

The influence of a mono-directional PTO on a self-contained inertial WEC

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Abstract

This paper looks at the effect that a mono-directional Power Take Off (PTO) has on the motions and power extraction of a Wave Energy Converter (WEC). A mono-directional damper is one where the resisting force only operates in one direction. The model comprises of a cylinder that is restrained to move in heave, reacting against an internal mass (also limited to move in heave) that is connected to the cylinder by a spring and mono-directional damper in parallel.

This paper presents experimental results for a variety of different damping constants for mono-directional dampers which operate in both in expansion and compression. The response amplitude operators to monochromatic waves for both the cylinder, the internal mass and the relative motion between them are presented. A Pierson Moskowitz spectrum is used to look at the effect of an irregular sea state and the power extraction is calculated from this spectrum. The results show a greater response of the cylinder, but also in certain cases the internal mass and relative motion, when a mono-directional damper is present than when there is no damper. It is postulated by the authors that this is due to a “latching” effect. This increase in motion results in a greater than expected power extraction.

Keywords: Experimental wave tank testing, Nonlinear Power Take Off, Inertial point absorber, Wave Energy Converters (WECs)

1 Introduction

A wave energy converter's (WEC's) motion is influenced by its Power Take Off (PTO) system, which in turn affects the potential power extraction of the device. The experimental results from using a mono-directional damper are presented, where a mono-directional damper is a damper that only provides a resisting force when the damper is moving in one direction.

Having a mono-directional PTO will have advantages in terms of cost and potential simplicity of design, although the disadvantages are that it may reduce the power captured and it could limit the possible control strategies that may need to be implemented. A number of WECs which currently use a mono-directional PTO system are in various stages of development including the Manchester Bobber [1] and the Langlee Wave Power [2].

The type of device being presented is a self-contained inertial slack moored point absorber. The entire structure of the device, including the PTO system is encased in a watertight shell and the moorings are slack and are not connected to the PTO system. This means that this type of device is highly deployable. The PTO operates by having a large inertial mass that reacts against the rest of the body, which aids survivability [3]. This mass resides within the device and is connected to the main body by a spring and damper in parallel. Both the internal mass and the overall device are limited to move in heave only. The relative motion between the external shell and internal mass is used by the damper to extract energy.

This device is generic, and is not meant to replicate or become a commercial device but to be used to further understand how having a nonlinear PTO influences both the overall motions of the device and the power extraction.

The device is at a 1:40 scale and has been tested in the University of Edinburgh's curved tank [4] in both regular waves and irregular sea states. Different damping constants are tested, for dampers that provide a resisting force in both expansion and compression.

In this paper the detailed experimental setup will be given in section 2, including photos of the device and details of how the dampers are calibrated. The results are presented and discussed in the third section, which contains the response amplitude operator graphs obtained from a regular sea for the overall body of the device, the internal mass and the relative motion. This section also shows the motion of the device in a Pierson Moskowitz (PM) sea [5] for the different bodies and the power ex-

tracted from the system for a variety of different sea states.

2 Experimental Setup

2.1 The model

The model comprises a 16 mm diameter, 1.5 m long ground stainless steel rod that is held vertical and limited to move in heave by two rod-end bearings with PTFE (polytetrafluoroethylene) sleeves attached at its upper and lower ends. The rod-end bearings are fixed to a rig attached to the internal platforms within the wave tank. Rigidly attached near the center of the rod is a clear plastic cylinder with plastic bases at the top, middle and bottom. The bottom is fully sealed but there are circular cutouts in the top plastic base to allow the motion of the internal mass to be observed and to allow access and removal. The middle base's role is to provide a platform for the damper to be located. On the rod between the bottom of the cylinder and the internal mass is a custom made spring, sitting freely on the rod with a spring stiffness of 200 N/m. A close up view of the cylinder containing the internal mass, spring and damper is given in Fig. 1, which is shown out of the water. The entire setup, including the fixed platform, the rig with the rod-end bearings, the cylinder and the markers used for data collection can be seen in Fig. 2.

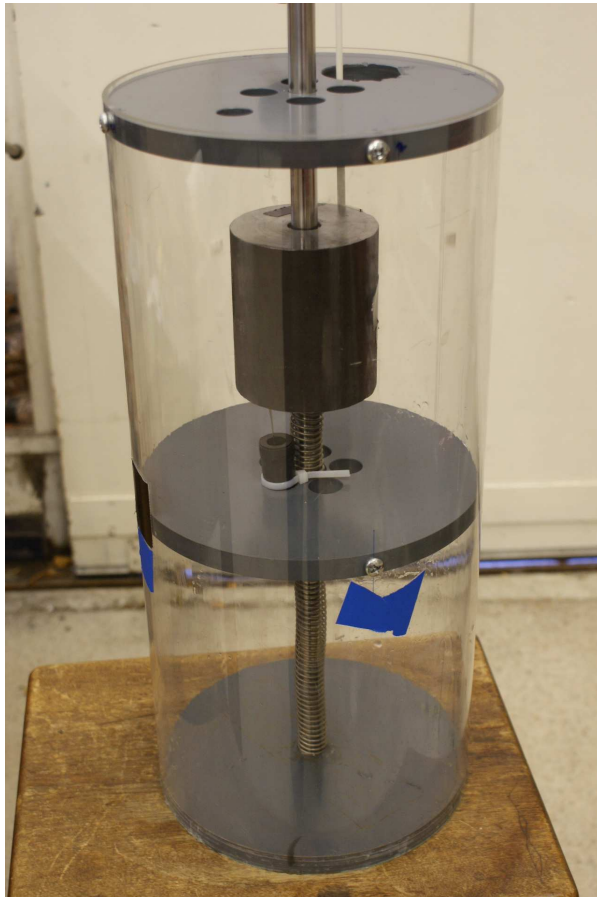


Figure 1: The experimental model, out of the water.

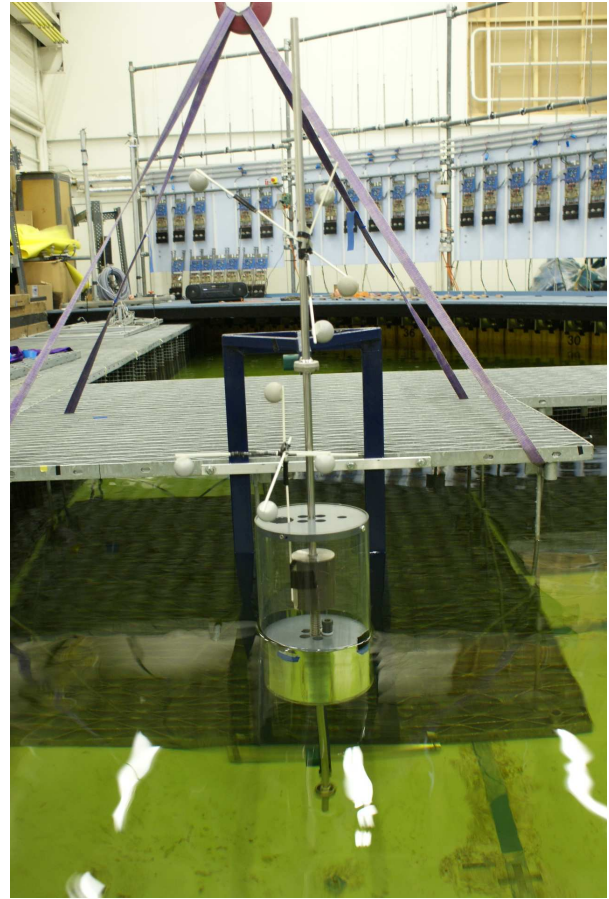


Figure 2: The experimental setup, along with the motion-detection markers.

The radius of the cylinder is 115 mm and it has a depth of 0.5 m with a draft of 0.285 m. The internal mass weighs 6.721 kg and the external body without the internal mass weighs 4.856 kg. The size of the internal mass and spring constant were chosen from previous work [6] based on Falnes' work on two body systems [7]. Since the model is at a 1:40 scale, a full scale device would have a cylinder radius of 4.6 m and an internal mass of 430 tonnes.

The positions of the cylinder and internal mass are monitored via markers which are observed by a Qualisys Motion Capture [8] infrared tracking camera system. The markers are attached to the rod and on a light dowel attached to the internal mass which protrudes from the cylinder and can clearly be seen in Fig 2 as the white spheres. The data collection from the markers is linked to the wave tank activation signal allowing data to be collected at a known time in the wave cycle, hence allowing different setups to be compared since they experience the same waves at the same known time.

2.2 Dampers

The dampers used are pneumatic and designed to have a linear response. They have the brand name Airpot [9]. Two types of dampers have been used: a compression damper, which provides a resisting force when the piston of the damper is compressed into the unit, and

an expansion damper, which provides a resisting force when the piston is expanding from the unit. There is a minimal constant resisting force in the opposite direction to the intended resisting force, this is generally assumed to be zero. The dampers are both adjustable via a screw to get a variety of damping constants. The dampers are sold as linear and there is a air spring effect of the dampers for the first 1-2 mm of motion, which produces a greater spring force for higher damping values.

2.3 Calibration of Dampers

The dampers were calibrated by rigidly fixing the body of the dampers, and using a 23 g and a 55 g mass that screws into the damper. A Qualisys marker is attached to the mass and the dampers are either manually extended or compressed (depending on which damper is being tested), released, and allowed to move under gravity due to the weight of the mass. The marker is tracked at 128 Hz and the extension / compression is repeated for a minimum of 128 s. For the damper where the marker is being recorded in compression, a plastic manual guide is used to keep the mass falling vertically, with as little interference to the motion as possible. The results are visually reviewed and individual results for which there has been difficulty obtaining a vertical descent are removed. Due to the manual input in this experiment the reliability of the dampers which produce force in compression is lower than the dampers that produce force in extension.

This obtains between 5 and 20 results for the mass falling under gravity which are averaged, and the overall damping factor is calculated using Equation 1.

$$c = \frac{m(g - a)}{v}, \quad (1)$$

where c [Ns/m] is the damping factor, m [kg] the combined weight of the mass and the marker, g [m/s^2] the acceleration due to gravity, a [m/s^2] the measured acceleration of the mass and v [m/s] the measured velocity of the mass. The resulting damping for each of the damper setups can be seen in Table 1.

Name	Direction of force	Damping constant [Ns/m]	Approx error [Ns/m]
Exp 1	Expansion	14.1	0.2
Exp 2	Expansion	31.1	0.5
Exp 3	Expansion	433	3
Com 1	Compression	26.8	5
Com 2	Compression	123	16

Table 1: Damping constants.

2.4 Friction

The main sources of unrequited friction and damping were in the two bearings which attach the rod to the

fixed rig and the bearing between the internal mass and the rod. The damping and friction from the two rod end bearings has been reduced by having the bearings able to rotate and using the PTFE sleeve. The level of damping is still non-negligible and increases as the body tries to move in pitch, which has a resonant frequency of 1 Hz. Since it is a direct stainless steel / PTFE contact it would be reasonable to assume that it is Coulomb damping. However for the same cylinder motion, regardless of which damper is used, this damping will be constant and linear, and it would be reducing the motion of larger oscillations in a consistent way. Therefore this damping can be neglected and it would be likely that there would be higher response of the cylinder if this damping was not present.

The damping between the bearing on the internal mass and the steel rod is more problematic, since for all motion, whether the damper is expanding or compressing, there will be an assumed Coulomb damping acting upon it and in opposition to motion at all times. This will interfere with our ability at looking at the effects of a mono-directional damper. The ratio of this damping to the mono-directional damper damping is unknown. Efforts are still being made to appropriately quantify this effect.

3 Results and Discussions

3.1 Experimental accuracy and repeatability

To test the repeatability and accuracy of the experiment for a single damper, a PM spectrum with a peak frequency of 0.90 Hz was used for 128 s to look at the correlation for 5 identical runs with damper “Com 1”. The runs were taken in succession with no physical interference to the model occurring between runs.

The data sets were used to find the R correlation, which is a linear measure of the normalized strengths of the relationships between two data sets, were an outcome of 1 is for identical data sets. The R value for the cylinder was above 0.985, with an average of 0.989. For tests with the internal mass the R values were above 0.975 with an average of 0.986.

An estimation of the spread of the data sets was calculated from Equation 2,

$$\frac{1}{N} \sum_{i=1}^N \left| \frac{X_i - x_i}{X_i} \right|, \quad (2)$$

where X_i represents one data set, and x_i represents a different data set which is being compared to the first, with the subscript i representing the time series progression and N the length of the set.

The spread for the cylinder were between 5.8% and 2.5% with an average of 4.1% for a 50 sec section that avoids values that are close to zero. The results for the internal mass were found to be between 4.1% and 10.2% with an average of 5.7%. Since the average position of the internal mass was near to zero, the results were reduced by 30 mm to have an average that is

approximately the same as the cylinder. This is to avoid having to divide by zero.

3.2 Response Amplitude Operator

The Response Amplitude Operator (RAO) is a ratio of the bodies response to the actual wave height and monochromatic waves have been used to obtain this. The waves were run for 16 s in order to reach steady state and results were recorded for the following 64 s. The average maximum response of both the internal mass and the cylinder were calculated. The wave heights were recorded using standard wave gauges. The wave heights were set to have an amplitude of 20 mm but the actually wave height varied around this value by a maximum of 4 mm. The results were obtained for 0.05 Hz to 1.10 Hz in 0.05 Hz increments, over the central range 0.67 Hz to 0.84 Hz which appeared to have the most significant response and further results were taken for each possible frequency of the wave tank. The wave tank is limited to produce waves of $\frac{n}{64}$ Hz, where n is an integer.

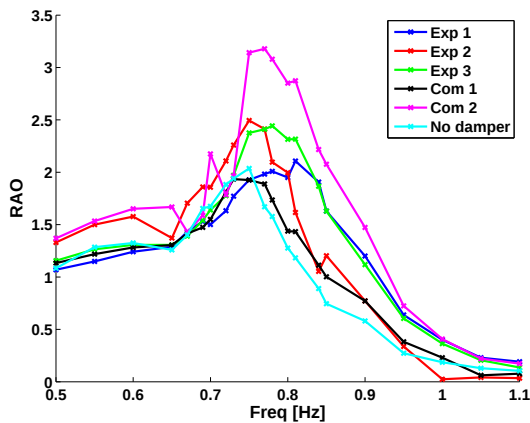


Figure 3: RAO of cylinder.

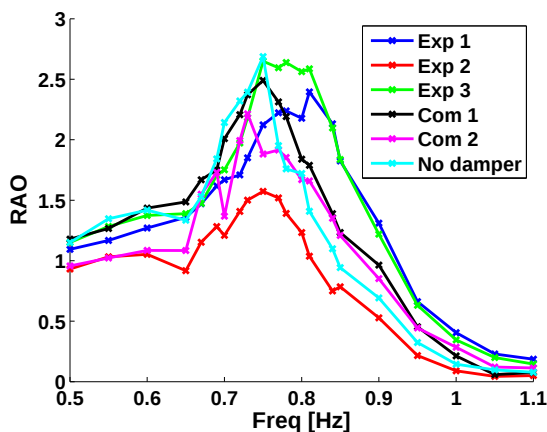


Figure 4: RAO of internal mass.

The results for the RAO of the cylinder are shown in

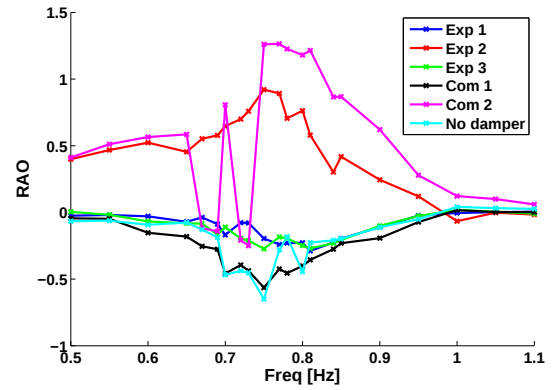


Figure 5: RAO of relative position.

Fig. 3 where each cross on the graph indicates a separate experiment. It can be seen that there is generally a greater response of the cylinder, when a damper is present to when there is no damper. This is seen for all dampers above 0.80 Hz and for two of the dampers below this frequency. There is not a simple pattern to how the different damping constants result in the different response to the waves. The compression damper with the higher damping results in a much greater cylinder response than the other dampers. The shape and height of the RAO of the three expansion dampers varies with the increase/decrease in damping. The non-simple nature of the response suggests that the link between the RAO of the cylinder and the damping factor is not linear. Experimental error is also possible, either in the data collection or the experimental setup. Further experimental testing is needed to obtain greater certainty in the results and see if any of the dataset's results are spurious.

Fig. 4 shows the RAO of the internal mass. For frequencies up to 0.75 Hz having no damper tends to have the highest motion, with higher frequencies having a more varied response. The results for both compression dampers are more closely approximated to the case with no damper compared to the expansion damper. The higher damping constant compression damper does not get such a high response around the resonant peak for the internal mass but outside this frequency range it follows the device without a damper closer. The expansion dampers response varies within the set and compared to the no damping case. The lower expansion damper of 14 Ns/m (Exp 1) has a 0.4 lower response ratio than the higher damped expansion damper of 433 Ns/m (Exp 3), while the lower value expansion damper of 31 Ns/m (Exp 2) has a 1.1 ratio lower response than both dampers although its damping constant is relatively close to the lower case. This implies that the response of the internal mass in this device and setup is quite sensitive to the actual damping constant and again indicates a nonlinear relationship between the response and the damping constant.

The relative position between the internal mass and the cylinder is highly relevant to the potential amount of energy that can be extracted from the system. The

ratio of this relative position to the wave height can be viewed in Fig. 5. It is hard to interpret any general trends from the damping values but it does show that for some cases of damping for both expansion and compression dampers a much higher relative motion occurs than with no dampers present. The apparently anomalous behavior of the cylinder and the internal mass for the damper “Com 2” is compounded here and shows a wild variation between 0.65 Hz and 0.75 Hz.

3.3 Time series response in irregular seas

The PM spectrum has been used with a variable peak frequency to test the response of the cylinders with different dampers. The University of Edinburgh curved tank [4] is a deterministic tank with a 64 s repeat period for all sea states. The waves are run for 16 s and then the data is recorded for a further 128 s, at 32 Hz. An example in the time domain for a section of the tests with a PM sea that has a peak frequency of 0.9 Hz, can be seen in Fig. 7 for the response of the cylinder, Fig. 8 for the response of the internal mass and in Fig. 9 for the relative motion between the internal mass and cylinder.

Fig. 7 and Fig. 8 show that although the results are generally similar the heights and to a limited amount the phase of the cylinder varies. The heights relative to the cylinder without damping change, for some dampers on a wave to wave bases.

Fig. 9 shows the relative position, most notably Exp 2 is 180 degrees out of phase with the other cylinders. The higher damping expansion damper (Exp 3), for the larger responses tends to have a much smaller negative component in comparison to its positive component, with the negative component going no lower than -5 mm whilst the positive value reaches 15 mm. In contrast, the higher damped compression damper (Com 2) has a mainly negative relative position, for the larger responses, where it has a maximum value of 7 mm but a minimum of -20 mm. The other dampers do not tend to follow this trend with approximately equal positive and negative relative positions.

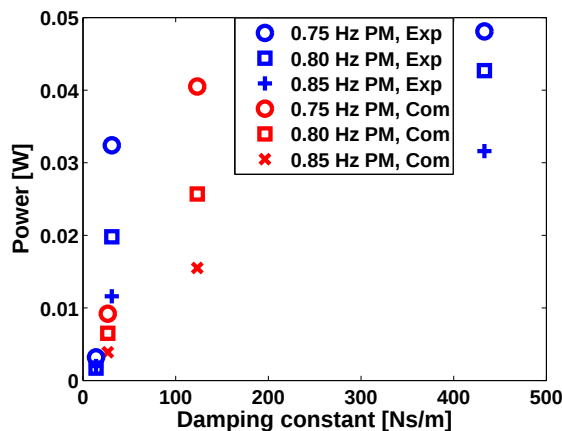


Figure 6: The time averaged power extracted for the dampers in different PM spectrums.

3.4 Power extraction

The power that is extracted has been calculated from the product of the square of the relative velocity and the damping constant when the velocity was in the direction that the damper was exerting a force, and zero for the opposite direction. It is calculated for three different PM spectrums with peak frequencies of 0.75 Hz, 0.80 Hz and 0.85 Hz. The tests were ran for 16 s to allow the system to establish and a further 128 s of data measurements. The time averaged power over this time frame has been calculated and presented in Fig. 6.

This figure shows the increase in the extracted power for stronger dampers, of both expansion and compression. These values would result in a full scale power of between 20 kW for Exp 3 in a 0.75 Hz peak frequency PM spectrum and 810 W for Exp 1 in the same sea. It should be noted that the bearing friction on the internal mass would not follow scaling laws, and hence it could be expected that these values would be higher for a full scale device.

Due to the limited number of samples, there is not a clear shape emerging. As the damping increases further, the power would decrease since no relative motion would be present.

3.5 General discussion

From studying Fig. 3 and Fig. 7 the cylinder is shown to consistently to have a higher response for most of the different dampers for the majority of the frequencies of interest than if it had no damper. This is not the intuitive result since by taking out energy from the system by having the dampers present, a lower response may have been expected. Although there is not clear evidence to confirm this, a possible explanation would be that the higher response from having the dampers present is due to some form of uncontrolled latching [10, 11] or partial latching of the internal mass occurring in the model.

This implies that for a self-contained inertial model where a control strategy is not implemented, a mono-directional damper may have a much higher power extraction than half of that produced by a bi-directional damper. This will be further investigated in future work.

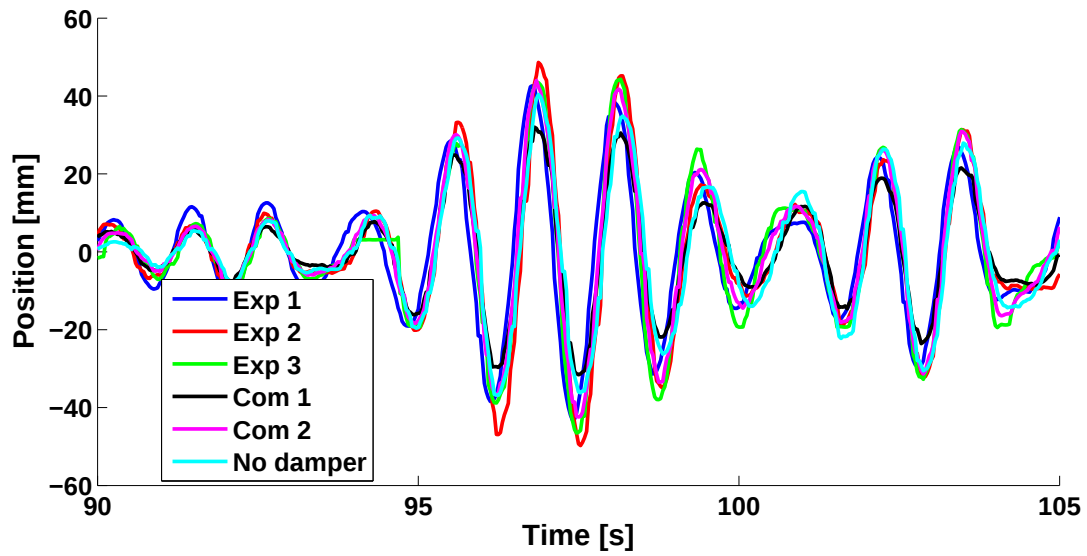


Figure 7: Position of cylinder for PM spectrum.

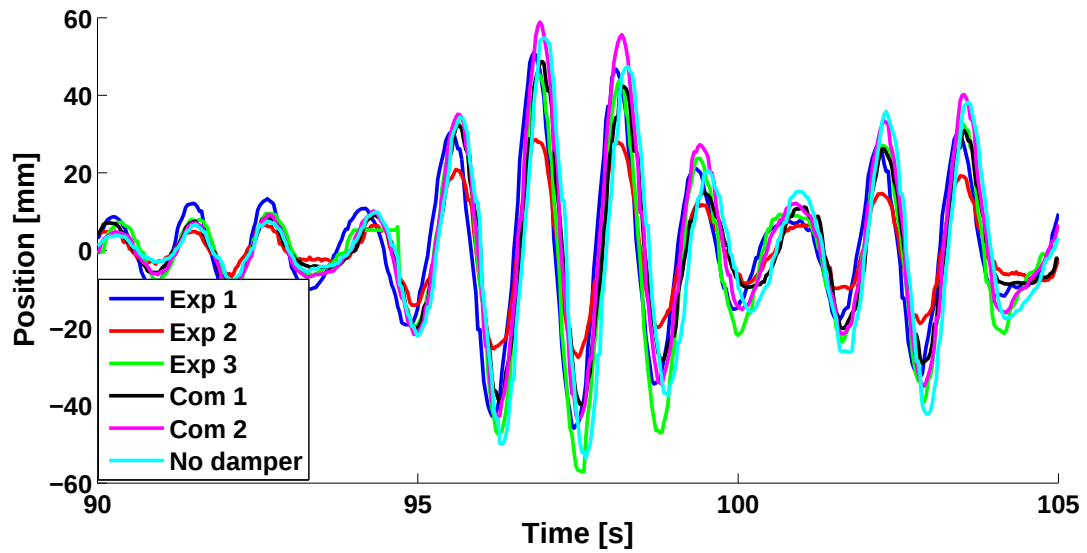


Figure 8: Position of internal mass for PM spectrum.

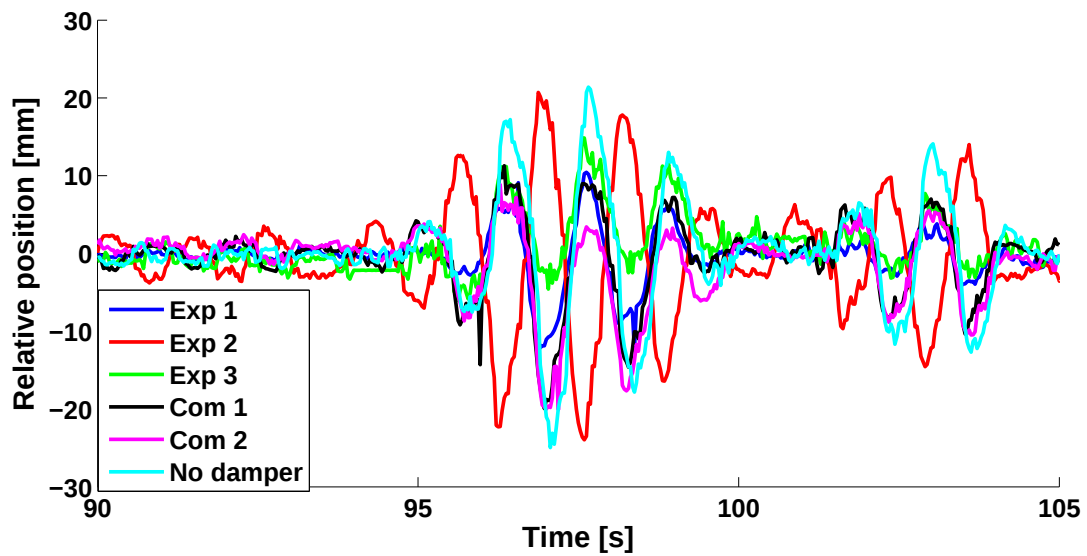


Figure 9: Relative position of internal mass to cylinder for PM spectrum.

4 Concluding comments

The results for regular and irregular waves for a mono-directional damper in an experimental setup comprised of a cylinder and an internal mass within the cylinder that both move in heave and relative to each other have been presented. The RAO for the internal mass, cylinder and the relative position between them have been given, showing that systems with a mono-directional damper has a higher response of the cylinder and often a higher relative motion, than without a damper, in this paper.

A time series example of the results for a PM spectrum were presented, showing the varying heights across the different dampers and how the relative heights tended to change with time.

The power extracted from the recorded positions of the bodies and the dampers was presented, for 3 different PM sea states. This showed a general increase in the power extracted for increased damping and implied that further experimental testing was needed in order to find the optimal mono-directional damper for maximum power extraction.

The reason for the increase in amplitude of the motion of the cylinder when damping is present to when not present was discussed and it was postulated that this could be because of a “latching” effect, although it was noted that there is currently not sufficient evidence to confirm this.

Acknowledgments

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