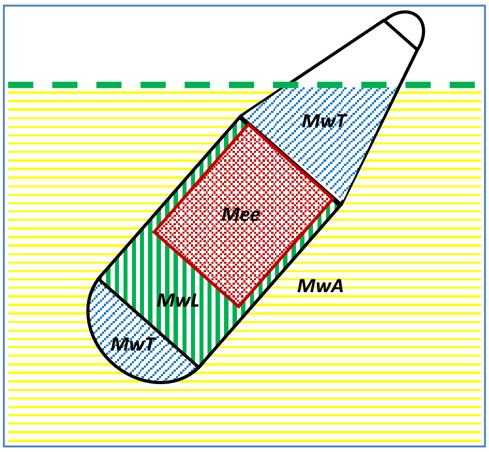

Fig.3. Masses classification for an object floating in water

For the calculation of the first three, (9) to (11) can be used:

$$Mee = \sum Mes_i + \sum Meq_j \tag{9}$$

$$MwL = \rho_w \cdot g \cdot \sum \int_{Vk} dv \tag{10}$$

$$MwL = \rho_w \cdot g \cdot \sum \int_{Vl \cap Vw} dv \tag{11}$$

Mes_i is the mass of each structural element; Meq_j is the mass of each device, ρ_w the density of water, g the acceleration of gravity, Vk the volume occupied by each tank and $Vl \cap Vw$ the intersection of the volume of a space communicating with sea with the halfspace below the sea surface.

For the inertia around the axis ξ, naming r_ξ the distance to the axis, and I_ξ to its own moment of inertia, the equations (12) to (14) are obtained.

$$Iee_\xi = \sum r_{\xi i}^2 \cdot Mes_i + \sum Ies_{\xi i} + \sum r_{\xi j}^2 \cdot Meqj + \sum Ieq_{\xi j} \tag{12}$$

$$IwL_\xi = \rho_w \cdot g \cdot \sum \int_{Vk} r_{\xi k}^2 \cdot dv \tag{13}$$

$$MwL_\xi = \rho_w \cdot g \cdot \sum \int_{Vl \cap Vw} r_{\xi l}^2 \cdot dv \tag{14}$$

4. MODELLING OF ADDED MASS

In fluid mechanics, added or virtual mass is the inertia added to a system in order to consider that an accelerating or decelerating body has to move (or deflect) some volume of the surrounding fluid as it moves through it.

For instance, the added mass can easily reach ¼ or ⅓ of the mass of a ship when and therefore represents a significant amount. In general, the added mass is a second-order tensor, relating the fluid acceleration vector to the resulting force vector on the body.

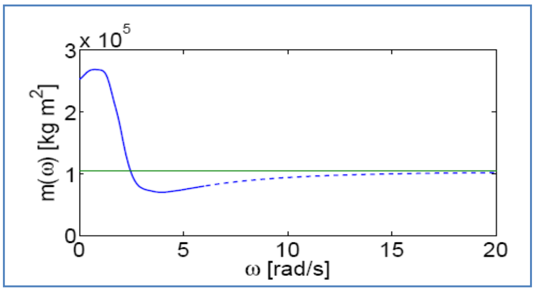

Fig.4. Added mass variation with frequency for a vertically oscillating buoy

Modelling the added mass of a body immersed in a fluid is not a simple problem, especially if it is floating. For that purpose, CFDs based applications or methods such as WAMIT panels [8], can be used for obtaining it. As it can be seen in Figure 4, taken from [5], some cases can present a significant variation with frequency. The added mass tensor is usually decomposed into two symmetric matrices, the mass matrix [Ma] and the moments of inertia matrix [Ia] (15):

$$[Ma] = \begin{pmatrix} \lambda_{11} & \lambda_{12} & \lambda_{13} \\ \lambda_{12} & \lambda_{22} & \lambda_{23} \\ \lambda_{13} & \lambda_{23} & \lambda_{33} \end{pmatrix} \qquad [Ia] = \begin{pmatrix} \lambda_{44} & \lambda_{45} & \lambda_{46} \\ \lambda_{45} & \lambda_{55} & \lambda_{56} \\ \lambda_{46} & \lambda_{44} & \lambda_{66} \end{pmatrix} \tag{15}$$

Fortunately, in the case of the study of manoeuvres of MREs devices, with big bodies and slow movements, it is sufficient to calculate its value for $\omega = 0$ and parametric modelling approaches can be used with good results. Furthermore, if the device has a feedback control system the errors due to approximations will be attenuated [2].

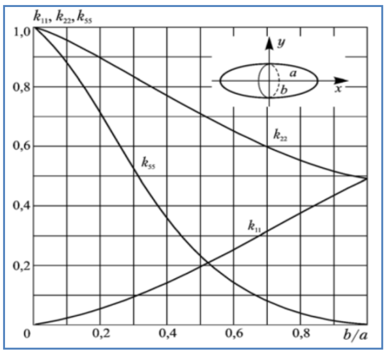

Fig. 5. Ellipsoid added mass coefficients.

As it can be seen in Figure 1, the overall device can be decomposed into a series of bodies, introducing a very limited error if each part is considered separately, approximating them to single bodies and then adding their effects. Basic modelling of the added mass of each body is based on the study of the potential flow around it. For example, in the case of a revolution ellipsoid, matrices are diagonal and their coefficients, k_{ij} in Figure 5 [11] are given by (16) and (17):

$$k_{11} = \frac{3\lambda_{11}}{4\pi\rho ab^2} \; ; \qquad k_{22} = k_{33} = \frac{3\lambda_{22}}{4\pi\rho ab^2} \qquad (16)$$

$$k_{55} = k_{66} = \frac{15\lambda_{55}}{4[\pi\rho ab^2(a^2+b^2)]}; \qquad k_{44} = 0 \qquad (17)$$

This method for modelling the forces in manoeuvring has been used to simulate the manoeuvres of various devices designed by the R&D group GITERM, using Simulink and OrcaFlex applications, including an original procedure for assessing the loss of mass added to the bodies partly out of the water volume [12], with good results.

Given the difficulty in obtaining experimental data from sea trials, a validation of the method has been performed through tests over the emersion manoeuvre of a cylindrical body, developed in the laboratory of ETSIN LEEyS [13]. Their results are shown in Figure 6, proving the validity of the method. In this work was of a great importance the theoretical and experimental identification of the parameters of viscous and inertial forces.

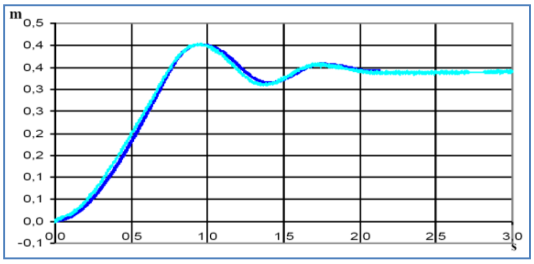

Fig. 6. Cylinder emersion simulation (blue dark) versus experimental results (blue light)

5. CONCLUSIONS

When considering operating manoeuvres of large bodies at sea, in addition to the own mass and inertia the added mass of water must be taken into account as far as it significantly affects their inertial behaviour.

Several of these masses are of variable character during certain manoeuvres, which must be considered in the design of control systems and in the simulation models.

Although that advanced tools can be used for modelling of added mass, most of industrial applications can be accomplished with a parametric model, which allows obtaining adequate results with reasonable cost and time.

When the actuation system for manoeuvring is based on the handling of large ballast tanks, modelling their behaviour and especially their free surfaces can be relevant. This aspect should be investigated in future works.

ACKNOWLEDGMENTS

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