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Experimental study of towing configurations for a floating wave energy converter

M. Eng. Julian Pforth[a*], Prof. Dr.-Ing. Christian Keindorf[a]

[a] *Kiel University of Applied Sciences, Grenzstraße 3, Kiel 24149, Germany*

Abstract

The essentiality to increase the use of renewable energy sources is driving research in ocean wave and current energy technologies. This study introduces the development of 'Aurelia WINO', a prototype of a floating wave energy converter (WEC), designed at Kiel University of Applied Sciences. The system, based on the principle for a point absorber, was constructed in partnership with the maritime industry. To facilitate safe transport to the designated test location near the FINO 3 research platform in the German North Sea, experimental towing trials were conducted using a 1:20 scale model with equivalent floating characteristics.

The experimental setup involved varying length ratios of the towing lines under different current and wave conditions, conducted in the marine flow lab at the Institute of Naval Architecture and Maritime Technologies. The goal was to identify a stable towing configuration that minimizes rolling and tilting. Results from trials indicated that a line ratio of 1.05 yielded the smallest mean tilt and roll angles, especially at current velocities up to 0.2 m/s. Numerical models and analytical calculations supported these experimental findings, demonstrating that the main force on the towing lines was current-induced, with waves contributing additional load.

The study concludes that an adjustable towing configuration with a typical line ratio of 1.05 is optimal for the prototype scale, ensuring minimal tilt and roll angles. This configuration can be adjusted in real-time during transport based on vessel speed, wave height and tidal currents. The integration of numerical, analytical and experimental approaches confirms that analytical calculations suffice for designing towing equipment. However, experimental and numerical analyses are critical for identifying limits on rolling and tilting. This research lays the foundation for scalable towing strategies for full-scale WEC deployment, contributing to the global advancement of marine renewable energy solutions.

Keywords: Wave Energy Converter; Experiments, Towing; Transportation; Offshore

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* Corresponding author. Tel.: +49 0431-210-2702;
E-mail address: julian.pforth@haw-kiel.de

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1. Introduction

The amount of renewable energy must be further increased not only in Germany but also internationally in order to minimize the impact of climate change. In addition to wind energy and solar energy systems, research and development work is also being carried on technologies to utilize the natural energy resource of ocean waves and currents. The waves close to the surface offer great energy potentials worldwide (Mork, et al. 2010). Due to the higher density of salt water (1025 kg/m^3) compared to the density of air (1,225 kg/m^3), flowing water particles have a dynamic pressure approximately 837 times higher than flowing air particles with the same particle speed and the same flow cross-section.

In order to utilize the energy potential of the oceans, a floating wave energy converter (WEC) was developed at Kiel University of Applied Sciences and manufactured as a prototype in cooperation with the maritime industry in a scale of 1:8. The basic principle of the WEC, named ‘Aurelia WINO’, is a so-called point absorber (Fig. 1a). This type of system corresponds to a spar buoy with a ring-shaped floating body that can move up and down with the waves. Thus, the heave motions will be used, especially the vertical relative movement between the spar buoy and the floating body, to drive two linear generators inside the spar buoy, which finally convert the mechanical energy into electrical energy. The prototype has a height of approximately 12 m (without antenna) and a diameter of 2.5 m on the ring float. The total weight is about 10 metric tons. The planned test location for the prototype is at the FINO 3 research platform nearly 80 km west of the island of Sylt in the German North Sea. The research team at Kiel University of Applied Sciences is currently working on a blueprint for the transportation and installation of the floating WEC. The transport of the prototype from its base terminal in Kiel (Baltic Sea) to the test site (North Sea) is planned to take place in two phases (Fig. 1b). In phase A the prototype will be transported on the deck of an offshore service vessel to minimize the travel time and costs for the crossing of the Kiel Canal. The first phase will end close to the Island Helgoland. At Helgoland the prototype of the floating WEC will be launched into water. In order to gain experience in towing behavior for a full sized WEC, in phase B the prototype will be towed until the test location is reached. For future full scale WEC’s a transportation on deck of a vessel will not be feasible.

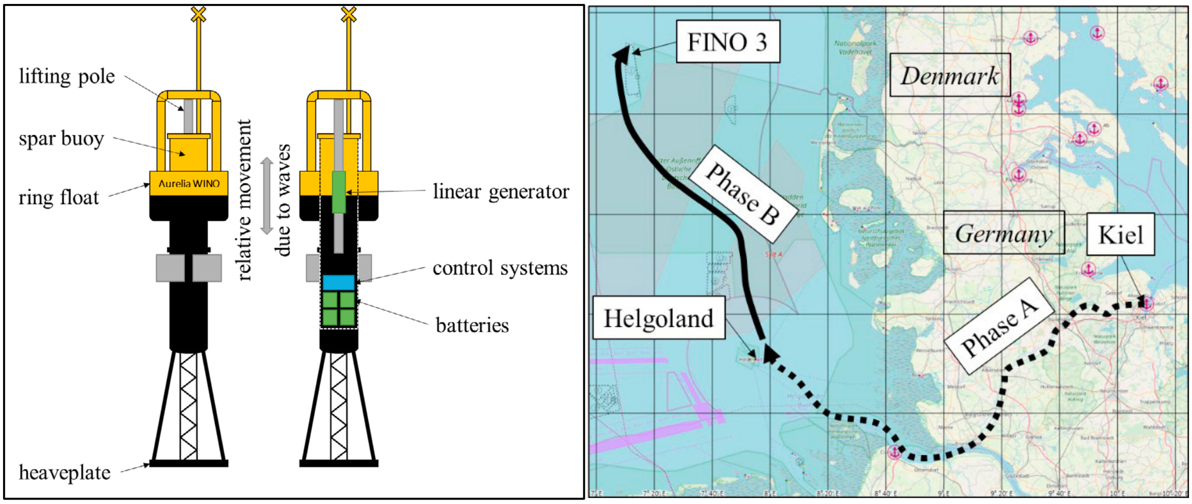

Fig. 1 (a) Schematic sketch of WEC 'Aurelia WINO' with its main components - side view left, sectional view right; (b) Transportation route from base terminal to location for open sea test (openseamap.org 2025)

2. Experimental Setup

In order to develop a blueprint for an adjustable towing configuration for the prototype a functional model in a scale of 1:20 with the same floating characteristics as the prototype was built to conduct a series of towing experiments in the marine flow lab of Institute of Naval Architecture and Maritime Technology. The experimental setup was made with different line ratios between towing line A (upper line) and towing line B (lower line) for two different series of trials (Fig. 2). The aim of the trials was to identify a stable vertical towing configuration for the WEC with minimal rolling and tilting throughout the tests. The ring float of the model was fixed at the upper end stop. This is a key requirement for transporting the prototype in order to protect it from damage during transport. In contrast to the towing process of the prototype, the model of the WEC was not towed through the water in the experiment, but the model was fixed in horizontal direction by the towing equipment and the water was flowing around the model. The scaled model was equipped with a three-axis inclination sensor to monitor the tilt angle (RX) and the roll angle (RY) over the duration of the tests. At the same time, the line forces (F_A and F_B) for the upper and lower towing line were measured continuously. To ensure that the force sensors were outside the water, the towing lines were guided around a deflection and fixed to the sensors above the water surface.

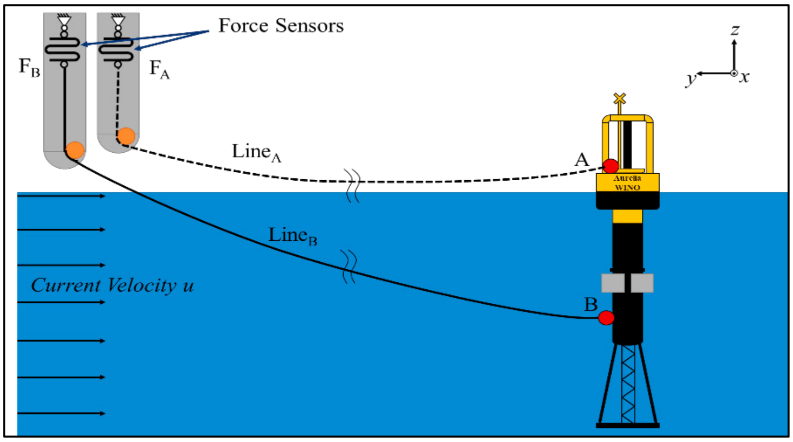

Fig. 2 Schematic sketch of experimental Setup for both trial series

Due to the boundary conditions of the flow tank, the minimum current velocity that can be set is 0.15 m/s, which, based on the prototype scale, already corresponds to a towing speed of 6 knots for the vessel available for the towing operation. Additional tidal currents during the towing process of the prototype may lead to a total relative flow speed of 7,8 knots which corresponds to a current velocity of 0.2 m/s in the model scale.

Table 1 Parameters for model-scale tests with current conditions (series C)

Trial no.	Current velocity u [m/s]	Line ratio $\frac{Line_A}{Line_B}$
C01	0.15 – 0.6 (in steps of 0.05)	1.15
C02	0.15 – 0.6 (in steps of 0.05)	1.10
C03	0.15 – 0.6 (in steps of 0.05)	1.05
C04	0.15 – 0.6 (in steps of 0.05)	1.00
C05	0.15 – 0.6 (in steps of 0.05)	0.95
C06	0.15 – 0.6 (in steps of 0.05)	0.90
C07	0.15 – 0.6 (in steps of 0.05)	0.85

The first experimental series was made with current only (series C) while the second series was made with current and waves (series CW). For both series a variation of towing configurations was tested with the parameters according to table 1 and 2. Therefore, the trial series C was conducted for ten different current velocities from 0.15 m/s to 0.6 m/s in steps of 0.05 m/s and with seven different line ratios from 0.85 to 1.15 in steps of 0.05. The lower line B is set to a fixed length of 2.0 m while line A is adjustable from 1.7 m to 2.3 m

The line ratio is defined according to equation 1:

$$Line\ Ratio = \frac{Length\ of\ Line_A}{Length\ of\ Line_B} \tag{1}$$

Table 2 Parameters for model-scale tests with current and wave conditions (series CW)

Trial no.	Current velocity u [m/s]	Line ratio $\frac{Line_A}{Line_B}$	Wave height h [mm]	Wave frequency [Hz]
CW01	0.20	0.95	5	1.1
CW02	0.20	0.95	18	1.1
CW03	0.20	0.95	30	1.1
CW04	0.20	1.00	5	1.1
CW05	0.20	1.00	18	1.1
CW06	0.20	1.00	30	1.1
CW07	0.20	1.05	5	1.1
CW08	0.20	1.05	18	1.1
CW09	0.20	1.05	30	1.1

For the series CW the current velocity was set constant with 0.2 m/s with three different wave heights (5 mm, 18 mm and 30 mm) and three different line ratios (0.95, 1.00 and 1.05) for each wave height.

3. Results

3.1. Model-scale tests for current conditions (C)

For each trial the mean values for tilt angle RX, roll angle RY as well as the line forces F_A and F_B were calculated for a data set of a duration with 30 s. The line forces increase in all tests with rising current velocity. In general, the upper line force F_A is smaller than the lower line force F_B except for a line ratio of 0.85.

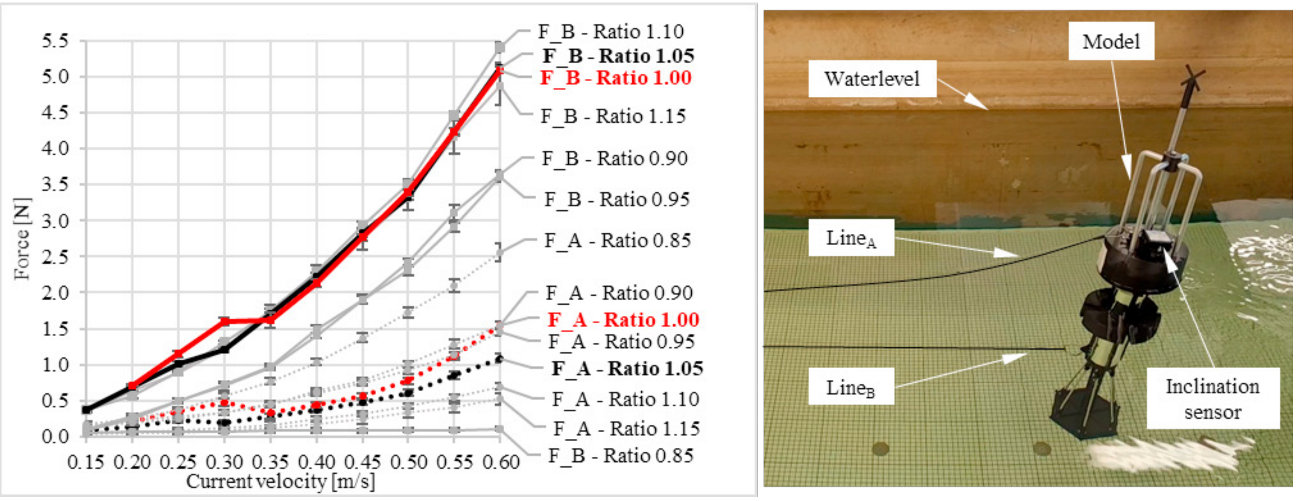

Fig. 3 (a) Experimental results for series C - Mean line forces; (b) Image from model-scale test C03

The smallest mean tilt and roll angles for current velocities up to 0.2 m/s occur for the line ratios 1.05 and 1.00 (trials C03 and C04) as highlighted in Fig. 4. The results for current velocities of up to 0.2 m/s are the most meaningful in relation to the prototype due to their scalability. The test series were nevertheless carried out with current velocities above this value in order to be able to extrapolate the results for flow velocities below 0.15 m/s.

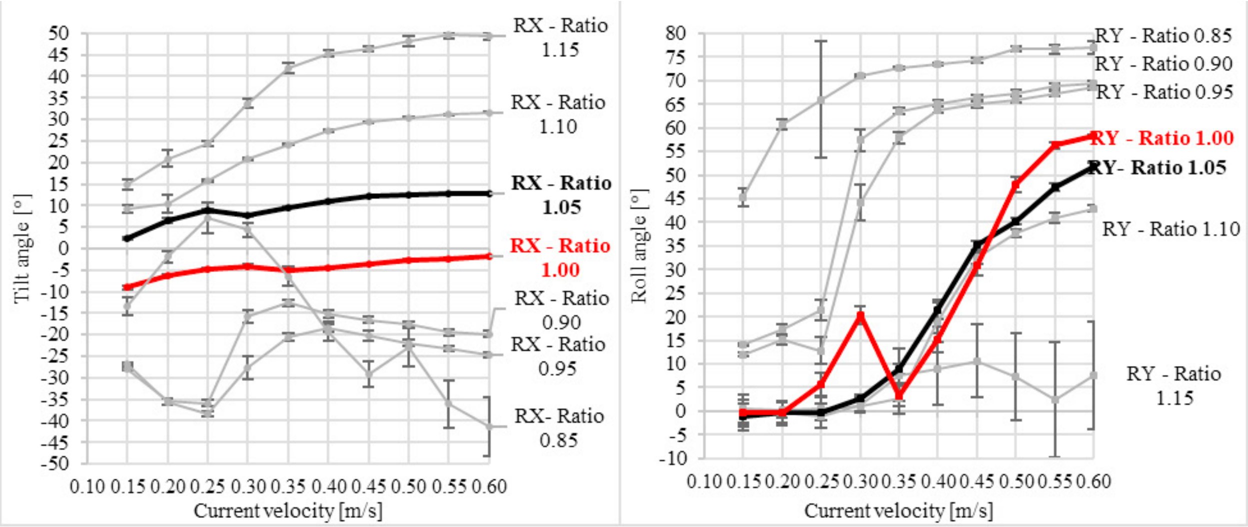

Fig. 4 Experimental results for series C - (a) mean tilt angle RX; (b) mean roll angle RY

The tilt angle RX nears a limit value in all experiments with increasing current velocity. For line ratios of 0.85, 0.90 and 0.95, the mean roll angle RY at minimum current velocity is greater 0°. In the tests with line ratios of 1.00, 1.05, 1.10 and 1.15 the mean roll angle RY is close to 0° for small current velocities up to 0.2°m/s. For current velocities greater than 0.2 m/s mean RY shifts from 0° to the positive direction. During the model-scale test C04 for a line ratio of 1.00 it was observed, that at current velocities around 0.3 m/s the model was laterally deflected and returned to the vertical swimming position shortly afterwards. This behavior can be explained by the lock-in effect caused due to vortex-induced vibrations. An analysis of the video recordings of the test series supports this assumption.

3.2. Model-scale tests for current and wave conditions (CW)

The results for the experiments with current and waves show that the mean values for the line forces, as well as the roll and tilt angles, are of the same order of magnitude as the results from the corresponding trial series C03 and C04. The standard deviations are greater in the experiments with current and waves than in the experiments with current alone.

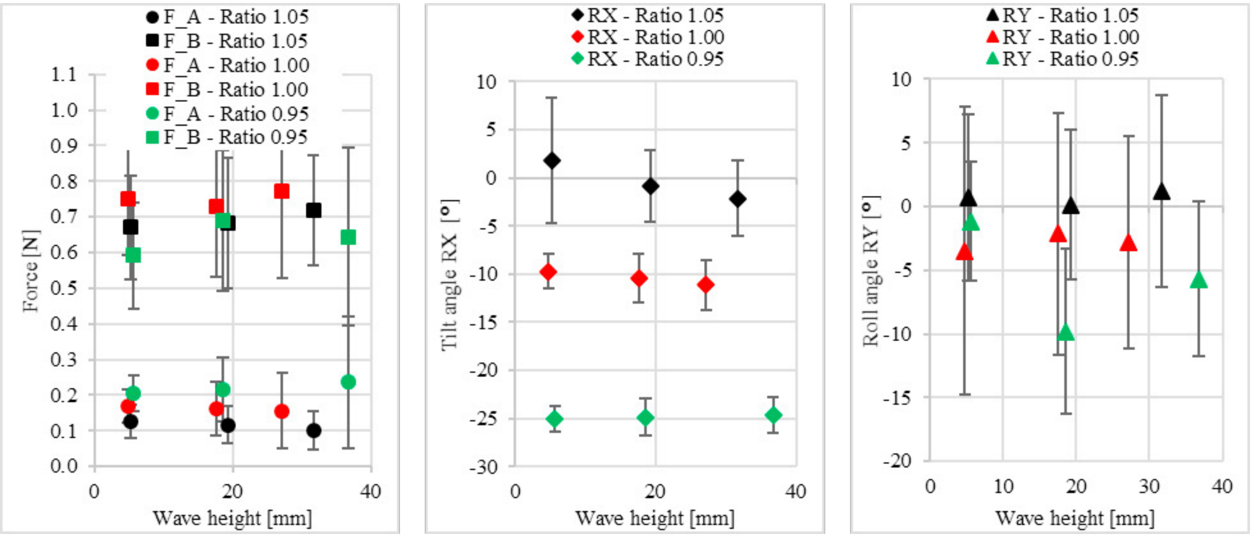

Fig. 5 Experimental results for series CW - (a) mean line forces; (b) mean tilt angle RX; (c) mean roll angle RY

When the results from two associated series are plotted on top of each other, it can be observed that the main force on the lines is caused by the current and that the waves add a pulsating load. Fig. 6 shows a time period of 4 seconds of the series for a line ratio of 1.05 (C03 and CW08) in relation to the water level deflection of CW08.

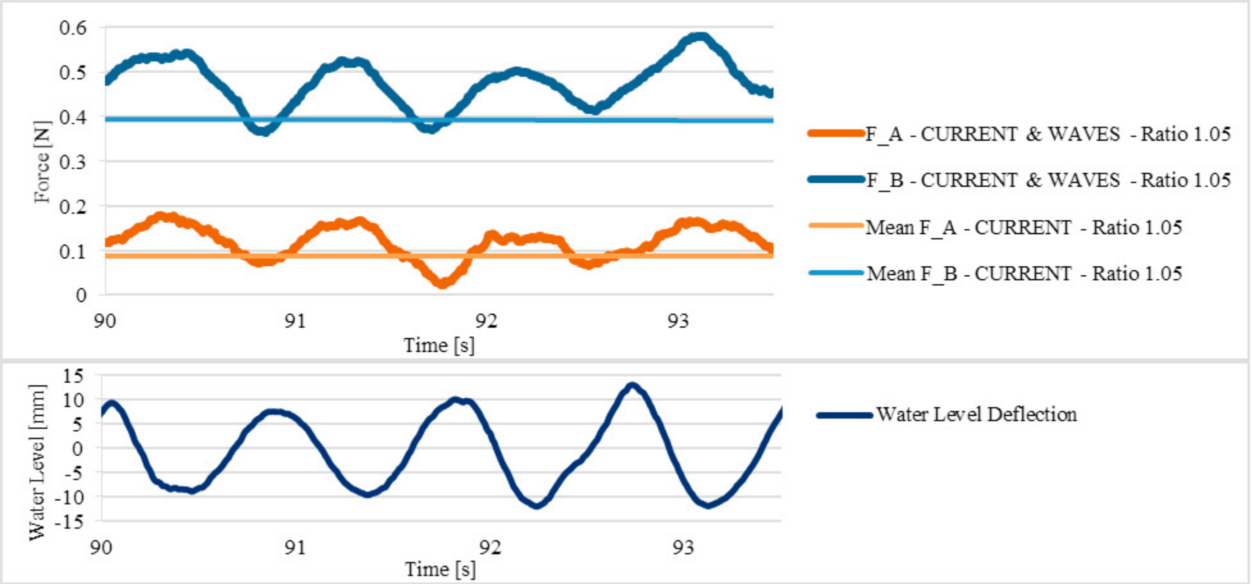

Fig. 6 Line forces - comparison from series C03 and CW08 in relation to the water level deflection

3.3. Numerical simulations and analytical calculations

For both experimental series, time-dependent numerical models based on the boundary element method with the same conditions and parameters as in the experiments were set up in ANSYS AQWA. The results for the experiment C03 are shown in Fig. 7 as an example for comparison with numerical results. The results match very well, only the results for the tilt angle RX are more conservative in the simulation than in the experiment.

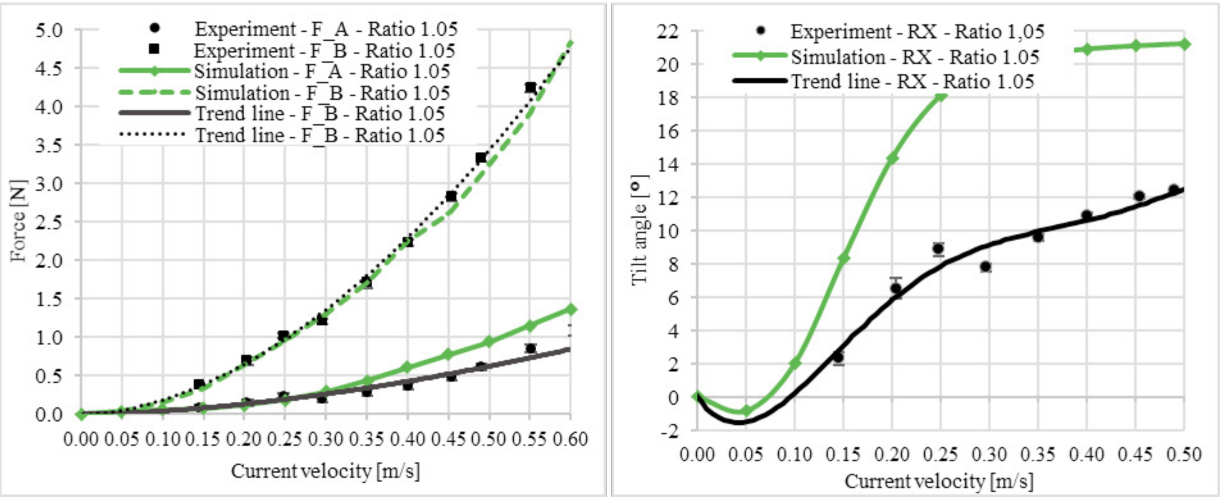

Fig. 7 Comparison of experimental and numerical results for series C03 - (a) mean line forces; (b) mean tilt angle RX

Furthermore, an analytical calculation of the drag force F_D according to Equation 2 was executed for current velocities from 0.05 m/s up to 0.6 m/s. To sum up the total drag force for the model floating vertically in the water, the drag forces of the individual parts of the model were calculated using typical coefficients according to literature (White 2011). A comparison between the analytical results and a summation of the horizontal components of the line forces from trial series C04 with a line ratio of 1.00 demonstrate that the analytical results correspond very well with the experimental results.

$$F_D = C_D \frac{1}{2} \rho v^2 A \quad \text{(White 2011)} \tag{2}$$

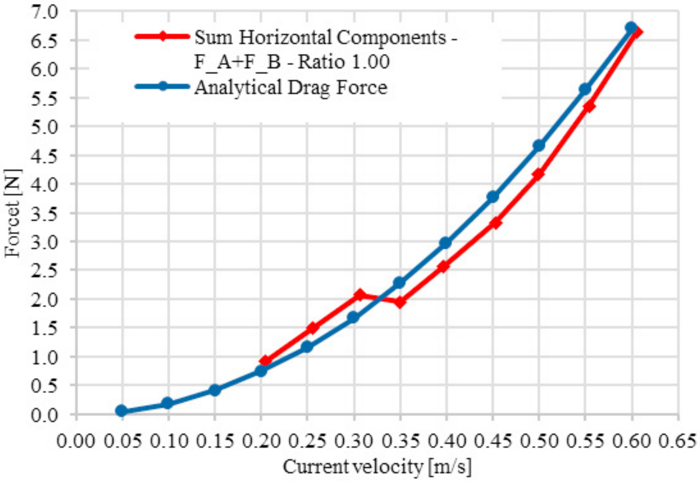

Fig. 8 Comparison of experimental and analytical results for series C04

The bend in the curve of the summed line forces (Fig. 8) can be explained by the lock-in effect caused by vortex-induced vibrations. At current velocities of around 0.3 m/s, the model is deflected to the side (see Fig. 4b) and has lower drag compared to the vertical floating position.

4. Findings and conclusion

Tilt and roll angles for line ratios above 1.05 and below 1.00 are not suitable for use on the prototype scale as they could lead to permanent submersion of the seal on the top cover of the WEC for the lifting pole. The seal is not designed for this type of load situation. The rolling of the model is known as vortex-induced vibrations. It is striking that the model always tilts in a positive direction around the Y-axis as the current velocity increases. One reason for this could be that the model as well as the prototype is not completely symmetrical. It can therefore be assumed that the tilted position represents a stable state for higher current velocities.

The experimental results demonstrate that for current velocities up to 0.2 m/s a towing configuration with a line ratio of 1.05 will have the smallest tilt and roll angles. An adjustable towing configuration in prototype scale on the tug boat can be realized with the winch on deck. Therefore, the upper line (A) can be shortened or extended via winch while the lower line (B) will be attached to a bollard with a fixed length. According to vessel speed, wave height and tidal currents the towing configuration can be adjusted during the route to minimize tilting and rolling of the WEC.

The comparison between numerical, analytical and experimental results shows that an analytical calculation is sufficient for the final design of the transportation phase, especially of the towing gear against failure in accordance with normative standards. Experimental or numerical analyses were carried out to identify limits for roll and tilt angles. The boundary element method (Ansys AQWA) is not suitable for capturing vortex-induced vibrations in simulations. To analyse this aspect in detail, further computational fluid dynamic simulations would need to be performed.

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