Operational issues surrounding the use of towing tanks for performance quantification of marine current energy converters

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Abstract— **Towing tanks are being utilised far more frequently for the performance quantification of Marine Current Energy Converters (MCECs) due to their relatively low cost and ease of use. In this paper a number of issues are addressed that arose during a series of experimental campaigns investigating the performance of both static and dynamic MCEC models. These include the lack of ambient turbulence, carriage vibration, repeatability, carriage advance speed, vortex-induced-vibration and blockage. Results of experiments are also compared to those in circulating flumes and the relative merits of each type of facility are presented. Recommendations are that specific types of experiments such as wake measurements, power capture etc. are better suited to a specific type of facility although it is acknowledged that facility availability is often the overriding factor. It is difficult to judge previous published and ongoing work but the authors believe that many of the issues quantified in the paper through real world MCEC experimental studies are easy to overlook and could lead to less accurate experimental results. Recommendations for measurement of experimental parameters through the various stages of experimentation are given in order that future studies can be more comprehensive and accurate.**

Keywords— **Towing tank, Measurement, Accuracy, Error**

I. INTRODUCTION

Despite the seeming advanced nature of many Marine Current Energy Converters smaller-scale experimental studies are still highly valued for concept, device design and even for testing deployment and operational actions. Small-scale testing offers lower risk and lower cost testing that can generally be conducted in a shorter time period than at sea [1].

A key difference between tank or flume work compared to in-situ ocean testing is that of control and acceptance. At smaller indoor facilities conditions can be accurately controlled such that steady state experimental work can be conducted. Quantification of performance across a pre-defined envelope of operating conditions can be planned and executed in minimal time. Both water conditions and device operational parameters can be modified in relatively short time. At sea the testing regime is governed by acceptance. The resource varies in both a spatial and temporal manner. You must wait for a specific metocean condition to occur and whilst this is predictable for velocity and direction other issues such as wave conditions might not be. Therefore small-scale testing is still seen as a valuable proving ground for a wide range of design concepts, parameters and processes.

II. CHARACTERISTICS OF TOWING TANKS AND FLUMES

In order to characterize the performance of small-scale marine current energy converters (MCECs) there are two potential methods; a) move the device through a static fluid field or b) keep the device static and move the fluid. Both concepts are depicted in Fig. 1.

Towing tanks have been used extensively in scale MCEC studies [2-5]. The facilities generally have relatively low operating costs with the largest proportion of this associated with the towing mechanism and wave-maker. All towing tanks have an intrinsic 'working' length characterized by the distance that can be maintained at a steady, set towing speed. Buffer zones at either end are for safety and for acceleration/deceleration of the carriage. This working length is reduced for faster towing speeds to enable safe acceleration and braking. Most wave makers are capable of generating regular and irregular waves. The most basic tanks have the wave makers situated at the downstream end with varying carriage velocity only 'into' the waves. Following waves can be generated if the reverse carriage speed is also variable.

For MCEC experiments the generation of waves whist towing is advantageous although a true-combined wave-current interaction is not observed. Turbulence in towing tanks is zero as the water is still hence downstream wakes observed by any other flow structures will not be as representative as flumes or water channels. Data acquisition is also more cumbersome with time lost accelerating, slowing, reversing the carriage and waiting for the tank to settle between towing runs. However the lower costs of towing tanks compared to water channels, wave-making facilities and good cross sectional area properties ensure that they are utilised for aspects of MCEC research.

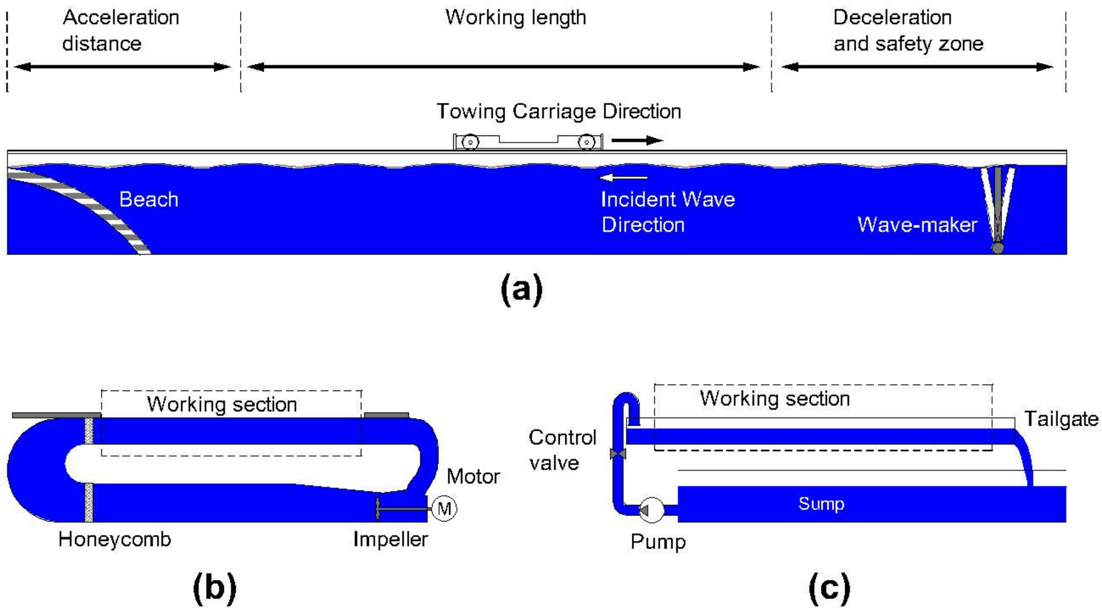

Fig. 1 - Side elevation of towing tank (a), circulating water channel (b) and circulating flume (c)

Flumes can be forced loops or an 'open' gravity driven design herein defined as 'water channel' or 'flume' respectively. Circulating water channels are permanently flooded and so can move large volumes of water easily thus working sections can be wide and deep. Disadvantages include installation of equipment (due to difficulty associated with draining down the flume) and varying water depth (again requires drainage). Gravity-fed flumes lift water from a sump and deposit at the upstream end of the working section. Flow rates and depths are often controlled via valves and a weir located at the end of the working section to create a backwater profile. These flumes are often long in length and the working section is dry when not in use so installation of equipment is simple. However, volumetric flow rates and cross sectional areas are generally significantly lower than circulating channels.

III. Types of Measurement Required for Quanatification of Marine Curent Energy Converter Performance Assessment

Measurements can be divided in a number of arbitrary ways. For the purpose of this work they will be classified as:

1) Inflow / natural environment
2) Device
3) Device-affected flow field

Herein we will principally address item 1 which shares some common issues with item 3. Measurements addressed herein include the quantification of towing speed, wave climates and the general flow field around the model MCEC. Other practical issues such as repeatability, ambient noise and base line condition are also addressed.

Due to the wide range of MCEC devices, modes of operation and device parameters that can be measured the reader is referred to Part IIB of the EquiMar protocols [6]. This gives valuable guidance on device measurement in addition to measurement of other test parameters. This paper shares the common aim with EquiMar to ensure the highest quality of small-scale testing possible and to this end some of the work addressed in this paper is represented in part IIB of the protocols.

IV. Experimental Setup

The experiments presented in this paper were carried out at Solent University's wave/towing tank (60m long x 3.7m wide x 1.8m deep – see Fig 2). A full-spanning motorised carriage can traverse down the tank at a maximum speed of 4m/s; Reversing speed is fixed at approximately 0.46m/s. a mid-depth-hinged wave maker is situated at the downstream end of the tank with the capability of generating both regular and irregular waves. The experimental issues addressed in the paper arose during a series of experiments involving a 1/15th-scale tidal turbine model (see Fig.3) was equipped with the capability to measure rotor thrust and torque (utilising a dynamometer) and rate of rotation (via optical sensors). The parameters of the model varied included: TSR (tip-speed-ratio), turbine yaw and turbine submergence depth. Testing was conducted over a range of tow speeds and wave climates.

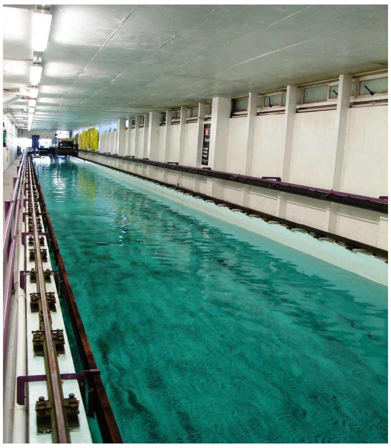

Fig. 2 - Towing tank facility

V. Issues Relevant to Accurate Performance Assessment in Towing Tanks

A. *Verification of Carriage Speed*

The repeatability of the towing carriage was verified. Sample 1 in Table 1 was omitted since the carriage motor and gearbox would need to be warm before the results could be representative. The variance in speed for subsequent runs was far lower. The standard error of the mean;

$$= \sigma / \sqrt{N} \quad (1)$$

for the carriage speed was essentially zero (to three decimal places) where σ is the standard deviation and *N* is the number of samples. Care must also be taken when towing models that impose a significant drag force upon the carriage. A brief check that the carriage set speed remains the same for towing with/without the model is recommended. Speed can be measured simply by timing the carriage over the working section (Fig. 1) or by using a device which has been independently verified i.e. a Doppler velocimeter or pitot tube.

TABLE I
VERIFICATION OF TOWING CARRIAGE SPEEDS

Sample	Forward average speed (m/s)	Reverse average speed (m/s)
1	0.460	0.463
2	0.455	0.459
3	0.453	0.457
4	0.453	0.458
5	0.455	0.457
6	0.454	0.458
7	0.453	0.455
8	0.456	0.456
9	0.455	0.457
10	0.456	0.456

B. *Flow field measurement*

There are a number of instruments that can be employed to characterize the flow field around a model MCEC. Pitot tubes, propeller meters, Doppler devices and wave probes will be addressed herein. In all cases the effective length of the towing tank and the rate of data acquisition will determine the quantity of data that can be collected. A sound judgement should be made as to the number of towing runs required to produce a robust and accurate data set. Repeatability of measurements is addressed in section V.D.

1) Pitot tubes

Pitot tubes offer a robust method of acquiring velocity data. Used in parallel several can be employed in a rake or array to facilitate fast data collection. They can only acquire in the principal direction of flow and at a single point. The determination of the forward velocity is based upon solid physical principals; the tube head has two tappings that measure the dynamic and static pressures.

$$V = \sqrt{2g(\Delta h)} \quad (2)$$

Where g is the acceleration due to gravity and Δh is the differential pressure (dynamic to static) measured at the manometer or pressure transducer. If Δh is large enough then the accuracy of a pitot tube is very high assuming pressure measurements can be read to a good degree of precision. Generally in steady flow the height of fluid in a monometer can be read to ±1mm. If the pitot tube is situated upstream of a model then this should be the case. In the wake of the device the damping caused by the inertia of water in the tubes may manifest as an oscillating value read by the transducer or a slowly oscillating column of fluid in the manometer. An average value should be recorded and the repeatability should ideally be checked with further towing runs.

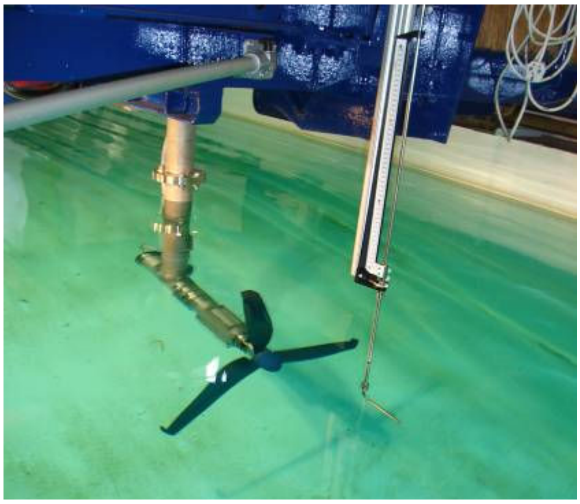

Fig. 3 - Pitot tube installed upstream of 1/15th – scale MCEC for verification of inflow velocity

There are a number of issues surrounding the setup of pitot tubes. The first is that all air is removed or bled from the flexible tubing between the pitot tube and the equipment used to measure the differential pressures (generally a manometer). The water in the tubes will lead to small changes in velocity being damped out due to the inertia of the water in the tubes and therefore pitot tubes can only really be employed to measure mean flow velocity over a towing run; faster sampling will not resolve rapidly changing flow structures. Ideally the manometer should be placed below the level of the tubes or as close as possible. This is often difficult as the tank is generally recessed below the carriage or general working area. At higher carriage speeds the pressures in the pitot tubes should be sufficient to overcome small differential heights between the tube heads and manometer. However, a calibration check against the set carriage speed or another device capable of measuring velocity should be conducted.

2) *Propeller meters*:

Propeller meters are simple devices that rotate in a plane orthogonal to the flow direction. The propeller creates a low voltage DC voltage output that varies linearly with flow speed. Implementation in towing tanks holds few practical issues. A recent calibration of the instrument should always be conducted before and after the testing period. Propeller meters often have an appreciable size meaning that use upstream of small models sensitive to disturbance is not advisable when acquiring other data. Voltage outputs can be acquired using a number of means but care should be taken not to sample at high frequency and expect coherent resolution of higher order flow effects such as turbulence. As with pitot tubes propeller meters are best employed for mean flow measurements. Their strength lies in having a simple output, low cost and ability to deploy in an array for multiple point measurement.

3) *Doppler Velocimenters*

Doppler velocimeters utilize the phase shift of light or sound as it is emitted from an instrument and is reflected from particles in the water back to a receiver. Measurements are taken in a small finite volume of fluid displaced below the sensor head. Generally at least 2 and usually 3 axes are resolved at high frequency allowing the quantification of both mean velocity and higher order flow effects. The principles of operation and accuracy issues are well documented for general use [7-9]. A key issue for the use of Doppler velocimeters is the amount of backscattering material suspended in the water. As the water in a towing tank is not regularly disturbed or circulated nearly all suspended matter will settle to the bottom. Therefore it is necessary to seed the water with small particles to provide strong return acoustic or light signals back to the Doppler velocimeter. Failure to seed the water will result in the acquisition of incoherent data as the device struggles to achieve sufficiently high return signal strengths. Circulating water channels and flumes generally return good results without the need for seeding; however results can normally be improved with a relatively small amount of seeding material.

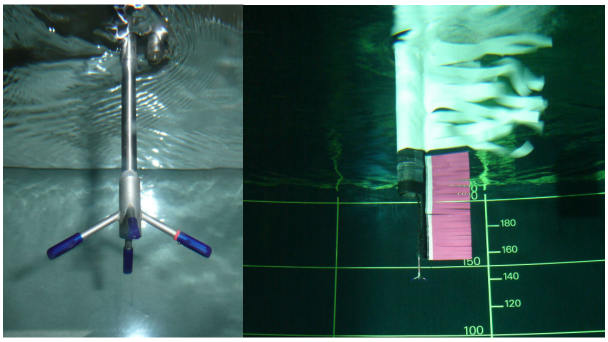

Fig. 4 - Acoustic Doppler Velocimeter head unit (left) and installed in turbulent flow (right)

Fig. 5 illustrates the reduction in data variability with even a modest amount of seeding material added to the tank. Data is shown for a steady towing speed over a period of 20 seconds sampling at 50Hz. The percentage occurrence is expressed as a decimal fraction.

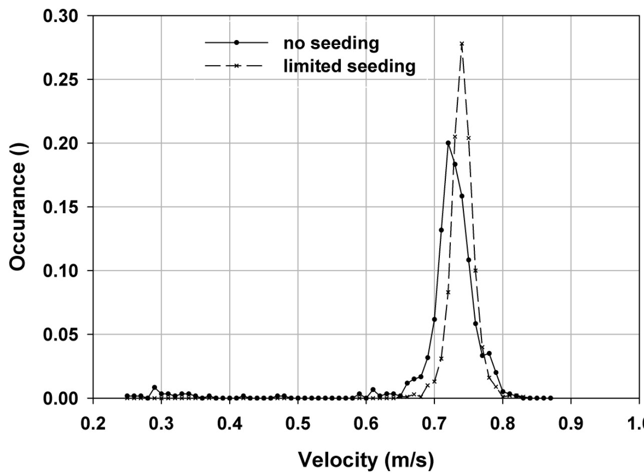

Fig. 5 – Increasing measurement accuracy for velocity for a single towing run by use of seeding particles (20 seconds data at 50Hz)

It can be seen that the variability in the received data is much reduced when more suspended matter is added to the tank. Aliasing errors and spiking prevalent in the clean water condition are removed. Seeding material should have a specific gravity close to 1. In the case of this work 13 micron hollow glass spheres were used with a specific gravity of 1.1. During testing it was necessary to partly re-seed the tank each morning. Seeding was added until instrument measurement quality parameters rose to acceptable levels. The amount of seeding required will vary depending upon:

- the size of the tank
- frequency of the emitted sound/light pulse
- any internal instrument data processing
- manufacturer recommended data quality

The first point is quite obvious. A useful mixing aid to distribute seeding throughout a static body of water is the operating model MCEC itself. The second issue pertaining to frequency is important as higher emitted frequencies will attenuate more rapidly in water according to Stokes' law and thus may require higher concentrations of backscattering material compared to a lower frequency instrument. Many devices return data quality indicators such as received signal strength (transmit signal divided by ambient noise level) and correlation scores. Some are more useful than others in defining data quality. For example the correlation score can often appear low in turbulent flows despite the data being good quality [10]. Other instruments perform internal data quality assessments and only output data above a specific threshold of accuracy. Users of Doppler devices should fully understand the working of the instrument before use. Some device manufacturers indicate lower bound values of parameters such as instrument signal to noise ratio or correlation to ensure good quality data. In the authors' experience this is not a definitive limit and should be exceeded to ensure maximum data quality. Often data requires further post processing but by maximising parameters such as device signal to noise ratio and correlation scores any data loss due to processing should be minimal.

Post processing can increase the data quality by removing spurious points. The precise method of filtering can sometimes appear quite arbitrary. There are a number of statistical methods and filtering techniques based upon physical phenomenon and the choice and inter-comparison is best left to the individual. Statistical methods include simple minimum/maximum thresholds. Fig. 5 above is a good example as the data can be seen to hold a roughly normal distribution. An example filtering criterion could be based upon the fact that 99.7% of data should lie within 3 standard deviations from the mean. Often significant spikes reach far beyond this limit so removal is sound.

Physical filters can be employed such as deleting sample points where the acceleration from or to the surrounding points is greater than g. The authors' preference is the velocity cross-correlation filter as proposed by Cea et. al [11]. This works by defining an ellipsoid around the varying velocity components of the sample in 3 dimensions. Data outside the ellipsoid is removed as shown in Fig 6. This filter works especially well when towing into waves and thus has been employed during studies of the 1/15th - scale model MCEC. Data shown is for wave amplitude of 0.088m, Period 1.34 sec, forward velocity 0.67m/s and depth 0.4m.

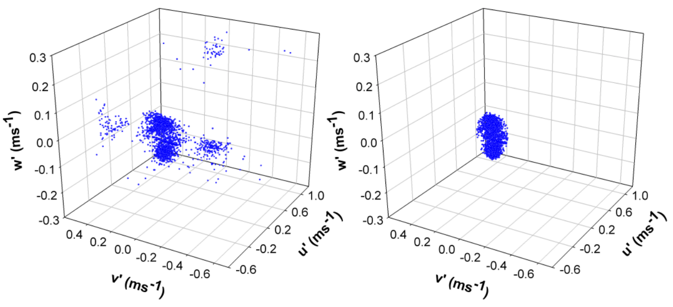

Fig. 6 - Effect of filtering Doppler velocimeter data. Raw sample set (left) and filtered data (right)

Fig 7. shows the time series data corresponding to that shown in Fig 6. Removed data points were replaced using shape-preserving cubic interpolation.

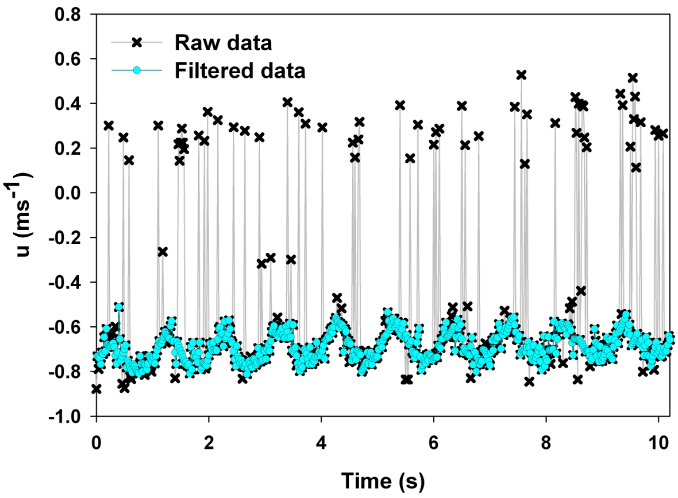

Fig. 7 - Time series velocity data for unfiltered and filtered conditions

Again it must be stressed that adequate seeding of towing tanks will facilitate the use of Doppler velocimeters and the multiple axis, rapid sampling that they can achieve with an associated reduction or even eliminating of post processing. In other cases more simple instruments are often better employed to measure axial mean velocities.

4) *Wave probes*

It is good practice to verify the input to the wave maker with a separate wave probe measurement and not to solely rely upon the settings stated on the driving software. A simple resistive wave probe can be employed a reasonable distance upstream of the wave maker to verify the output wave parameters. Wave probes should be regularly calibrated. Fig. 8 shows a typical wave series propagating up the towing tank.

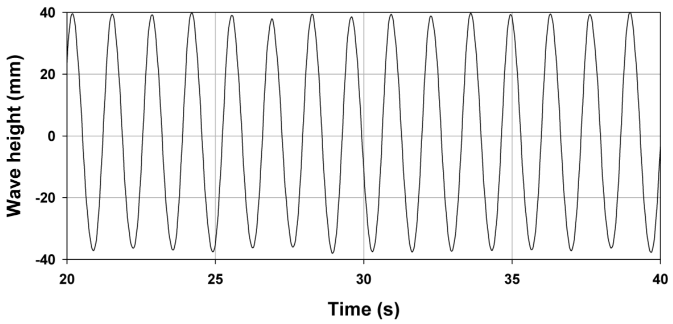

Fig. 8 - Wave height reading from resistive wave probe in towing tank

Data was collected over a 90-second period for the wave conditions specified at the wave maker of 1.34s period and 0.088m amplitude. Measured data gave an average period of 1.34s and average wave height of 0.076m. Whilst data in Fig.8 appears quite regular the wave height is not close to that specified. The discrepancy was remedied by adjusting gain parameters at the wave maker but this again highlights the importance of the quantification of baseline conditions.

If towing into waves the carriage should commence moving once the waves have reached the turbine. This will ensure that one the carriage is up to speed the initial waves (which are often not representative of the remaining series) have passed. Similarly, reflected waves from the beach must be avoided.

C. *Carriage motion and Vortex Induced vibrations*

Baseline conditions are an important aspect of any testing. In towing tanks it is probably unrealistic to assume that the carriage motion is perfectly steady. We can easily determine the forward speed with time using a number of instruments addressed above in section VB. Towing tank carriages generally run on rails of relatively short length. Despite best efforts in aligning the rails there is always the likelihood that the carriage will move vertically (or laterally) along the passage down the tank. If this occurs it is likely to affect many of the device measurements recorded. Quantification can be made by utilising accelerometers mounded upon the support structure of the model MCEC. Placement is important as the model is likely to be supported away from the main carriage and carriage/tank contact point (rails) thus the magnitude of any vibration is likely to be amplified whilst frequency may be reduced. Doppler velocimeters are another useful instrument to quantify any such vibration with travel (assuming the water is well seeded).

It is recommended that any carriage shake or rumble be identified ahead of the testing phase. This will allow an assessment to be made as to the duration and severity for each towed run. Also it might be that the problem manifests at or above certain speeds. Mitigation could include using elastomers or similar to damp down any oscillations transferred from the carriage to the MCEC device.

When water passes a submerged bluff body, vortex shedding can occur causing regular or random vibration. The generation and remediation of this Vortex Induced Vibration (VIV) is an entire subject in its own right and is of great concern in many heavy industries, most notably offshore hydrocarbons.

The propensity for VIV will depend upon a number of factors including inflow direction, velocity and the shape and sectional stiffness of the body in the water. Sequential shedding of vortices often lead to a lateral oscillation commonly referred to as 'bowing'. Fig. 9 shows the energy spectra from an acoustic Doppler velocimeter attached to a bowing stainless steel tube. The lateral oscillations are evident as a peak in the energy spectra at approximately 4Hz (centre trace).

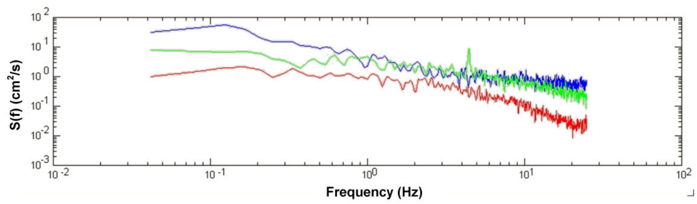

Fig. 9 – Lateral resonance of cylindrical support arm holding ADV instrument.

There are a number of solutions to this issue. Often resisting the motion by increasing the stiffness of the body in the water will only result in a small decrease (if any) of motion. A better approach is to either change the section shape to avoid vortex shedding or to damp down the vortices using strakes or feathered material as depicted in Fig 4. (right).

D. *Measurement Repeatability*

Repeatability of the tank conditions is an important aspect of any experimental programme. Testing in towing tanks does involve a good deal of lost time spent accelerating, decelerating, reversing and waiting for the tank to settle between runs. Therefore ascertaining the limits for the number of runs required to accurately quantify each point of MCEC device performance is essential.

For example, in section VA above the steadiness of the carriage forward tow speed is demonstrated. Similarly the waves generated from the wave maker also demonstrated very low variance between each run. If the baseline conditions are relatively steady then there is a good chance that the MCEC will operate in a steady fashion (when carriage is up to speed) and thus a small number of runs will suffice to accurately quantify performance at any operational point. Evidently the more levels of parameters that are recorded, the greater the systematic error e.g. it is likely that velocity measurements will be more repeatable than load measurements since the load measurements are also reliant upon the incident velocity.

Whilst there are no absolute standard prescribed for the accuracy and repeatability for experiments there is a very strong need for the maximisation of accuracy. This will be dependant upon the nature of the experiments and any constraints but it should be noted that for robust results all practical measures should be taken to minimise errors and ensure a high degree of accuracy. Section IIB of the EquiMar protocols [6] gives guidance on the reporting of data accuracy and this should always be provided so that independent assessment of the experimental accuracy can be made.

VI. Conclusions

This paper has addressed a number of issues pertaining to the accuracy and repeatability of experiments to quantify MCEC device performance in towing tanks. Such facilities generally have lower operational expenditure compared to large circulating flumes hence they are commonly utilised for the quantification of performance parameters of Marine Current Energy Converters (MCECs).

Whilst towing tanks offer a lower cost and wave-making capabilities this has to be balanced against the lack of ambient turbulence and a greater time required for data acquisition due to the discrete length of a towing run compared to the time required for acceleration, deceleration, reversing and tank settlement.

This paper has highlighted a number of issues that should always be considered in any towing tank to assess the baseline conditions. These include verification of carriage speed, wave properties and carriage shake (unsteady motion). Once the Model MCEC is in place measurement systems and instruments should also be carefully checked for setup parameters and signal feedback strengths/accuracy. These include onboard systems (e.g. rotor thrust/torque) and any peripheral measurements such as those used to quantify the characteristics of the surrounding flow field. Care should be taken with Doppler instruments to ensure strong return signals and pitot tubes require a careful setup and may be inappropriate for some tanks or for low advance speeds.

Once the setup and baseline conditions have been verified an assessment of the accuracy and repeatability of measurments associated with the operation of the model MCEC should be conducted. Whilst there are no absolute limits the operator should ensure that the highest practical level of accuracy is achieved and that this is quantified in any reporting. Examples are given in this paper and also in part IIB of the EquiMar protocols [6].

Post processing of data can be employed to further increase accuracy of results. Once again details should be provided in any experimental report and the operator must ensure that both the raw acquired data is always saved and that any filtering/post processing techniques are understood and fit for purpose. If the above techniques and actions are employed then the quality of work conducted in towing tanks for the performance quantification of MCECs should be enhanced benefitting both the person(s) conducting the testing, the wider marine energy community and any further development/up-scaling of the MCEC device in question.

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