

Design of a non-linear power take-off simulator for model testing of rotating wave energy devices

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Abstract

Eddy current brakes provide a versatile way of simulating the power take-off system (PTO) in the model testing of wave energy converters at small scale. These are based on the principle that a conductive material moving perpendicularly to a magnetic field generates a braking force proportional to its velocity.

This was applied in the design of the PTO simulator of a bottom-hinged flap wave energy converter model, at 1/16 scale. The efforts put into the accurate dynamic simulation of the device led to the development of a controllable PTO simulator, which can be applied to other small scale rotating wave energy device models.

A special power source was built to provide the required controllable current intensity to feed the magnetic field generating coils. Different non-linear damping PTO characteristic curves can be simulated by basing the current control on real-time velocity measurement.

The calibration of the system was done by connecting the device to a constant rotating speed motor and measuring the resistant torque produced by the PTO with a torque meter for different values of current intensity through the coils.

Keywords: Wave energy, non-linear PTO, experimental modelling, eddy current brake.

1 Introduction

The design of the power take-off system (PTO) simulator is one of the most important challenges in the design of a wave energy converter small scale model. This is enhanced when the specified PTO damping characteristic is non-linear and different characteristic curves are to be tested. For small scale models, the extracted energy is more conveniently converted to heat, as the extracted power scales down with the power of 3.5 of the length. Throttling processes are often used to convert pneumatic or hydraulic power into heat. These methods have however several limitations as the damping level is difficult to control and calibrate, and undesirable non-linearities tend to occur.

This paper presents the design and calibration of a controllable PTO simulator based on eddy currents, which was used for the testing of a 1/16 scale model of the WaveRoller¹ wave energy converter. This wave energy device consists of a fully submerged bottom hinged plate that takes advantage of the large horizontal velocity component associated with shallow water waves.

This type of geometry has been studied analytically in 2D by several authors, using potential flow methods in a variety theoretical cases. Evans [1] studied the wave diffraction by a submerged vertical plate with small oscillations, obtaining expressions for the forces and the scattered waves away from the plate. Evans and Porter [2] addressed the hydrodynamic characteristics of this type of moving plate, obtaining a semi-analytical solution for the added inertia and radiation damping for dif-

¹<http://www.aw-energy.com/>

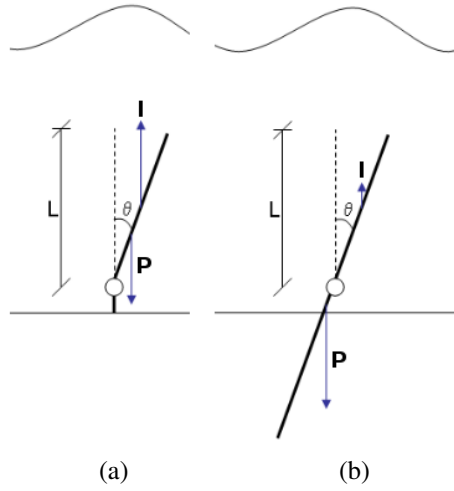


Figure 1: Two equivalent distributions of weight and buoyancy forces on a rotating plate.

ferent water depth to plate height ratios.

Nearshore seabed mounted wave energy devices based on this concept have been studied by the research group at Queen's University Belfast. Several of papers document the modeling of this type of geometry, which led to the development of the *Oyster* wave energy converter (see [3], [4] and [5]).

Eddy current brakes are a well known application of induced magnetic fields. A simple application of this type of brake is presented in [6]. An extended review of electromagnetism can be found, for example, in [7].

The application of eddy current brakes has been previously used at the University of Edinburgh, in model scale study of the *Sloped IPS Buoy* heaving/surging device. The basis for the design of the *Sloped IPS Buoy* PTO model are presented in a paper by Taylor and Mackay [8], and results for the device performance at constant damping are reported in [9].

In the case of the bottom-hinged rolling plate, which is the object of the current study, a low-speed rotating eddy current brake was designed, with the electromagnets being located inside a watertight box. Six pairs of electromagnets create a magnetic field perpendicular to the rotating aluminum disc, which causes the disc to be braked proportionally to its angular velocity. By means of the variation of the current intensity on the electromagnets as a real time function of the measured angular velocity, the damping coefficient can be time variable and follow any given function of the angular velocity.

2 Mathematical model

A mathematical model for the problem can be established, considering a time-dependent rotation of the bottom-hinged plate, θ , induced by the incident water waves. From a static point of view, when the plate is displaced from its equilibrium position, a restoring moment occurs, as the plate density here is smaller than the water density. Figure 1a presents a schematic representation of the geometry of the device and the applied forces in a

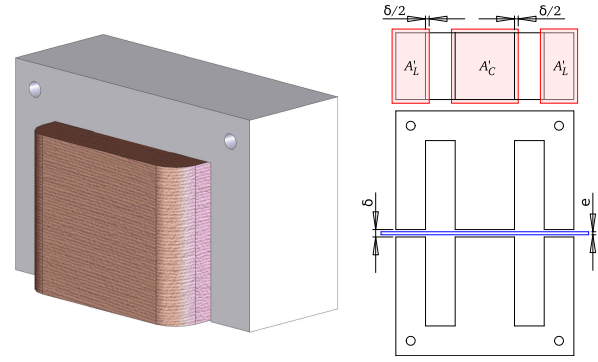


Figure 2: Definition of the *E-type* magnetic core geometry: the effective area A' (shaded) is larger than the area of the central and side leg faces.

static situation.

The rotation equilibrium equation may be established as,

$$I_m \ddot{\theta} = M_d + M_r + M_{hs} + M_{PTO} + \Phi, \quad (1)$$

where I_m is the plate moment of inertia, M_d the excitation (diffraction) moment caused by the incident waves, M_r is the radiation moment, M_{hs} is the the hydrostatic restoring moment, M_{PTO} is the moment applied by the PTO and the term Φ is a force that accounts for the real fluid viscous effects in the water. The two last terms are generally described as non-linear functions of the plate velocity.

The hydrostatic moment M_{hs} can be described as

$$M_{hs} = (-\rho_w g V_b \hat{x}_b + m g \hat{x}_g) |\sin \theta|. \quad (2)$$

Here ρ_w is the water density, V_b the plate volume, m the plate mass, $\hat{x}_b$ the distance from axis of the plate's centre of buoyancy and $\hat{x}_g$ the distance from axis of the plate's centre of mass.

The existence of the PTO simulator underneath the plate, but connected and rotating with it, will correspond to a different mass distribution of the system, as compared to the prototype. The diffraction and radiation moments in Eq. (1) are not changed by the mass distribution at model scale, provided that the geometric dimensions of the plate are scaled correctly. The scaling and modelling of the moment applied by the PTO is the central part of this study.

In the experimental model, the PTO simulator is made of an aluminium disc rotating around a vertical axis. The aluminium disc and its connections to the plate are axisymmetric. As a consequence, they do not introduce differences in the hydrostatic restoring moment term of Eq. (1), but they increase the moment of inertia. This needs to be compensated by a corresponding reduction in the plate inertia, as to obtain similitude between the model and prototype according to the Froude criterium, the moment of inertia must be accurately scaled. The overall increase of the moment of inertia of the model could be only be compensated by a decrease in the added inertia of the radiation moment, which would be complex and is not followed here.

Even though the restriction on the moment of inertia, it is possible to change the variables in Eq. (2), as long as

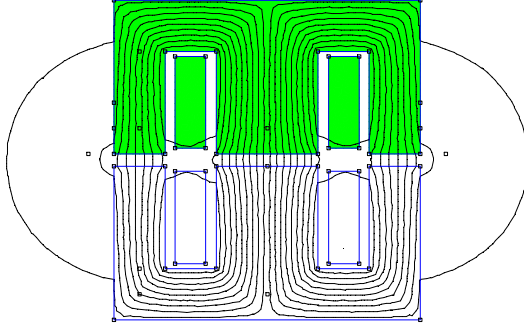


Figure 3: Magnetic field lines of a middle cut diagram of two iron-silicon-core electromagnets facing each other.

the hydrostatic restoring moment M_{hs} remains constant. This means that the plate gravity centre could even be located below bottom level, keeping similitude conditions, as exemplified in Fig. 1b. As a consequence, it is possible that both the weight and buoyancy cause restoring moments, as long as their sum is equal to the original restoring moment.

Scaling the mass of the system, the plate volume and the mass and buoyancy centers is therefore not necessary, as long as M_{hs} is constant, but a very thin and light plate may be required so to compensate the increased contribution for the moment of inertia by the PTO simulator.

3 Design concept

3.1 Electromagnets

Moving a conductive material perpendicularly to a magnetic field produces a force between them, which is proportional to the relative velocity. This electromagnetic braking force density, $\mathbf{F}$, is given by the vector product of the current density $\mathbf{J}$, and the flux density $\mathbf{B}$,

$$\mathbf{F} = \mathbf{J} \times \mathbf{B}. \quad (3)$$

For an aluminium conductor it is considered that the current density is proportional to the electric field $\mathbf{E} = \mathbf{v} \times \mathbf{B}$, as expressed by

$$\mathbf{J} = \sigma \mathbf{E} = \sigma (\mathbf{v} \times \mathbf{B}), \quad (4)$$

where σ is the electric conductivity of the material moving at velocity $\mathbf{v}$. In this way,

$$\mathbf{F} = \sigma (\mathbf{v} \times \mathbf{B}) \times \mathbf{B}. \quad (5)$$

Assuming $\mathbf{B}$ orthogonal to $\mathbf{v}$, we obtain

$$F = \sigma v B^2, \quad (6)$$

where $B = \|\mathbf{B}\|$.

For a rotating disc, at constant angular velocity $\dot{\theta}$, the absolute value of the braking torque is

$$M_{PTO} = N_p \int \sigma r^2 \dot{\theta} B^2 dV = \sigma \bar{r}^2 \dot{\theta} \bar{B}^2 e A', \quad (7)$$

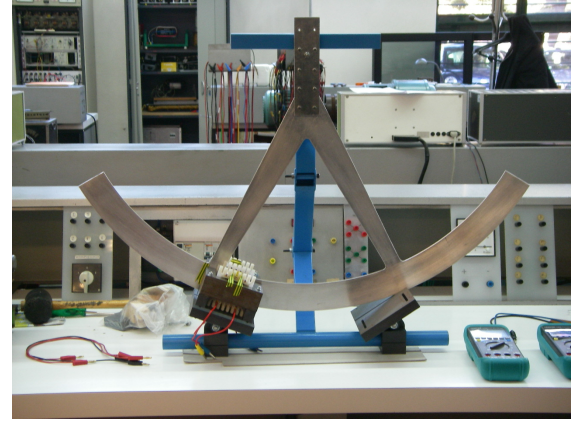


Figure 4: Preliminary tests with an aluminium pendulum.

where N_p is the number of electromagnet pairs, $\bar{B}$ is the average absolute value of the magnetic field, $\bar{r}$ and e are the rotating disc average radius and thickness, $A' = A'_C + 2A'_L$, $A'_C = k_C A_C$, $A'_L = k_L A_L$, A_C and A_L are the area of the central and side leg *E-type* cores faces (see Fig. 2), k_C and k_L are correction factors to take into account the fact that the effective area is higher than the area of the core faces due to the existence of round shaped flux density streamlines.

Considering that the magnetic circuit is represented only by the air gap reluctances, we define the equivalent magnetic reluctance

$$R_{eq} = R_C + \frac{R_L}{2} = \frac{\delta}{\mu_0} \frac{2A'_L + A'_C}{2A'_L A'_C}, \quad (8)$$

where

$$R_C = \frac{\delta}{\mu_0 A'_C} \text{ and } R_L = \frac{\delta}{\mu_0 A'_L} \quad (9)$$

are the central and side leg magnetic reluctance, and δ is the length of the air gap (Fig. 2) and μ_0 is the magnetic permeability. As shown in Eq. (9), δ shall be as close as possible to e to minimize the magnetic reluctance, but this is limited by the geometric accuracy of the PTO manufacture.

A current intensity I in the N_s turns winding produces a flux $\phi = \bar{B} A'$ in the magnetic circuit central leg

$$\phi = \frac{N_s I}{R_{eq}}, \quad (10)$$

where N_s is the total number of wire turns.

Current intensity I can be easily related with damping factor $C = M_{PTO} / \dot{\theta}$ by combining Eq.s (7), (8) and (10), giving

$$C = N_p \frac{(2A_C A_L I N_s \bar{r} \mu_0)^2 e \sigma}{(2A'_L + A'_C)^3 \delta^2}, \quad (11)$$

where N_p is the number of pairs of electromagnets and each pair corresponds to N_s turns. In the present design is $\delta = 3.5$ mm, $e = 2$ mm, $\bar{r} = 180$ mm, $A'_C \simeq 2A'_L = 0.0016$ m², $\mu_0 = 1.257 \times 10^{-6}$ N·A⁻², $N_s = 2000$, $N_p = 6$.

Figure 3 shows the flux density streamlines in the magnetic circuit, obtained as given by a 2D Finite Element software [10]. As can be seen in Fig. 3 the majority

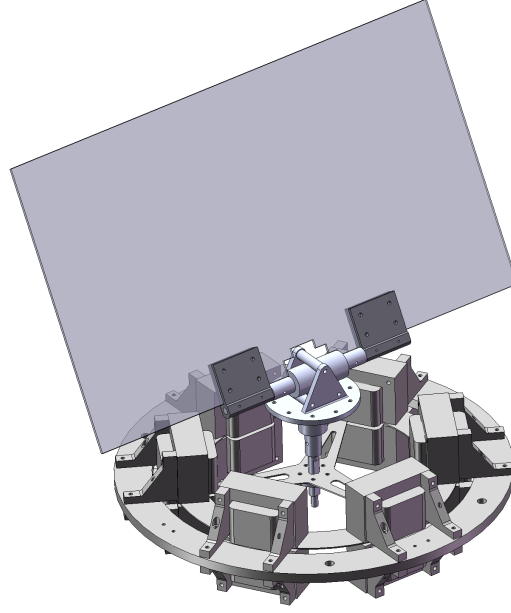


Figure 5: Schematic representation of the PTO simulation system.

of the magnetic field lines are enclosed in the iron-silicon core and in the air gap region. Results plotted in Fig. 3 also show that the magnetic flux density streamlines are mostly straight lines in the air gap.

The reference design condition for the PTO simulation system was the specified maximum damping factor $C_{\max}$ for which a system with six pairs of electromagnets was chosen. Each pair of magnets is connected in serial, such that the electric connection assures the magnetic flux between the cores, and that the generated magnetic fields do not cancel out.

A first concept demonstration test with an aluminium pendulum passing a pair of electromagnets was performed, as represented in Fig. 4. In these tests, the pendulum was started from a fixed point and the current intensity in the coils was changed.

3.2 Mechanical Components

The plate is connected through two aluminium hinges and a bevel “tee” gearbox to a 2 mm thickness rotating aluminium disc (see Fig. 5), located beneath the tank bottom level (inside the tank pit) in a watertight box. In the present case, the gear ratio of the bevel “tee” gearbox is 1:1. If this was not the case it should be noted that the moment of inertia of the disc should be multiplied by the gear ratio.

The aluminium disc rotates about a vertical axis, its angular rotation being the same predicted for the plate, i.e., maximum of 45 degrees to each side from the equilibrium position.

The disc movement is damped by six pairs of electromagnets. The cover watertight box is connected to the atmosphere through two 100 mm diameter flexible tubes, used simultaneously for cabling and ventilation.

4 Control Device

As described in Section 3, PTO model was designed to provide a specified

$$M_{\text{PTO}} = C(\dot{\theta})\dot{\theta} \quad (12)$$

relationship, which might be easily modified within the given working range. Here C is required to be dependent on the plate velocity and this is achieved by properly feeding current into coils (see Eq. (11)).

A specific dedicated electronic device was developed to provide a controllable and reliable level of DC current. This has three main components: (i) sensor part including position, temperature and current sensor; (ii) power control device comprising phase control integrated circuit and pair of thyristor/diode modules; (iii) peripheral interface controller comprehending dsPIC 30F4013 micro-controller and computer for data storage.

The position sensor is attached to the PTO simulator disc shaft to measure the angular position θ of the rotating aluminium disc. The angular position information is acquired by the dsPIC.

The dsPIC acquires signals, performs calculations, generates the control signal to feed current into the coils and sends the logged data to the computer for storage via a RS-232 connection. The main task of the dsPIC is to compute angular velocity $\dot{\theta}$ in real-time and adjust the control output voltage accordingly. The calibration described in section 5 enables a table to be build with different values of current I as a function of the angular velocity $\dot{\theta}$. Those values are then stored in the dsPIC memory. Based on 0 to 5 V DC input signal, the power control device provides the required 0 to 10 A DC current to the braking coils, which is measured by a LTS15NP Hall effect current transducer to allow feedback control.

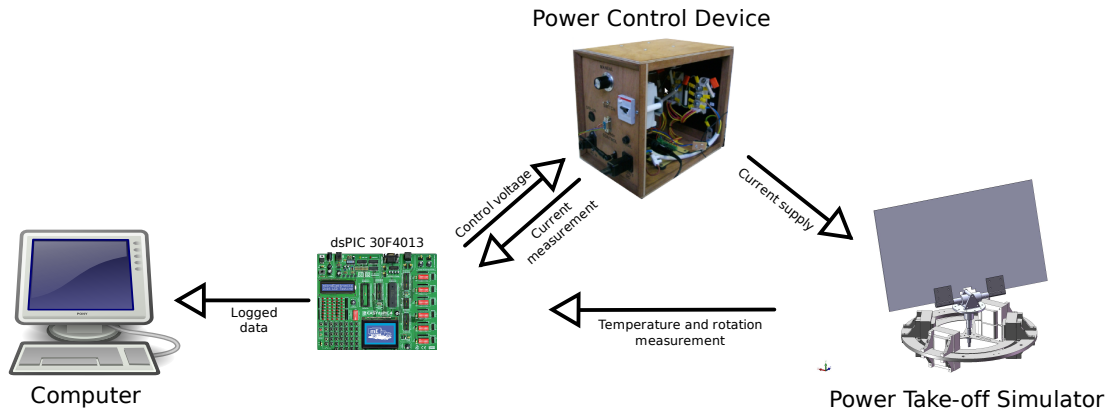


Figure 6: Relation between the peripheral interface controller, the power control device and the power take-off system.

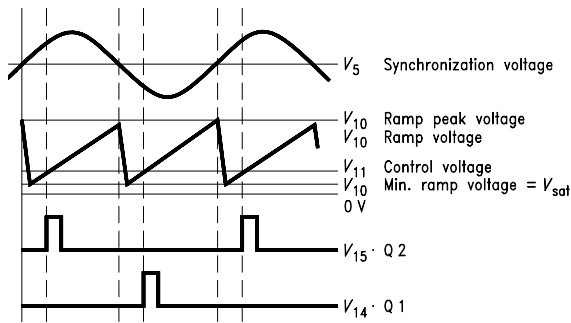


Figure 7: Phase control TCA785 IC relevant pulses.

The power control device was built specifically for this work and consists of a half-controlled single-phase bridge circuit with two trigger pulse transformers for low-power thyristors, a current sensor and a 230 V AC to 15 V DC transformer and rectifier. The AC current feeds the thyristor bridges and the transformer and provides the synchronization signal to the half-controlled single-phase bridge circuit. The 230 V AC to 15 V DC transformer supplies both the dsPIC micro-controller and the electronic circuits inside the power control device box. The latter controls a single-phase bridge circuit with two trigger pulse transformers for the low-power thyristors, which produces a rectified DC output current ranging from 0 to 10 A.

A TCA785 phase control integrated circuit was used to control the pair of thyristor/diode modules. This circuit allows the recognition of zero passage, and provides a large ramp 250 mA output current. The synchronization signal is obtained via a high-ohmic resistance from the electrical grid. A zero voltage detector evaluates the zero passages and transfers them to the synchronization register, which controls a ramp generator. If the ramp voltage exceeds the control voltage, a signal is processed to the TCA785 logic. Depending on the magnitude of the control voltage, the triggering angle can be shifted within a phase angle between 0 and 180°. For every half wave, a positive pulse of approximately 30 μ s duration appears at the outputs. The pulse duration can be prolonged up to 180° via a capacitor. Relevant pulse shapes are shown in Fig. 7 including the electrical grid 50 Hz

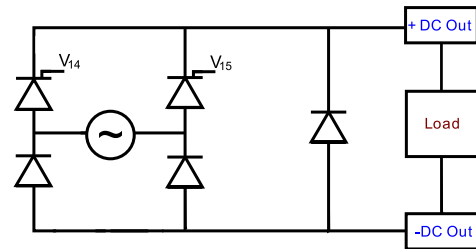


Figure 8: Electric connection between the thyristor/diode modules.

voltage, V_5 , the 100 Hz ramp voltage, V_{10} , which is combined with the control voltage, V_{11} , as described above, originating the thyristors trigger pulses V_{14} and V_{15} . A LM358 integrated circuit was also included to transform dsPIC 0 to 5 V control voltage to TCA785 0 to 15 V control voltage.

An ideal diode turns off, and becomes an open circuit, when its current decreases through zero. It turns on, and becomes a short circuit, when its voltage increases through zero. An ideal thyristor is the same as an ideal diode except that its turn on is inhibited unless the thyristor firing pulse is on. Thyristors are mainly used when high currents and voltages are involved, and are often used to control alternating currents, when the change of polarity of the current causes the device to automatically switch off (zero cross operation). The device can be said to operate synchronously as, once the device is open, it conducts current in phase with the voltage applied over its cathode to anode junction with no further gate modulation being required. Present configuration adopted two pairs of SKKH27/16E thyristor modules in combination with a power diode, as shown in Fig. 8. A resistor-capacitor (RC) snubber circuit was also included between thyristors anode and cathode terminals in order to limit the dV/dt to prevent triggering by a high rate of rise of off-state voltage.

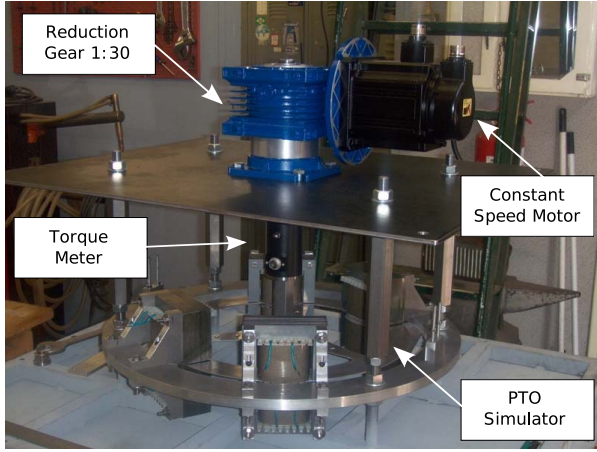


Figure 9: Calibration with controllable constant rotation speed motor and torquemeter with identification of its components.

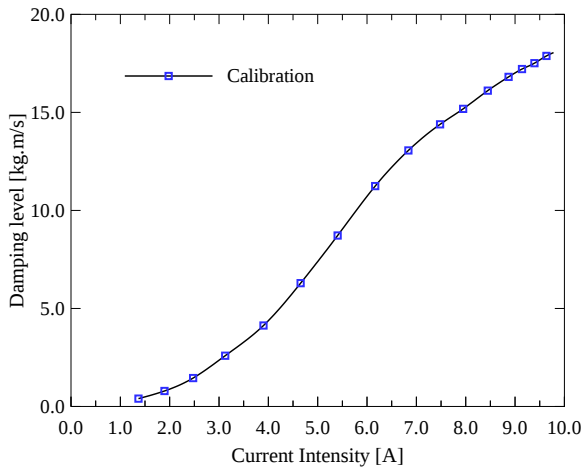


Figure 10: Brake performance for magnet spacing $\delta = 3.5$ mm.

5 Model Calibration

The experimental set-up for the calibration is presented in Figure 9.

The PTO simulator was connected to a motor controlled to produce fixed speed. As the desired range of angular velocities to use in the calibration is under 1.0 rad/s (9.55 rpm) and typical motors have a higher nominal rotation speed, a 1:30 reduction gear was used in order to use the motor within its normal working range.

A torquemeter with a nominal torque of 50 N·m was installed between the motor and the PTO simulator. A set of tests was performed for constant angular velocity, varying the current intensity through the coils and measuring the correspondent torque value for each case.

During the calibration, the PTO simulator was connected to the “tee” gearbox to which the plate is attached during the tank tests. At the same time as having all the friction sources connected during calibration, this allowed to have an estimation of the friction torque in the system when no current is fed into the coils. This torque was estimated to be 0.27 N·m at 10 rpm, which can be considered an acceptable value considering the

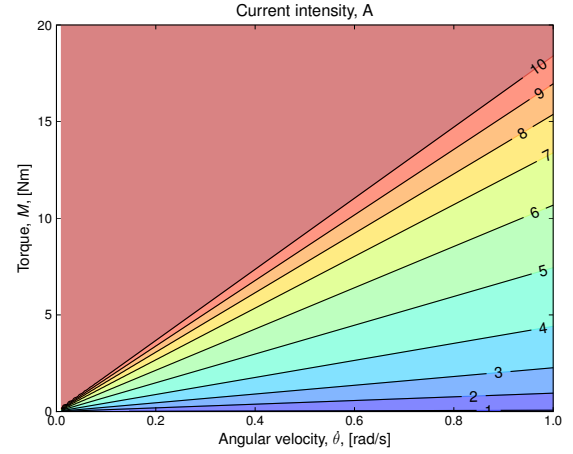


Figure 11: Schematic representation of the design space for the configuration presented in this paper. The current intensity in the coils is limited to 10 A.

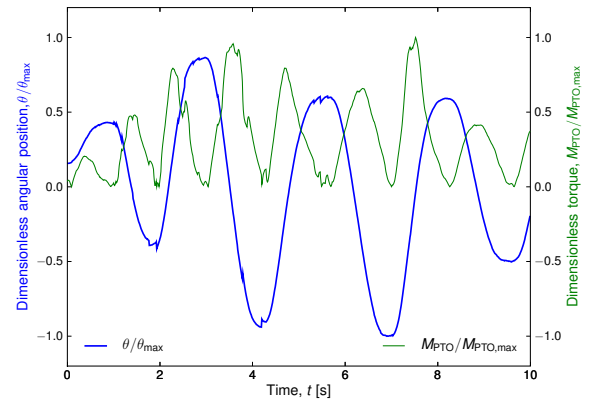


Figure 12: Example time series of plate rotation and corresponding torque for a non-linear power take-off law.

target values in the simulation, which is around 20 N·m.

The values obtained for damping coefficient, C , for different values of current intensity, I , are represented in Fig. 10 obtained for a PTO simulator with six pairs of electromagnets and $\delta = 3.5$ mm. Although the target value for damping was achieved, the fact that the expected parabolic shape of this curve is not verified for the higher current intensity suggests that a saturation phenomenon may be happening, which will be further investigated.

Figure 11 represents the application of the calibration function on a torque-angular velocity space, considering the current limited to 10 A, as given by inverting the curve fitted to the data plotted in Fig. 10.

Considering a specified relationship between the torque M_{PTO} and the angular velocity $\dot{\theta}$, for a given wave energy converter model, the values of the current intensity needed for the corresponding damping and velocity are obtained from results plotted in Fig. 11.

A lookup table representing the final curve $I(\dot{\theta})$ is included in the dsPIC real-time control program in order to perform the specified non-linear PTO damping characteristic curve (Eq. (12)).

Figure 12 presents a time series of the wing rotation, showing the correspondent torque applied to the system by the PTO simulator. This was obtained using a non-linear PTO curve within the design space of the device.

Conclusions

A real time controllable eddy current brake PTO simulator for small-scale model testing of rotating wave energy converters was designed and tested at Instituto Superior Técnico. Eddy current brakes are based on the principle that a braking force proportional to the velocity is produced when a conductive material moves perpendicularly to a magnetic field. In the present device, the magnetic field is generated by electromagnets, being the braking force function of the current intensity in the coils. The rotor is an aluminium disc which is connected to the rotating part of the wave energy model.

A special power source was built to provide the required controllable current intensity level. Different non-linear damping PTO characteristic curves can be simulated by basing the current control on real-time velocity measurement.

The calibration of the system was done by connecting the device to a constant rotating speed motor and measuring the resistant torque produced by the PTO with a torque meter for different values of current intensity through the coils.

This device was successfully used in the 1/16 model scale wave tank testing of the WaveRoller wave energy converter. In this application the PTO was located beneath the tank bottom level (inside the tank pit) in a watertight box, which allowed realistic non-intrusive PTO simulation conditions. The described PTO simulator constitutes a useful innovative device for experimental modelling of wave energy converters that will be further used in disclosed wave energy converter small scale model testing.

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