Combination of waves and current in AquaSim

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Summary:

This document describes how AquaSim models the combined effects of waves and current, focusing on how current modifies the wave propagation through Doppler shifting and wave action conservation.

When waves travel with the current, they become longer with decreased amplitude. When waves travel against the current, the waves become shorter with increased amplitude. AquaSim interprets the input wave period as valid for an observer moving with the current. Meaning, if the period relative to an earth fixed point is to remain constant, the input period must be adjusted depending on current direction and velocity.

A case study from (Faltinsen et. al., 2025) is reproduced with AquaSim analyses. The AquaSim results are compared with the test results. The results show how AquaSim captures the main physical effects correctly when Doppler corrections are applied.

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Content

1 Introduction

Ocean waves are significantly influenced by currents, which alter their propagation characteristics, including wavelength and wave height. This document explains how ocean current affects a wave field, focusing on the key observation that waves traveling in the same direction as the current become longer with decreased amplitude, while waves traveling in the opposite direction become shorter with increased amplitude. These effects arise primarily from the Doppler effect and changes in wave steepness, with implications for oceanography, marine engineering, and navigation, e.g. see (Kundu et. al., 2008), (Phillips, 1977) and (Peregrine, 1976).

AquaSim assumes that the waves ride on top of a current field. This means that the wave period given as input will be valid for an observer moving with the same velocity as the waves. For an observer standing still the wave period given as input to AquaSim will have a doppler effect where the observed period will differ from the wave period.

The interaction between a current and a wave field modifies the wave's propagation through two primary mechanisms: the Doppler effect, which alters the observed frequency and wavelength, and the conservation of wave action, which influences wave height. These effects are particularly pronounced for deep-water gravity waves, and this document only considers infinite depth.

2 Theoretical background

When a wave propagates in a medium with a current of velocity *U*, from an earth fixed observation point, the observed (encounter) angular frequency ω_e differs from the intrinsic frequency ω_0. For deep-water waves, the Doppler-shifted encounter frequency is approximated as:

$$\omega_e = \omega_0 + \frac{\omega_0^2 U}{g}$$

where:

- $\omega_e = \frac{2\pi}{T_e}$ Encounter angular frequency (rad/s) (Earth fixed).
- $\omega_0 = \frac{2\pi}{T}$ Intrinsic angular frequency (rad/s) (Following current).
- *U*: Current velocity (m/s), positive if in the same direction as wave propagation, negative if opposing.

The wave number $k = \frac{\omega_0^2}{g}$ and the wavelength is $\lambda = \frac{2\pi}{k}$. The phase speed of deep-water waves is $c = \frac{\omega_0}{k} = \sqrt{\frac{g}{k}}$, but in the presence of a current, the effective phase speed becomes $c+U$.

2.1 Influence of current on Wave Height and Wave Period

The wave height is influenced by the conservation of wave action (or wave energy flux), which states that the wave action is conserved along the wave path. The wave action is proportional to the wave energy density (wave energy divided by the intrinsic wavelength) and the group velocity. In the presence of a current, the wave energy density $E \propto a^2$ (where a is the wave amplitude) and the group velocity c_g, are modified. When a wave meets a current field, the earth fixed wave period ω_e, remains the same, meaning that:

For waves traveling with the current ($U > 0$):

- The wavelength increases as shown in Section 2.2.
- Conservation of wave action leads to a decrease in wave amplitude a, resulting in lower wave height.

For waves opposing the current ($U < 0$):

- The wavelength decreases, increasing the wave steepness as shown in Section 2.3.
- Conservation of wave action increases the wave amplitude, resulting in higher wave height. See Section 2.4.

This effect can lead to wave breaking in strong opposing currents, as the increased steepness makes waves unstable.

For a real-life case, current mixed with waves can introduce more complex effects as highlighted in e.g. (Faltinsen et. al., 2025).

2.2 Waves in the Same Direction as the Current

If the current is in the same direction as the wave ($U > 0$), the encounter frequency ω_e increases:

$$\omega_e = \omega_0 + \frac{\omega_0^2 U}{g} > \omega_0$$

This corresponds to a shorter encounter period $T_e = \frac{2\pi}{\omega_e} < T$. The effective phase speed increases to $c + U$, leading to a longer wavelength:

$$\lambda_e = \frac{c + U}{f_e}$$

Since $f_e = \frac{\omega_e}{2\pi}$ is higher and $c + U > c$, the wavelength λ_e is longer than the intrinsic wavelength. This is illustrated in Figure 1.

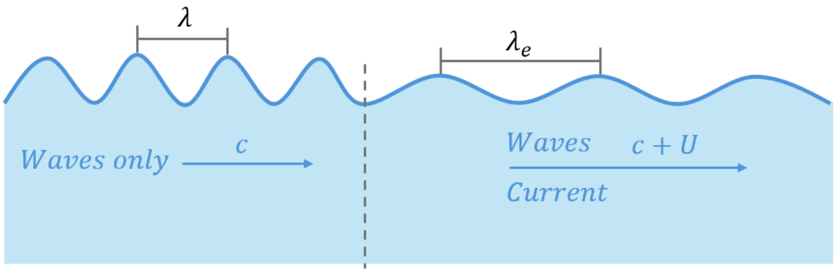

Figure 1 Illustration of waves and current in the same direction

2.3 Waves and Current in Opposite Directions

If the current opposes the wave ($U < 0$), the encounter frequency decreases:

$$\omega_e = \omega_0 - \frac{\omega_0^2 |U|}{g} < \omega_0$$

This results in a longer encounter period ($T_e > T$). The effective phase speed is reduced to $c - |U|$, leading to a shorter wavelength:

$$\lambda_e = \frac{c - |U|}{f_e}$$

Since f_e is lower and $c - |U| < c$, the wavelength λ_e is shorter than the intrinsic wavelength.

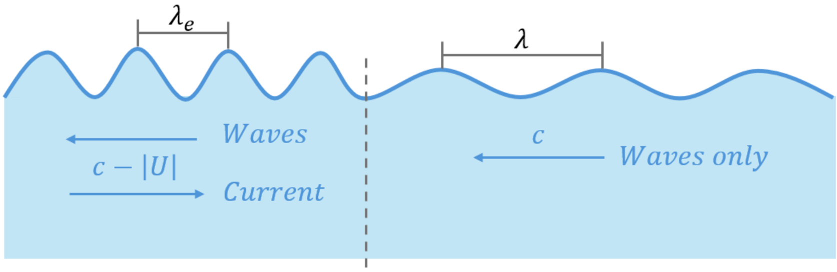

Figure 2 Illustration of waves and current in the opposite direction

2.4 Wave Energy Flux of a Propagating Deep-Water Gravity Wave

In hydrodynamics, the wave energy flux (also known as wave action or wave power per unit crest width) for a propagating water wave in infinite depth (deep water, where the water depth is much greater than the wavelength) describes the rate at which wave energy is transported horizontally. For linear gravity waves, this is derived from the wave's energy density and its group velocity. Below, we will explain the key concepts and derive the expression step by step, assuming a monochromatic sinusoidal wave in the linear approximation (small amplitude compared to wavelength).

2.4.1 Dispersion Relation and Group Velocity for Deep-Water Gravity Waves

The starting point is the dispersion relation, which relates the angular frequency ω to the wavenumber $k = 2\pi/\lambda$ (where λ is the wavelength):

$$\omega^2 = gk$$

Here, g is the gravitational acceleration. This holds for infinite depth, where bottom effects are negligible.

The phase velocity c (speed of the wave crests) is:

$$c = \frac{\omega}{k} = \sqrt{\frac{g}{k}} = \frac{g}{\omega}$$

The group velocity c_g (speed at which energy propagates) is the derivative:

$$c_g = \frac{d\omega}{dk} = \frac{1}{2}\sqrt{\frac{g}{k}} = \frac{c}{2} = \frac{g}{2\omega}$$

2.4.2 Wave Energy Density

The total average wave energy density E (energy per unit horizontal surface area) for a linear gravity wave is the sum of kinetic and potential energy. For a sinusoidal surface displacement $\eta(x, t) = a \cos{(kx - \omega t)}$, where a is the amplitude, the average potential energy per unit area is $\frac{1}{4}\rho g a^2$, and the kinetic energy is equal to this (by the virial theorem for irrotational flow). Thus, the total energy (kinetic + potential) is given by:

$$E = \frac{1}{2}\rho g a^2$$

Here ρ is the water density.

(Note: Sometimes this is expressed in terms of wave height $H = 2a$, giving $E = \frac{1}{8}\rho g H^2$, but we will use amplitude a here.)

2.4.3 Deriving the Wave Energy Flux

The wave energy flux J (power per unit width perpendicular to the direction of propagation) is the product of the wave energy density and the group velocity, as the group velocity governs energy transport:

$$J = E \cdot c_g = (\frac{1}{2}\rho g a^2) \cdot (\frac{c}{2}) = \frac{1}{4}\rho g a^2 c$$

Substituting $c = g/\omega$:

$$J = \frac{1}{4}\rho g a^2 \cdot \frac{g}{\omega} = \frac{\rho g^2 a^2}{4\omega}$$

Alternatively, in terms of c_g:

$$J = \frac{1}{2}\rho g a^2 \cdot c_g$$

Or using wave height $H = 2a$:

$$J = \frac{1}{16}\rho g H^2 c = \frac{1}{8}\rho g H^2 c_g$$

Or in terms of wave period T:

$$J = \frac{\rho g^2 H^2 T}{32\pi}$$

Equation 1

This is the time-averaged energy flux for a propagating wave. It can also be derived more rigorously by integrating the product of dynamic pressure and horizontal velocity over depth, but the wave energy density times group velocity approach is standard in linear wave theory.

For context, this assumes inviscid, irrotational flow and neglects nonlinear effects, which are valid for small-amplitude waves. In real water waves, additional factors like wind input or dissipation may apply, but the question focuses on the basic propagating case.

As seen from Equation 1 the wave energy flux is proportional to the wave period meaning that if the wave period increases, the wave amplitude must decrease to keep the wave energy flux constant.

3 Implementation to AquaSim

AquaSim assumes that the wave period given as input is a wave period for an observer following the current velocity, this means that when waves and current rides in the same direction and the period of encounter is kept constant, then the period given to AquaSim should be increased appropriately. As an example, Figure 3 leads to the same period of encounter (4.2s) which is the period that will remain constant for a wave entering a current field.

☑	Nr	Amp[m]	T[s]	V[deg]	cX[m/s]	cY[m/s]	wX[m/s]	wY[m/s]
☑	1	0.4	4.2	0.0	0	0	0	0
☑	2	0.4	4.75	0.0	1	0	0	0
☑	3	0.4	4.9	0.0	1.3	0	0	0

Figure 3 Periods in analysis giving the same (4.2s) period of encounter

Note that this document expresses no change in how this is to be introduced to AquaSim.

4 Case study

A recent paper by (Faltinsen et. al., 2025) illustrates this effect and presents analysis results and model test tank results for a case seen in Figure 4.

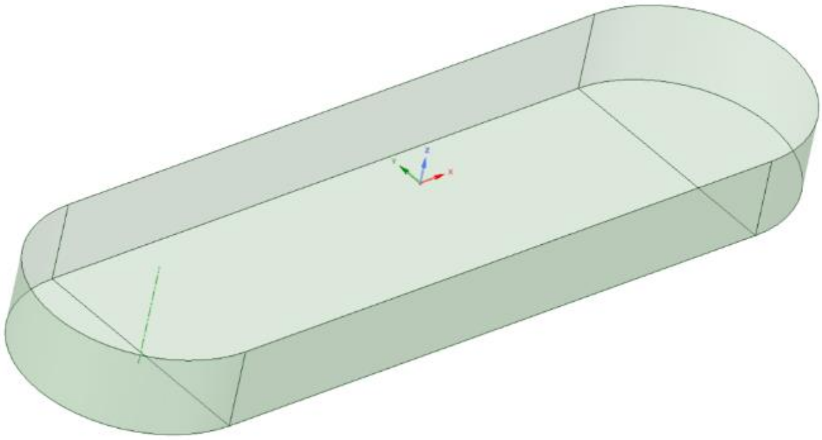

Figure 4 Pontoon: two semicircular cylindrical ends with a rectangular box in between. Full-scale length (L), breadth (B) and draft (D) are 53m, 14.9m and 5m, respectively, (Faltinsen et. al., 2025)

The model tank test is shown in Figure 5.

Figure 5 Tank test arrangement

4.1 Results from Faltinsen et. al. (2025)

Figure 6 shows RAO of the linear horizontal wave force Fx (in local x-direction) on the pontoon versus the wave period in full-scale conditions, with coinciding head sea wave and current directions.

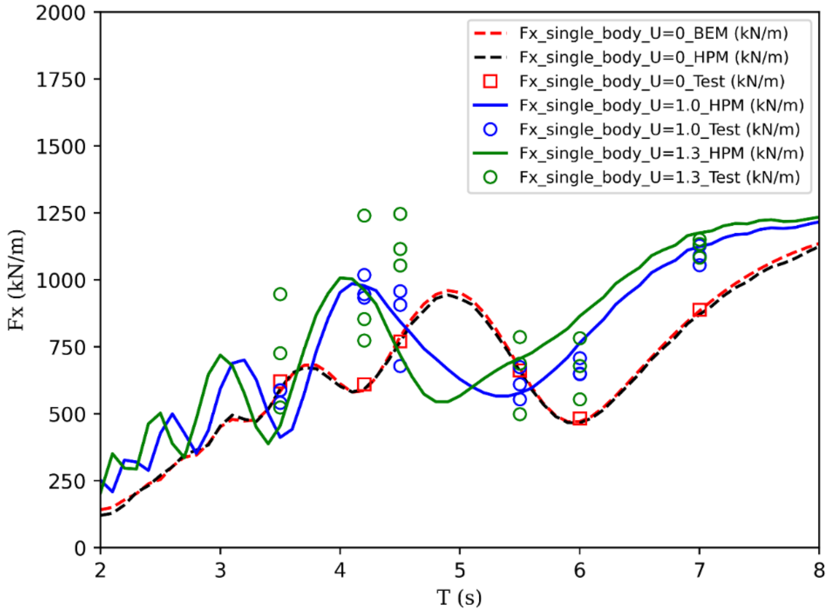

Figure 6 RAO of the linear longitudinal wave force Fx on the pontoon versus the wave period in full-scale conditions. Coinciding head sea wave and current directions. Numerical and experimental results for different full-scaled current velocities U in m/s, (Faltinsen et. al., 2025)

Figure 7 shows RAO of the linear vertical wave force Fz on the pontoon versus the wave period in full-scale conditions, with coinciding head sea wave and current directions.

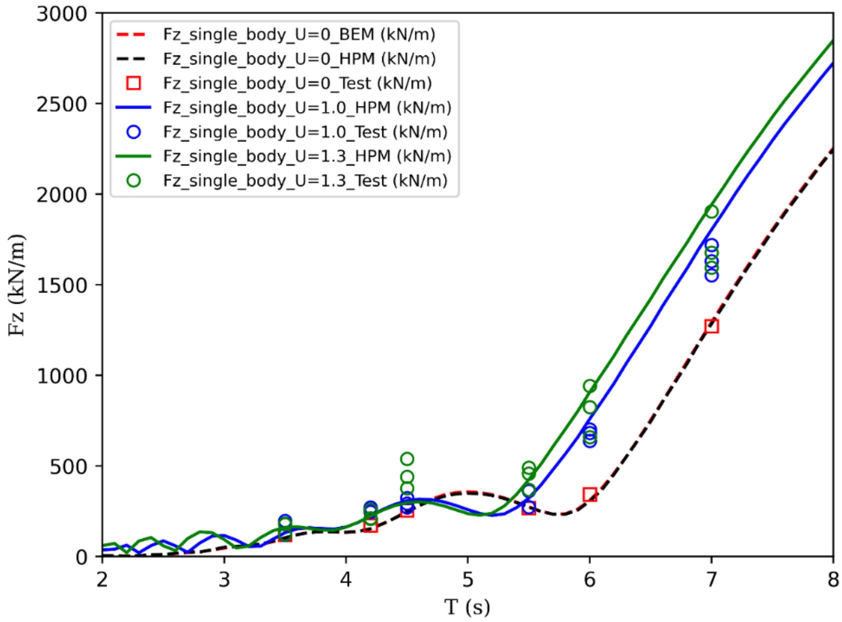

Figure 7 RAO of the linear vertical wave force Fz on the pontoon versus the wave period in full-scale conditions. Coinciding head sea wave and current directions. Numerical and experimental results for different full-scaled current velocities U in m/s, (Faltinsen et. al., 2025)

4.2 AquaSim model and analysis

An AquaSim analysis model has been established as shown in Figure 8 and Figure 9.

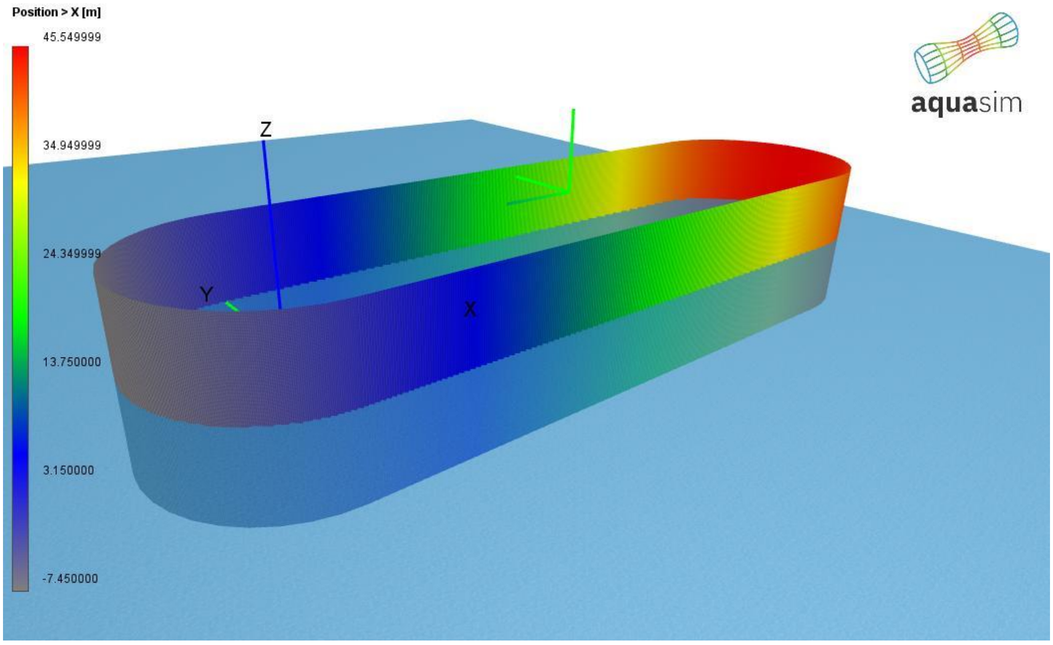

Figure 8 Analysis model AquaSim

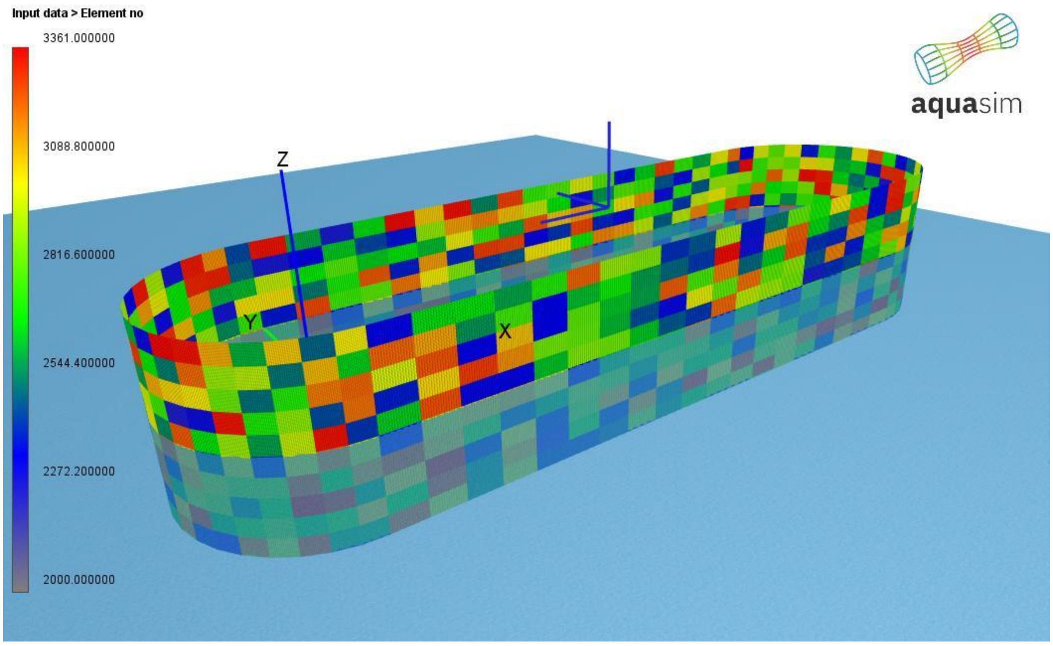

Figure 9 Elements in analysis model approximately 1100 panel elements and 2000 beam elements for force distribution

Results have been extracted from AquaSim analysis in two ways:

- Results from AquaSim have been extracted from by linearized forces found in the #hydro.txt file in the output from AquaSim, meaning as linear RAO coefficients.
- Results taken out by modeling the full floater including such that results include nonlinear effects and drag according to coefficients.

4.2.1 Results in terms of RAO coefficients

Figure 10 shows horizontal forces in [kN], calculated by AquaSim as a function of wave period in [s].

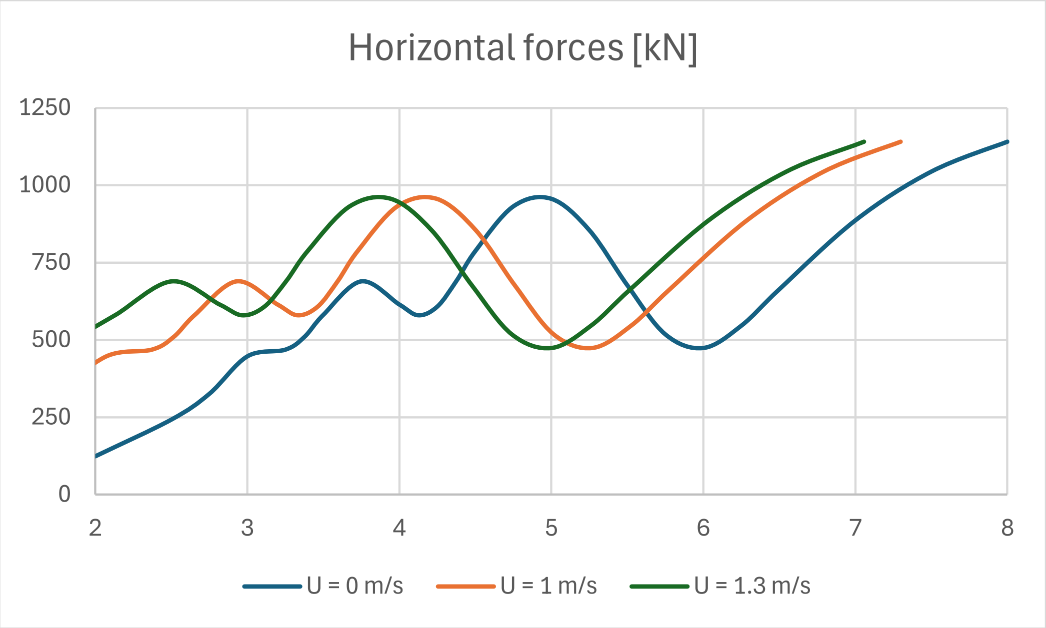

Figure 10 Horizontal forces from AquaSim analysis assuming doppler shift to obtain correct period

By comparing results in Figure 10 with Figure 6, it is seen that results seem reasonable by introducing the appropriate phase shift.

Figure 11 shows results for vertical forces in [kN], calculated by AquaSim as a function of wave period in [s]. By comparing these results with Figure 7 it seems to capture the effect of current appropriately.

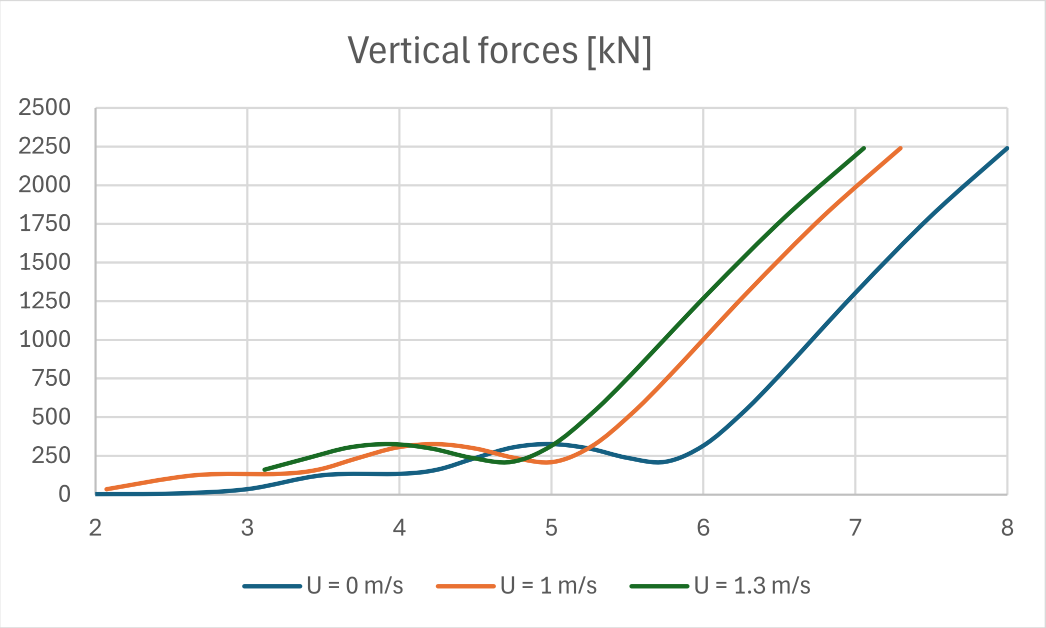

Figure 11 Vertical forces from AquaSim analysis assuming doppler shift to obtain correct period

4.2.2 Results by full analysis

The analysis model has been established to include stiff beams connecting to the vessels center point and then 3 trusses have been introduced to fixed points to capture integrated forces in all directions as shown in Figure 12.

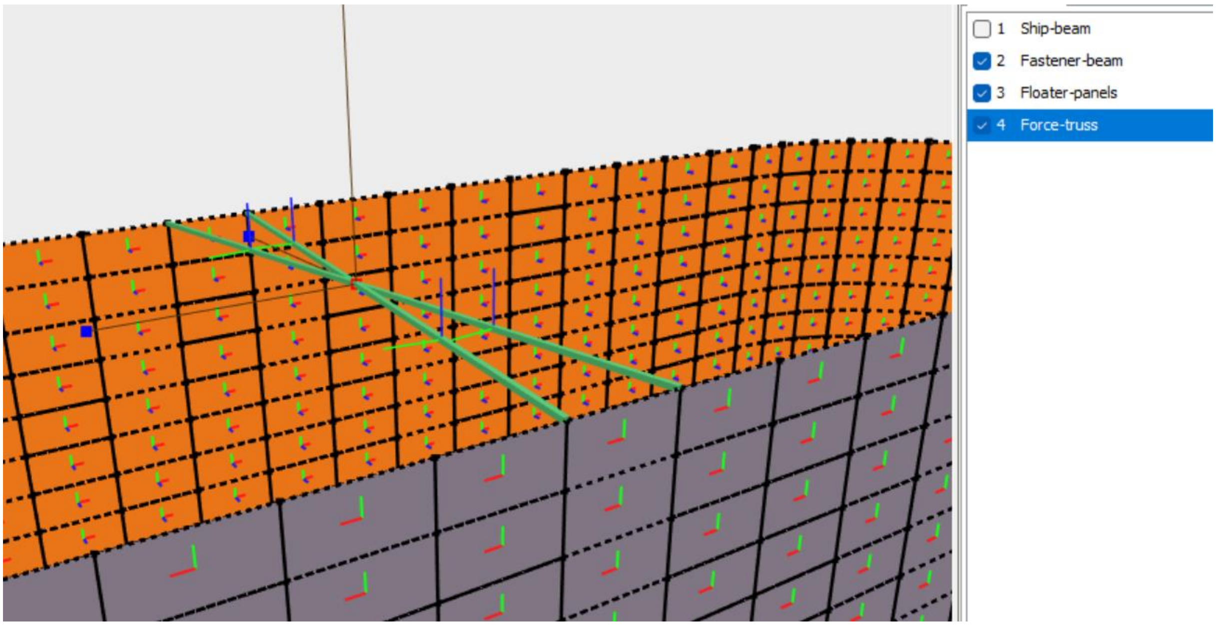

Figure 12 Capturing of forces in analysis model

Drag parameters (acting on the incident flow only) are as shown in Figure 13.

Drag	
Drag coefficient upstream	0.4
Drag coefficient downstream	0.2
Skin friction coefficient	0.0
Lift coefficient	0.0

Figure 13 Drag parameters for model in AquaEdit

Analysis was carried out with a wave amplitude of 1 m. Figure 14 - Figure 16 shows results for a case with T_0 = 4.20s, 4.75s and 4.90s, and current velocities of 0.0m/s, 1.0m/s and 1.3m/s respectively, meaning that T_e is approximately 4.20s for all cases. Results for horizontal forces are shown in Figure 14, Figure 15 and Figure 16.

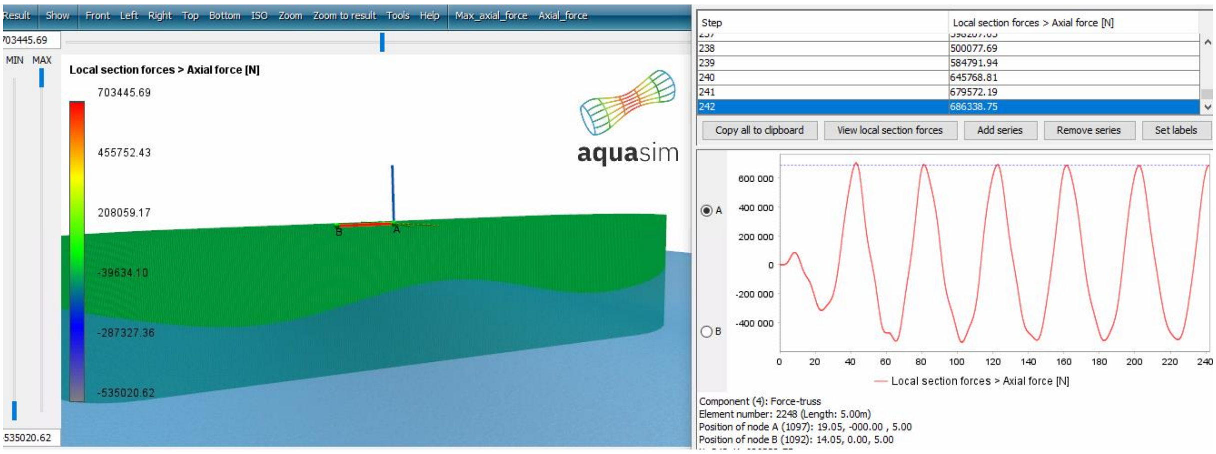

Figure 14 T_0 = 4.20s, no current

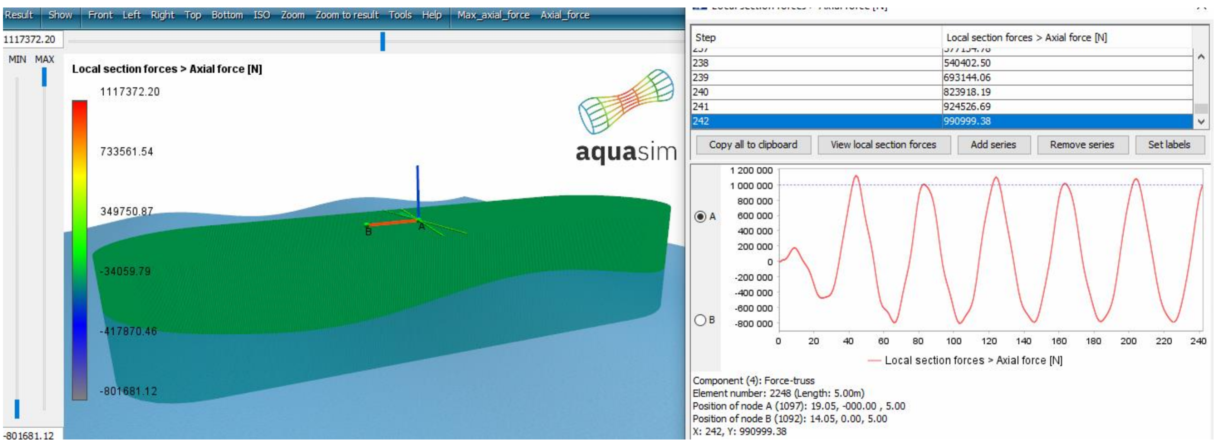

Figure 15 T_0 = 4.75s, current velocity 1.0m/s

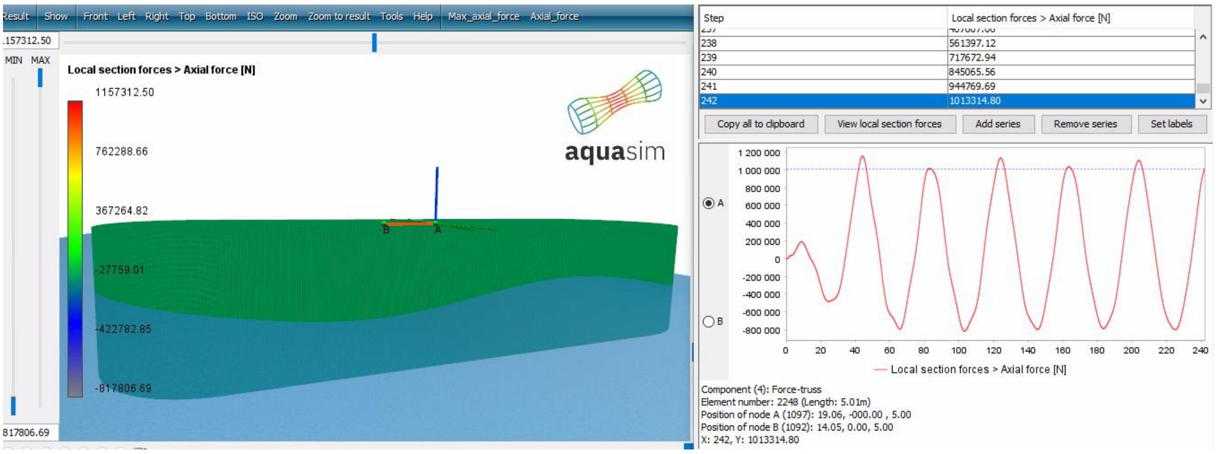

Figure 16 T_0 = 4.90s, current velocity 1.3m/s

Results presented in these figures (Figure 14 - Figure 16) correspond well with the test results in Figure 6.

The next figures present the vertical forces for a case where T_e is 6.0s.

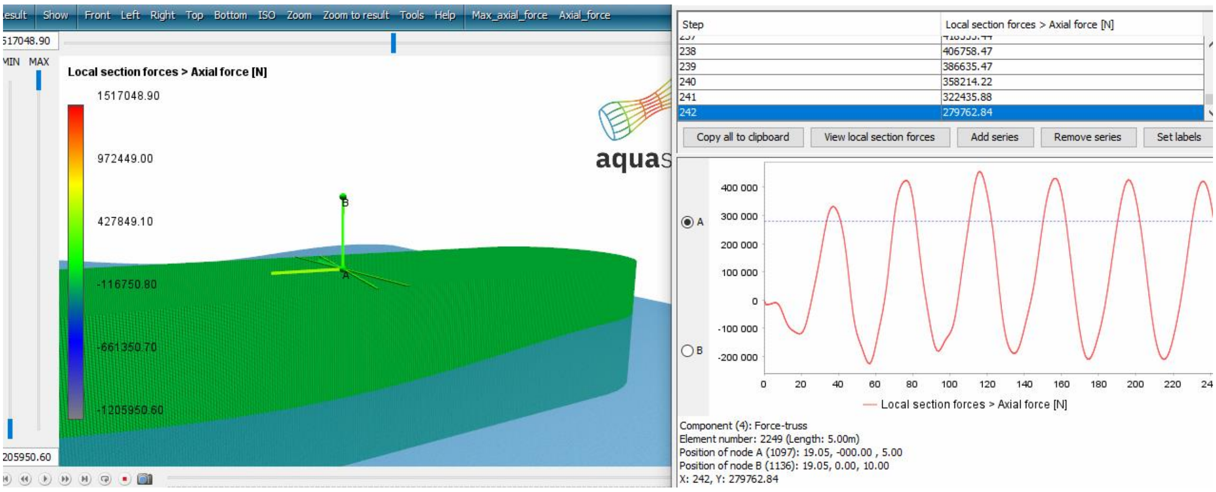

Figure 17 T_0 = 6.00s, no current

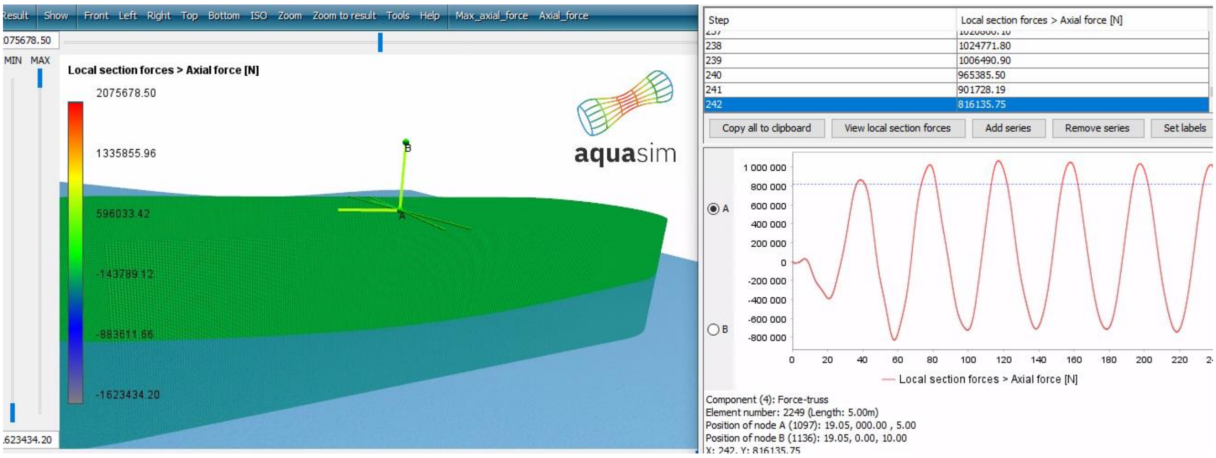

Figure 18 T_0 = 6.60s, current velocity 1.0m/s.

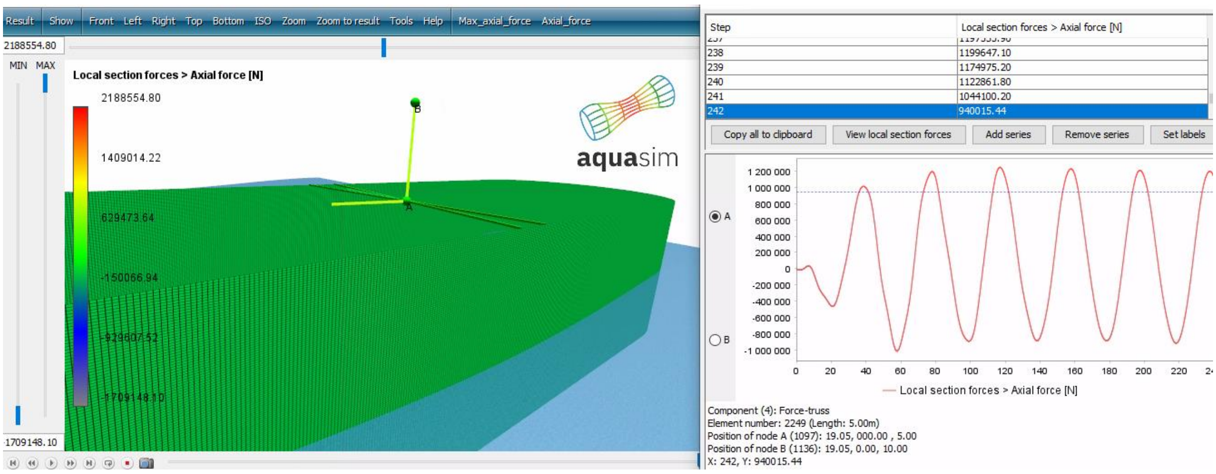

Figure 19 T_0 = 6.75s, current velocity 1.3m/s

5 Conclusion

This document describes how AquaSim models the combined effects of waves and current, focusing on how current modifies the wave propagation through Doppler shifting and wave action conservation.

When waves travel with the current, they become longer with decreased amplitude. When waves travel against the current, the waves become shorter with increased amplitude. AquaSim interprets the input wave period as valid for an observer moving with the current. Meaning, if the period of encounter is to remain constant, the input period must be adjusted depending on current direction and velocity.

A case study from (Faltinsen et. al., 2025) is reproduced with AquaSim analyses. The AquaSim results are compared with the test results. The results show how AquaSim captures the main physical effects correctly when Doppler corrections are applied.

6 References

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