L07 Wave drift load analysis

Introduction

This example demonstrates how wave drift effects can be modelled in OrcaFlex. We have chosen to consider a scenario where Newman's approximation may perform poorly. Instead, we employ OrcaWave to calculate full quadratic transfer function (QTF) wave drift load data. Later we discuss how OrcaFlex can be used to model the system response to wave drift loading.

Note: the models referenced in this description document were developed for the purpose of this example and are based on our interpretation of the materials available. If you use or refer to this model as part of your own analysis, you must carry out the appropriate checks to confirm the model properties are correct.

First order and second order wave loading

Load RAOs are used to model wave loads that are proportional to the wave amplitude and excite OrcaFlex vessel motion at the frequency of the wave components present in the model environment. Furthermore, OrcaFlex can model wave added mass and radiation damping loads associated with vessel motion. In reality, structures also experience wave loading at a range of other frequencies. The magnitude of these loads is typically smaller than those at wave frequency, however when these effects excite a resonance, the result can be significant.

Users can include second order wave effects in an OrcaFlex analysis to broaden the range of frequencies over which a vessel object experiences wave loading. Second order wave loads are divided into two categories, sum frequency loads and wave drift loads. These effects represent the load experienced by the body when considering every conceivable pair of wave components and are proportional to the wave amplitude squared.

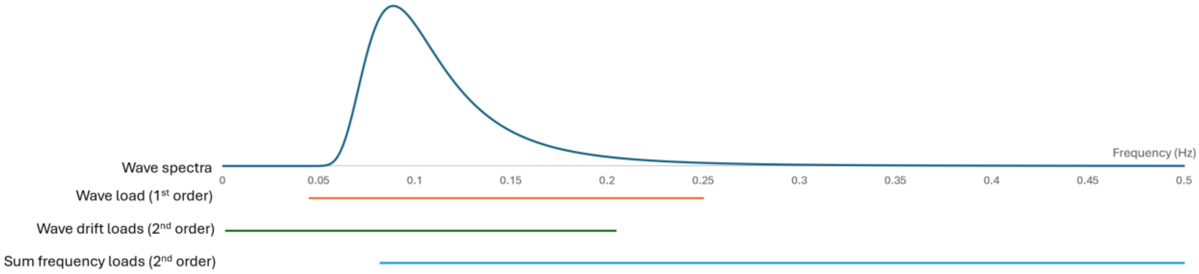


Figure 1: Comparison of the frequency range over which first and second order sources of wave loading may act.

In example L06, we demonstrate the calculation of sum frequency QTFs for a tension leg platform in OrcaWave. Sum frequency QTFs can be used to model the sum frequency load on a vessel in an OrcaFlex analysis. In this example we will focus on the calculation of difference frequency QTFs and show how they can be used to model wave drift loading on a vessel in OrcaFlex.

Newman's approximation & full QTF

OrcaFlex accepts wave drift load data in one of two forms. Firstly, you can supply mean drift load vessel type data. Mean drift loads represent the diagonal entries in the wave drift load matrix where the difference frequency is zero. OrcaFlex can estimate the off-diagonal entries (time varying wave drift loads) using Newman's approximation (see OrcaFlex help). This method is convenient since mean drift loads can be calculated in an OrcaWave diffraction analysis without solving for the second order potential, which significantly reduces the computational workload. However, there are situations where application of Newman's approximation may be inappropriate:

- Newman's approximation can be poor in shallow water.
- Newman's approximation can be poor if there is significant spreading of wave components.
- Newman's approximation is often effective at estimating the wave drift load for entries close to the diagonal which are of longer period. However, it is less effective at estimating shorter period (higher frequency) wave drift loads. Furthermore, if you are interested in higher frequency loading you may need to model sum-frequency QTFs, for which there is no analogous approximation and a full QTF analysis is necessary.

Alternatively, you can choose to ignore Newman's approximation and specify the complete matrix of difference frequency QTF data directly. OrcaWave is capable of calculating this full QTF data. Application of this data in an OrcaFlex analysis is more computationally demanding, but free from the limitations discussed above.

In this example, we have chosen to model a diffraction body in shallow water. Recognising the limitations of Newman's approximation, we will calculate wave drift loads directly via full QTF diffraction analysis.

System description

We consider a scaled version of the Korean Research Institute of Ships and Ocean Engineering (KRISO) very large crude carrier (VLCC) reference ship #2. The vessel is moored in shallow water. A hawser connects the vessel to a simple CALM buoy mooring system, similar to that presented in Example C06. A winch connected at the stern of the vessel approximates the action of a tug providing heading control. The model environment includes a JONSWAP wave train, current and wind conditions.

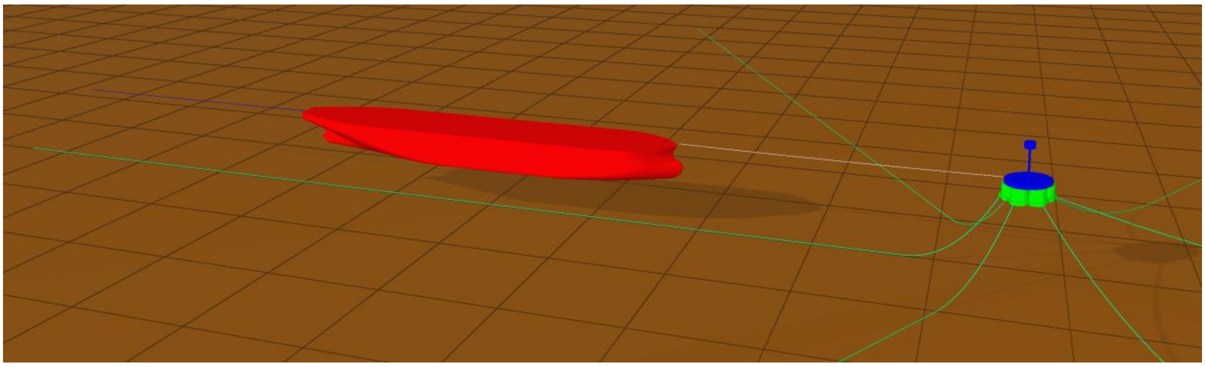


Figure 2: OrcaFlex system.

Scaled hull particulars

Parameter	Value
LBP	106.67 m
Mass	11868.06 te
LCG	3.70 m
VCG	–0.75 m
Ixx	709762.58 te.m^2
Iyy=Izz	8439507.49 te.m^2

Environment

Parameter	Value
Water depth	20.00 m
Water density	1.025 te/m^3
Wave Hs	3.00 m
Wave Tz	6.00 s
Wave spectrum	JONSWAP
Current speed	0.25 m/s
Wind speed	5.00 m/s

Tables 1 & 2: System properties. LCG relative to amidships. VCG relative to waterline.

OrcaWave analysis

We have addressed the calculation of load RAOs, added mass, damping and mean drift loads in our other diffraction examples. In a full QTF analysis, OrcaWave goes further and calculates time varying quadratic loads and potential loads for wave difference and/or sum frequencies. The potential loads can themselves be divided into two components: a body forcing potential load and a surface forcing potential load. When combined with the mean drift load, these give the full QTF dataset.

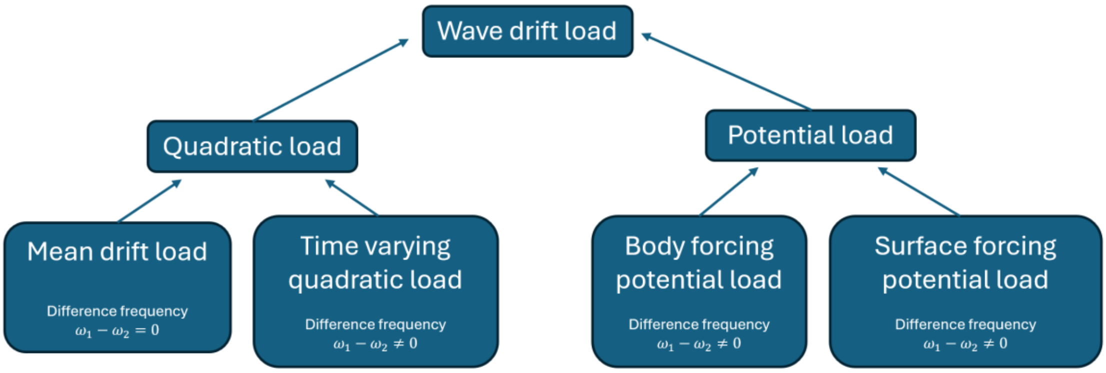


Figure 3: Wave drift load construction.

Meshes

The body mesh is an important part of any diffraction analysis, directly influencing the quality of the results. In this case the body was discretised into triangular panels. Those panels adjacent to the waterline were then vertically refined, creating slender panels of small vertical height. This targeted refinement is valuable when calculating second order loads as it helps reduce the discretisation error arising from integrals around the body waterline. Horizontal refinement of the body mesh close to the waterline is less significant in this regard. In addition, OrcaWave has been instructed to augment the body mesh with interior surface panels to suppress irregular frequency effects. Since OrcaWave uses the body mesh vertices at the waterline to construct the interior surface panels, horizontal refinement of the body mesh at the waterline would cause an unnecessary increase in the number of interior surface panels and an increase in the memory demand.

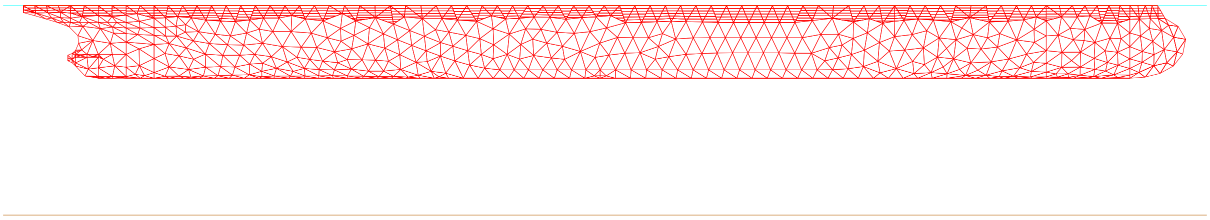


Figure 4: Targeted body panel refinement at the waterline.

To support the calculation of the quadratic load component of the full QTFs, we use OrcaWave's capability to draw control surface meshes. We have set a target *panel size* to match that of the body mesh. The separation between body mesh and control surface is arbitrary. In this case we have applied a fixed separation of 5m.

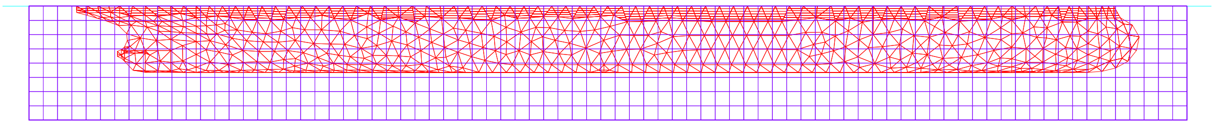


Figure 5: Control surface mesh (purple).

In order to calculate the surface forcing component of the potential load, the free surface must also be discretised. OrcaWave can consider a free surface panelled zone, quadrature zone and an asymptotic zone. Consequently, a full QTF diffraction analysis relies on a larger number of OrcaWave model variables. The process of parameterising the diffraction model and then verifying that it can deliver converged results is time consuming. Example L06 demonstrates a workflow described in the OrcaWave help designed to make this task more manageable.

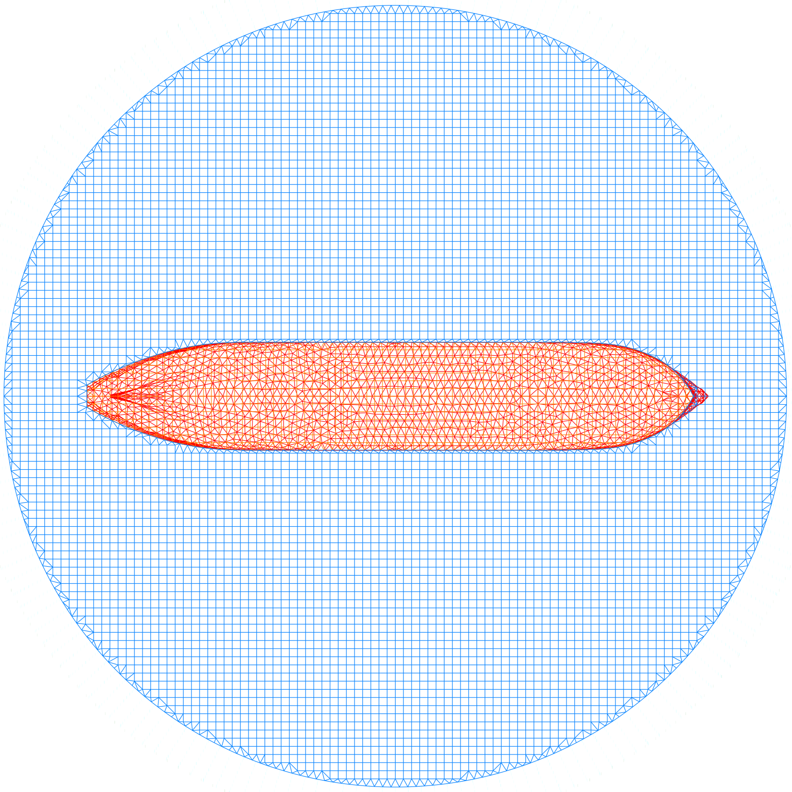


Figure 6: Free surface mesh (blue), quadrature zone nodes (cyan), asymptotic zone (extends from the outer circle to infinity).

OrcaWave has detected some panels in the body mesh with large aspect ratio. Similarly, there are body panels which are large in comparison to the shortest wavelength. Our sensitivity study has shown that we can report converged results despite these validation warnings. Further details about working with meshes in OrcaWave can be found via the technical note on the topic**.**

Wave periods & headings

OrcaWave wave periods and wave headings are chosen to ensure that the relationship between loading and wave period/heading is well captured. Ultimately OrcaFlex will interpolate within this dataset and so it is important that we provide enough data points for that interpolation to be appropriate. We have chosen to include waves of period 3 – 25s. Primarily this choice was based on the range of wave components used to construct the irregular wave train present in our OrcaFlex analysis.

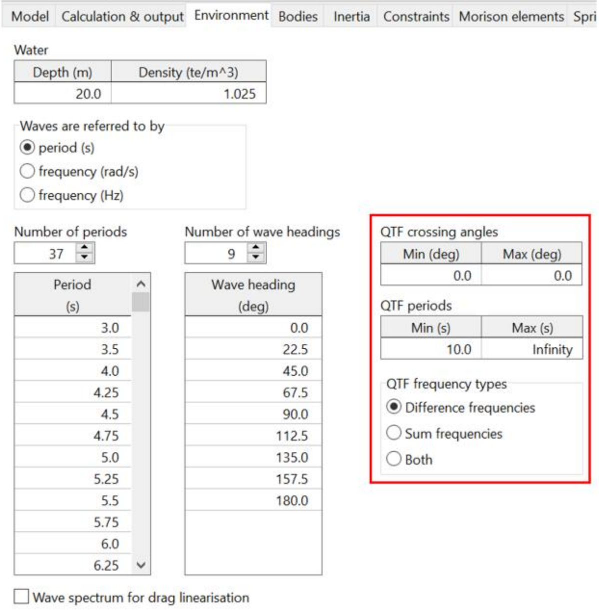
Second order wave pairs

In this example, we are interested in modelling wave drift effects. OrcaWave can calculate wave drift effects for every conceivable pair of waves defined in the diffraction analysis. For each pair of waves, we are interested in the load acting at the corresponding difference frequency. Typically, this results in a low frequency (or long period) loading effect.

In the interest of saving run time and limiting wasted effort, it is wise to restrict the calculation where possible. For example, we are only interested in wave drift effects here, so the calculation has been configured to ignore sum frequencies.

Furthermore, rather than considering every conceivable pair of waves, we have restricted the range of difference frequencies to include the longest period effects but ignore wave pairs where the QTF period is small. Modal/free decay analysis (see pages 13–14) will show that our system has very long period modes in surge, sway & yaw. We expect wave drift loads acting with short period (e.g. <10s) to have negligible impact on the system response. On OrcaWave's *Environment* page, we define period limits, rather than frequency limits here, respecting the *Waves are referred to by* selection made on the same page.

Finally, recognising that we intend to model long crested waves in OrcaFlex, we have limited the QTF analysis to unidirectional wave pairs only. We have done this by setting the *QTF crossing angles* to zero.



Water

Depth (m)	Density (te/m^3)
20.0	1.025

Waves are referred to by
● period (s)
○ frequency (rad/s)
○ frequency (Hz)

Number of periods: 37

Period (s)
3.0
3.5
4.0
4.25
4.5
4.75
5.0
5.25
5.5
5.75
6.0
6.25

Number of wave headings: 9

Wave heading (deg)
0.0
22.5
45.0
67.5
90.0
112.5
135.0
157.5
180.0

QTF crossing angles

Min (deg)	Max (deg)
0.0	0.0

QTF periods

Min (s)	Max (s)
10.0	Infinity

QTF frequency types
● Difference frequencies
○ Sum frequencies
○ Both

☐ Wave spectrum for drag linearisation

Figure 7: Limiting the OrcaWave full QTF diffraction analysis to consider unidirectional wave pairs where the difference period is greater than 10s.

When conducting sensitivity studies to test the diffraction analysis results for convergence, it is beneficial to restrict the model further. We suggest limiting the calculation to a small number of key wave periods and wave headings. Then, once convergence has been demonstrated, the remaining wave periods and headings are reintroduced for the final production run.

External stiffness and damping

On the *constraints* page, a linear stiffness matrix representing the mooring system has been included. This stiffness matrix was calculated using the same methodology outlined in Example L02. This stiffness acts between the body and the global reference frame and directly influences the calculation of the displacement RAOs. The stiffness matrix will be replaced by a system of buoys and lines in the OrcaFlex model.

Additional roll damping has been included to represent viscous sources of damping such as vortex shedding and skin friction. This additional roll damping is specified as a percentage of critical damping. An arbitrary target level of 5% has been chosen. OrcaWave computes the additional damping necessary to increase the total damping to the target level for the wave period that excites the largest roll amplitude. This damping is included in the calculation of displacement RAO motion and will be modelled as *other damping* in the OrcaFlex model.

Result convergence study

Construction of this example included a sensitivity study, testing the convergence of a range of results to variation in the discretisation of the body, the control surface and the free surface. Given the large amount of data and the repetitive nature of a sensitivity study, it is usually more convenient to extract this data using the application programming interface (OrcFxAPI), where it can then be processed and presented. Results are also available for inspection on the *graphs* & *tables* pages of the OrcaWave user interface.

See example L06 for a thorough description of a full QTF sensitivity study.

Load RAOs, added mass & damping

Testing the sensitivity of load RAOs, added mass and damping to body panel size is still valuable when undertaking a full QTF diffraction analysis. Firstly, it is likely that these results will be used in the global analysis and so it is important that they are of good quality. They are also typically greater in magnitude than the second order wave loads and so are often dominant. Furthermore, load RAOs, added mass and damping are used in the calculation of displacement RAO motion. Displacement RAOs describe the motion of the body due to first order wave loading and contribute to the calculation of full QTFs, so it is desirable to verify that they have converged. Finally, a sensitivity study focussed on first order wave loads presents an opportunity to identify a body panel size that will return first order wave results of acceptable error whilst the run time of the diffraction analysis is relatively small.

Mean drift loads

Mean drift loads are an example of a quadratic load where the difference frequency is zero. Testing the sensitivity of the mean drift loads to body panel size and control surface panel size can give insight into the convergence of time varying quadratic loads without the overhead of running a full QTF analysis.

Furthermore, the momentum conservation *quadratic load calculation method* – available on OrcaWave's *calculation & output* page – is known to be effective at calculating converged mean drift loads in the horizontal DOFs. Comparison of mean drift loads calculated via pressure integration or the control surface method with those calculated by momentum conservation can be a useful check of convergence. Once you progress to the calculation of time varying quadratic loads, the momentum conservation method becomes unavailable.

Time varying quadratic loads

Mean drift loads are available from all diffraction solve types, whilst time varying quadratic loads are only calculated when the 'Full QTF calculation' diffraction *solve type* is selected on the *calculation & output* page. They represent another component of the full QTF. Sensitivity of the time varying quadratic load can be investigated independently of the potential load component of the full QTF analysis by reporting the total quadratic load from the OrcaWave results.

Potential loads

When setting the diffraction *solve type* to 'Full QTF calculation', a page named *QTF* appears in OrcaWave. On this page the user selects the potential load calculation method and sets the parameters used to discretise the free surface. These modelling choices influence the potential load component of the full QTF only. The potential load has two subcomponents:

- A body forcing subcomponent which is influenced by the body mesh and is therefore analogous to the load RAOs in a first order analysis; here, however, OrcaWave solves for the second-order potential on each body panel.
- A surface forcing subcomponent which relies on discretisation of the free surface and a larger number of model variables.

These subcomponents are not reported explicitly, however given that they depend on differing model parameters, we can run sensitivity tests to establish whether each subcomponent has converged. This can be a large undertaking given the surface forcing subcomponent is dependent on many model variables. The OrcaWave help provides some guidance on making a first estimate of the free surface parameters.

A series of tests can then be undertaken to establish whether the potential load results are sensitive to change in the free surface or body mesh properties. See example L06 for a thorough description of a sensitivity study of this type.

Production run

Having configured the OrcaWave model in such a way that we are confident that the results are of good quality, finally we run a diffraction analysis including all wave periods and wave headings. This will produce a results file (*L07 Wave drift load analysis.owr*) that we import into OrcaFlex.

OrcaFlex analysis

OrcaFlex model construction

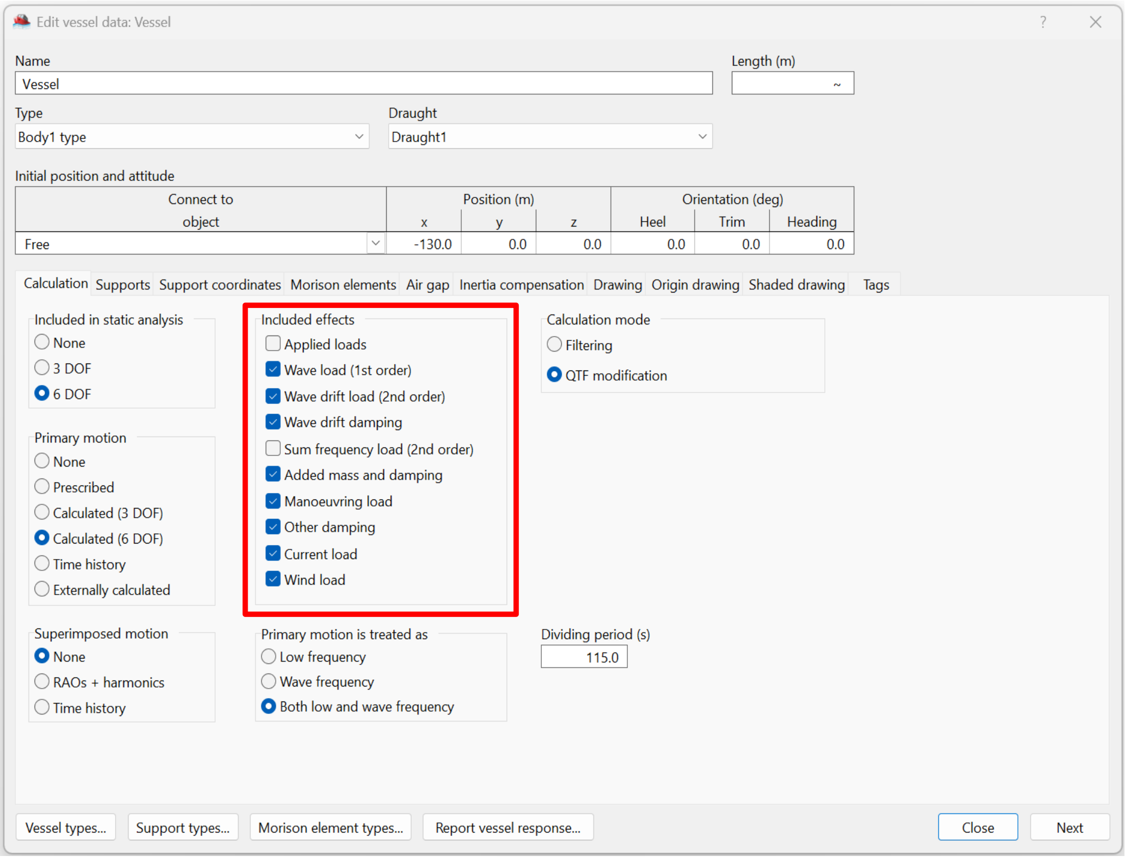
Our OrcaFlex model (*L07 Wave drift load analysis.sim*) consists of a vessel object and a mooring system represented by line objects and buoys. The mooring system is very similar to that discussed in example C06. Simplified analytic catenary mooring lines have been employed to minimise run time while we focus our attention on the impact of second order wave loading on vessel motion.

The vessel is connected to the CALM buoy mooring system via a line object connected at the bow. The line represents a hawser with relatively soft axial properties. A constant tension winch representing a tug has also been connected to the stern of the vessel to help maintain heading control. An irregular wave train, current, and wind conditions are also present.

The vessel type wire frame drawing has been overwritten. Rather than inheriting the mesh from the diffraction analysis, a mesh of uniform refinement which extends above the waterline to the deck has been used.

Loading effects

The vessel object has calculated degrees of freedom and experiences loading from a range of sources. Vessels with calculated degrees of freedom experience hydrostatic and connection loads automatically. All other loading effects are enabled/disabled by ticking the appropriate *included effects*.



Name: Vessel

Length (m): ~

Type: Body1 type

Draught: Draught1

Initial position and attitude

Connect to object	Position (m) x	y	z	Orientation (deg) Heel	Trim	Heading
Free	-130.0	0.0	0.0	0.0	0.0	0.0

Included in static analysis
- ○ None
- ○ 3 DOF
- ● 6 DOF

Primary motion
- ○ None
- ○ Prescribed
- ○ Calculated (3 DOF)
- ● Calculated (6 DOF)
- ○ Time history
- ○ Externally calculated

Superimposed motion
- ● None
- ○ RAOs + harmonics
- ○ Time history

Included effects
- ☐ Applied loads
- ☑ Wave load (1st order)
- ☑ Wave drift load (2nd order)
- ☑ Wave drift damping
- ☐ Sum frequency load (2nd order)
- ☑ Added mass and damping
- ☑ Manoeuvring load
- ☑ Other damping
- ☑ Current load
- ☑ Wind load

Primary motion is treated as
- ○ Low frequency
- ○ Wave frequency
- ● Both low and wave frequency

Calculation mode
- ○ Filtering
- ● QTF modification

Dividing period (s): 115.0

Figure 8: Vessel object data form, included effects.

Wave drift QTFs

The focus of this example is the calculation and application of wave drift loads. Wave drift loads are applied by ticking the included effect named 'Wave drift load (2nd order)' on the vessel object data form. This included effect references the wave drift data stored on the *Wave drift QTFs* page of the *vessel type* data form. On that page there are two radio buttons which control how the wave drift loads are defined. In this case we intend to use our full QTF data and choose the radio button named 'Full QTFs'. Note that the table of mean drift loads made visible when selecting Newman's approximation has also been populated when the OrcaWave results were imported.

During an analysis, OrcaFlex interpolates within the grid of QTF data, calculating and then applying loads according to the wave components present in the environment. If the environment contains wave components that are longer than the longest period specified in the table of wave drift load data, OrcaFlex will linearly extrapolate towards zero QTF at infinite period. In contrast, when the environment contains wave components with period shorter than the shortest period specified in the wave drift load data, OrcaFlex will truncate the data, taking the QTF for the shortest period given in the table (see OrcaFlex help). Notice this relationship is different to the handling of wave load RAOs which are assumed to tend to zero at zero period. When running the example model, we encounter a warning informing the user that QTF extrapolation/truncation is present.

When using full QTF wave drift load data, users can also nominate a QTF *cutoff period* in OrcaFlex. Recognising that wave drift loads are typically a long period effect, the cut off period represents the difference period below which wave drift load effects are scaled down or omitted (see OrcaFlex help). We have already discussed a similar feature in OrcaWave where we set a minimum QTF period to limit the calculation of wave drift load data to difference periods of 10s or more. Examination of the QTF data imported into OrcaFlex will show that QTFs with a difference period of less than 10s have amplitude and phase of zero. Rather than interpolate within this grid of zeros, we have applied a consistent cut off period in OrcaFlex, reducing run time.

At this point we will take a moment to examine and compare the matrix of full QTF data with the data calculated via Newman's approximation. By comparing Newman and full QTF data for this shallow water case, we may expose one of the weaknesses of Newman's approximation described during the introduction of this example. OrcaFlex does not report the full matrix of QTFs derived using Newman's approximation. For the purpose of this comparison, we have reproduced the data through external post processing of the mean drift load data. See the OrcaFlex help for details of Newman's Approximation.

Figure 9 is a visual comparison of Newman and full QTF data presenting the magnitude of the surge wave drift load for each combination of wave pairs assuming unidirectional waves of heading 180 deg. The first contour plot presents the amplitude of the full QTF data, whilst the second contour plot presents the amplitude of the QTF data derived from mean drift loads using Newman's approximation. The two plots present data sourced from the same OrcaWave diffraction analysis. They share the same mean drift load data and agree exactly along the diagonal where the difference frequency is zero. However, they differ away from the diagonal due to the different calculation methods.

Most significantly, the contour plots show that Newman's approximation fails to register the larger amplitude QTFs for wave pairs involving a low frequency component (less than 0.15 Hz). There is also inconsistency when comparing the blank regions of each contour plot where the amplitude of the QTF is zero. The full QTF plot lacks data for difference frequencies greater than 0.1 Hz. These cases were neglected in our OrcaWave diffraction analysis when setting the minimum QTF period to 10s. In contrast, the blank regions on the plot of Newman QTF data indicate wave pairs where the mean drift loads considered during Newman's approximation have opposing sign.

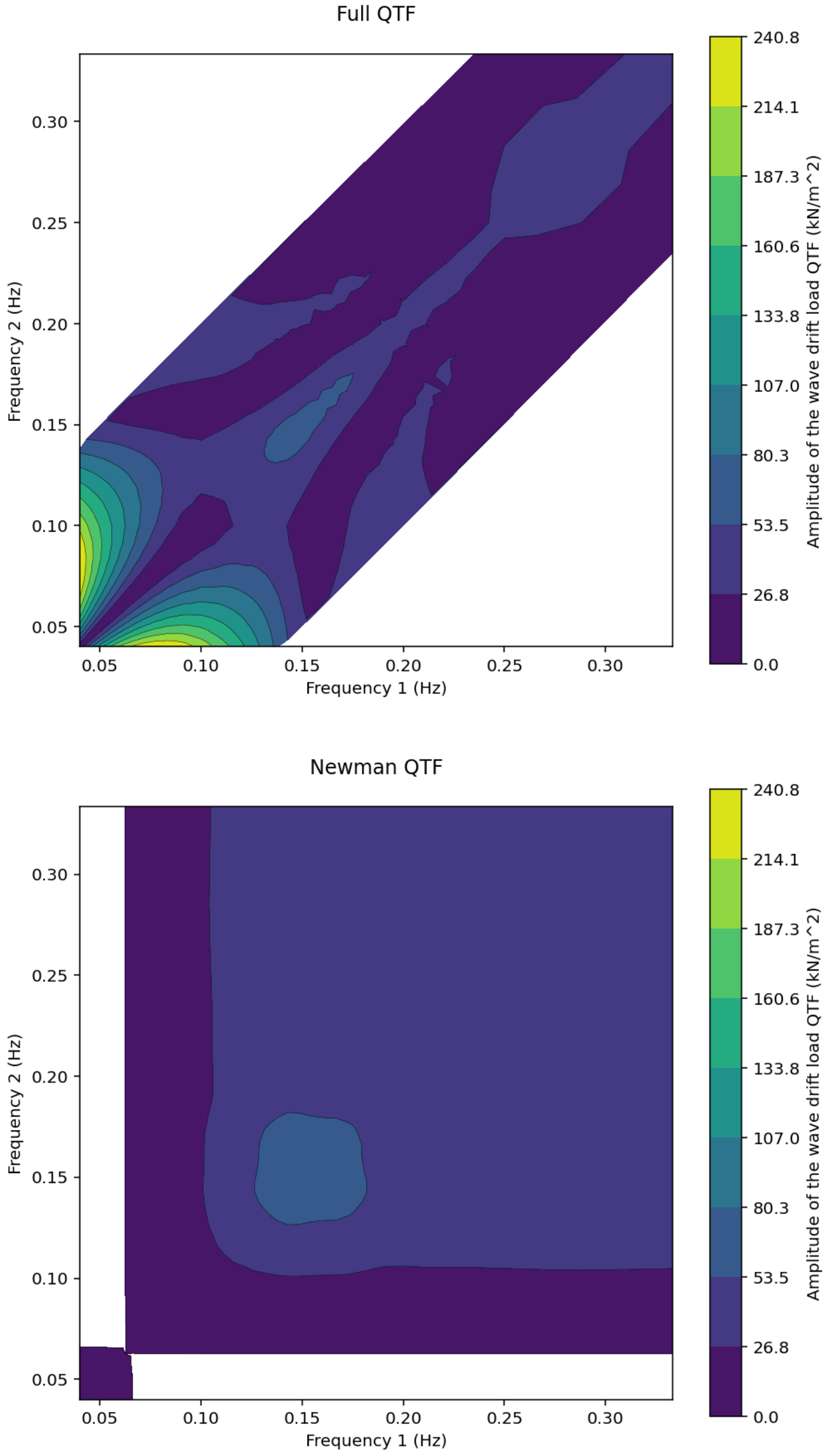


Figure 9: A comparison of full QTF and Newman QTF data. Plotting the amplitude of the surge wave drift load for each combination of unidirectional wave pairs (180 deg, 180 deg).

Wave drift damping

Wave drift loads acting at difference frequencies can excite the low frequency modes of a floating system. Whilst wave radiation damping is one of the dominant sources of damping at wave frequency, it is less effective at damping lower frequency body motion. Consequently, other sources of damping may be considered.

Model tests have shown that slowly drifting bodies experience an additional damping load when the body is drifting in the presence of waves. Often the total wave drift load decreases when the body drifts in the direction of the wave heading whilst increasing when the body drifts in a direction opposing the wave heading.

When included, wave drift damping acts to modify the calculation of the wave drift load, taking into account the vessel's low frequency velocity relative to the current. The QTF coefficients are selected based on encounter period and encounter heading and a scaling factor is applied (see OrcaFlex help).

Wave drift damping can be included provided wave drift load data is already present, no additional vessel type data is required. Wave drift damping can be applied when modelling wave drift loads via Newman's approximation or full QTFs.

The wave drift damping model assumes that the vessel is drifting at a speed which is small in comparison to the wave speed. In scenarios where this is false, the theory is no longer valid. To ensure the model is not applied in such a case, the effect of wave drift damping for a given wave component can be no greater than (and opposite to) the wave drift load itself for that component.

Manoeuvring load

The OrcaFlex manoeuvring load is a low-speed effect. It represents an inviscid damping load experienced by slowly moving bodies in flat water. It is analogous to the current included effect which represents a viscous load.

The manoeuvring load is calculated using low frequency added mass data along with the low frequency translational and angular velocity of the vessel, measured relative to the current. No additional vessel type data is required.

The manoeuvring load includes a Munk moment term acting in the yaw degree of freedom. This Munk moment contribution is also typically present in the current load data. If both manoeuvring load and current load are included, OrcaFlex will omit the Munk moment term from the manoeuvring load to avoid double counting (see OrcaFlex help).

Current & wind load

The current load represents the effect of hydrodynamic drag and skin friction on the vessel hull. The OrcaFlex current load model is based on the OCIMF approach developed for modelling surge, sway and yaw loads on VLCCs (see OrcaFlex help). The model has been implemented in a generalised form in OrcaFlex and can be used to model current loading in all six degrees of freedom using direction dependent coefficients. An additional drag load due to yaw rate can also be modelled. The current load is calculated using the fluid velocity relative to the low frequency primary motion of the vessel.

For vessel objects with large superstructures, aerodynamic loading may also be significant enough to damp slow drift motion. The vessel wind load is based on the same OCIMF model used to model current load. Note, in this example no attempt has been made to estimate the size of any superstructure and the wind load areas specified are an underestimate.

For more information on modelling vessel slow drift motion, see the OrcaFlex help.

Other damping

The external roll damping that was calculated and applied in OrcaWave is now treated as linear *other damping* on the OrcaFlex *vessel type* data form. This *other damping* has been configured to damp wave frequency vessel roll motion only.

Treatment of primary motion & vessel calculation mode

Our vessel object has been configured to experience a range of loading sources. Each included effect is calculated based on a particular component of the vessel's primary motion. In order for this to be successful, we must instruct OrcaFlex how to treat the vessel primary motion.

In this example we have chosen to treat the vessel primary motion as having 'both low and wave frequency' components. We have also specified a *dividing period*. This dividing period will be used in a filtering operation designed to isolate the low and the wave frequency components of the vessel primary motion.

This filtering operation takes place during the simulation and is inherently imperfect. To limit the undesirable effects of leakage across the filter, we aim to specify a *dividing period* which is much longer than the longest period of the vessel wave frequency response. Similarly, we are looking for a *dividing period* which is much shorter than the lowest period of significant slow drift response.

We expect the vessel wave frequency response to arise from first order wave loading. Therefore, we can estimate the range of the wave frequency response by examining the wave components present in the irregular wave train. Similarly, we can use the results of a modal analysis to estimate the range of low frequency motion that may arise from excitation of the system long period modes (see Table 3). Based on this information and consideration of the filter cutoff graphs, we ran a short sensitivity study, monitoring time histories of the filtered vessel motion and finally settled on a *dividing period* of 70s.

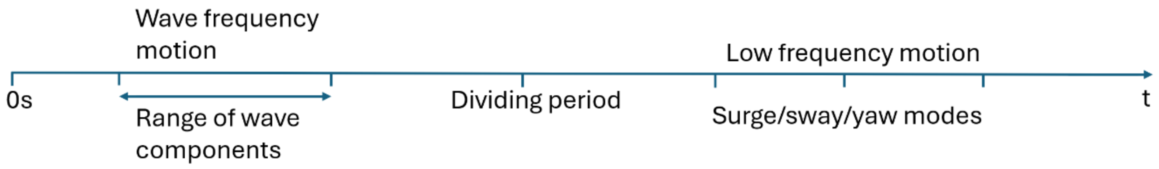


Figure 10: Dividing period selection.

When testing the sensitivity of the vessel response to the chosen *dividing period*, we observed unrealistically large roll responses when exposing the system to extreme wave conditions. To overcome this, the vessel *calculation mode* has been set to 'QTF modifications'. The vessel calculation modes represent two different methods for dealing with common second order loads. In most cases, varying the vessel calculation mode from 'Filtering' to 'QTF modifications' has minimal effect. However, as in this example, some long slender vessels can experience unrealistic roll motion when using the 'Filtering' mode.

Modal analysis

Before we begin our analysis of the system, we may run a modal analysis. The modal analysis tool can be accessed from the OrcaFlex *Results* menu and is capable of reporting the system modes based on the system static equilibrium condition. A modal analysis of the 'whole system' often shows the longest system modes relate to long period surge, sway and yaw motion of the vessel. These modes will become interesting as we investigate the effects of second order wave loading.

As part of a modal analysis OrcaFlex reports the system's undamped modes. The effect of frequency dependent added mass is also ignored. To improve the estimate of the system modes, you may consider including some constant added mass data. Alternatively, you could build a free decay test. In a free decay test, the vessel object is offset from its equilibrium position and excluded from the static analysis. Then once dynamics begins, the vessel degrees of freedom are released, and we see the system response decay towards the equilibrium condition. Free decay tests are run in time domain dynamics where the effects of damping and frequency dependent added mass can be included. Again, in this case we have chosen to simplify the mooring lines using the 'Analytic catenary' line *representation*. One of the consequences of this choice is that the effects of hydrodynamic drag acting on the mooring lines is ignored.

Mode	Period (s)	Frequency (Hz)
Swaying mode	900	0.00111
Yawing mode	246	0.00406
Surging mode	217	0.00461

Table 3: System long period modes estimated through free decay analysis.

System static response

Moving on, we consider a load case where wind, wave and current conditions are spread with heading 170 – 180 deg. Current and wind conditions are included in the static analysis, as are mean drift loads which represent the components of the wave drift load matrix with difference frequency equal to zero. OrcaFlex solves to find a static equilibrium condition where the vessel heading is approximately 0 deg, bow facing towards the incoming environmental conditions.

System dynamic response

The dynamic simulation includes a build-up period of 50s where dynamic effects such as time varying wave loads are ramped up. This is followed by a final dynamic stage of duration 1hr where the environmental conditions are fully developed.

The 3D replay shows that environmental loading causes the vessel to spring back and forth on its mooring system, we also see variation in the vessel heading. We do not have any experimental data to verify these results. However, we can use this information to draw conclusions on the inclusion of wave drift loads, the impact of additional damping and the effectiveness of Newman's approximation in this shallow water case.

Inclusion of wave drift loads

Figure 11 is a comparison of the position of the vessel origin reported in the global X direction when wave drift loads are included/neglected. We can interpret these results as tracking the vessel response in the surge DOF, since the vessel heading is close to zero throughout.

First of all, Figure 11 shows that the inclusion of wave drift loads leads to a change in the static equilibrium position of the vessel. This affects the vessel's position at the beginning of the dynamic simulation and comes about through application of mean drift loads in the static analysis.

Then, once dynamics begins, Figure 11 shows that the vessel surges at a frequency similar to that estimated during modal and free decay analysis. Closer inspection also shows that there is a wave frequency variation in vessel *X* position driven by first order wave loads, but this high frequency variation in vessel position is much smaller in amplitude.

Most notably, Figure 11 shows that the amplitude of vessel surge motion grows significantly when wave drift loads are included. The results suggest that inclusion of second order wave loads at low frequencies have excited a resonance in the system.

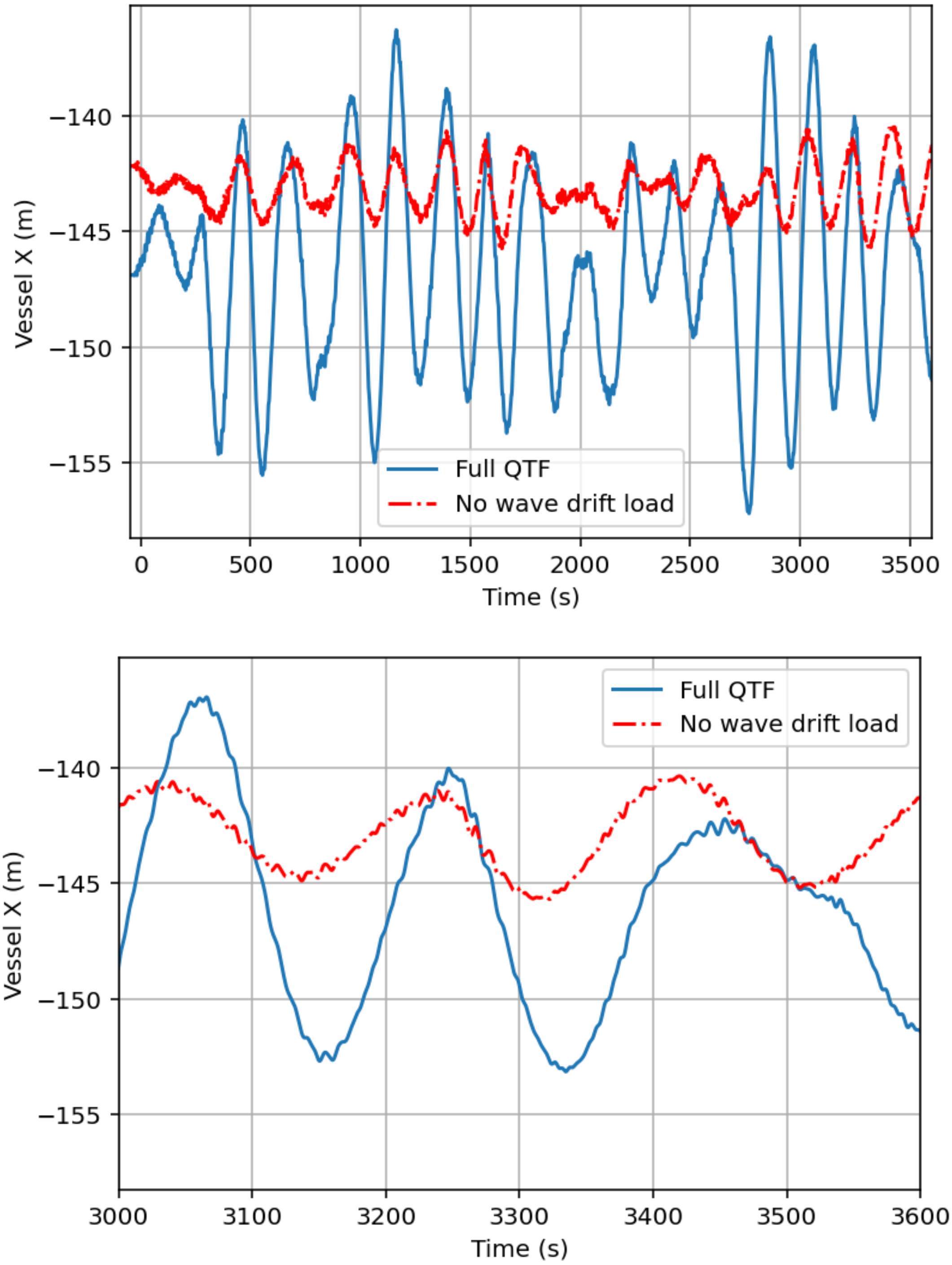


Figure 11: Time histories of vessel X position with/without wave drift loads.

Inclusion of wave drift damping and manoeuvring load

Once again in Figure 12 we present a comparison of vessel *X* position. This time we observe the impact of removing wave drift damping and manoeuvring load included effects. These included effects are typically employed to damp low frequency vessel motion.

Both manoeuvring load and wave drift damping take account of the vessel's low frequency motion relative to current. Whilst the vessel may be stationary during static analysis, a constant current is flowing. Consequently, we see that wave drift damping and manoeuvring load can influence the vessel's static equilibrium position. We see this as a discrepancy in the vessel *X* position at t = –50s.

As the dynamic motion of the system develops, we see that omission of wave drift damping and manoeuvring load leads to an increase in the amplitude of vessel *X* position.

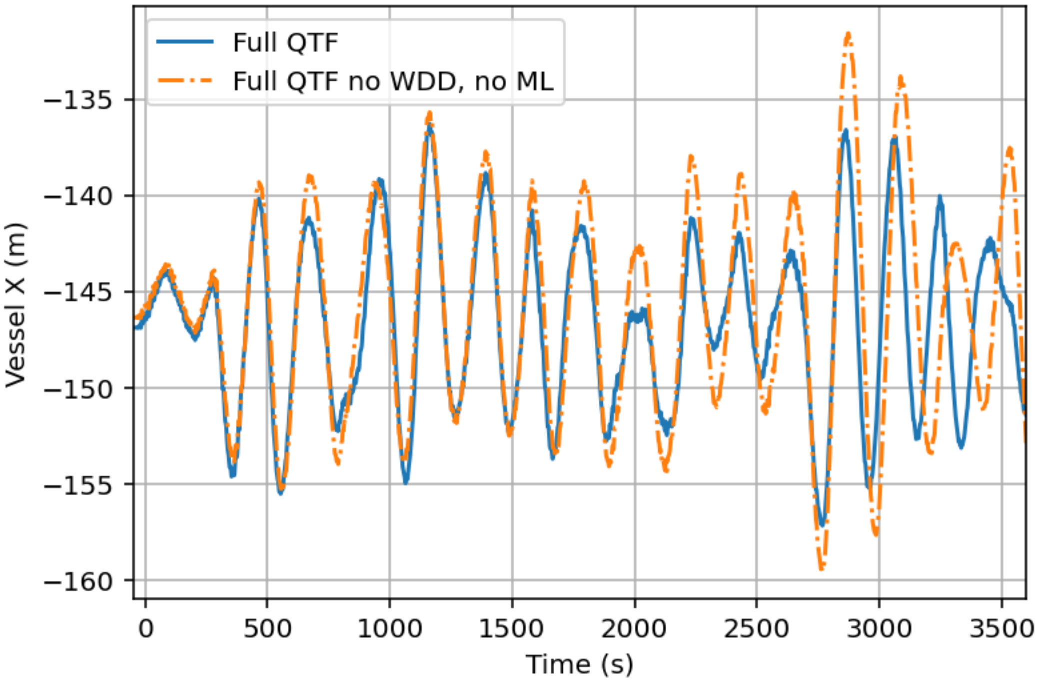


Figure 12: A time history of vessel X position with/without wave drift damping and manoeuvring load.

Comparison with Newman's approximation

Finally in Figure 13 we plot the rotational response of the vessel to inspect the effectiveness of Newman's approximation at modelling wave drift loads in this shallow water case. In this plot we focus on vessel *Rotation 3* which is the first of three successive Euler angles describing the orientation of the vessel axes relative to the global axes system. In this case we are using *Rotation 3* to monitor the yaw response of the vessel.

Figure 13 shows that the vessel begins dynamics with heading close to zero. We see the same static condition, whether using wave drift loads described by Newman's or full QTFs, because the mean drift loads are identical in both cases.

Once dynamics begins, we see the vessel yaw motion build. The combination of environmental and connection loads responsible for the variation in vessel heading are complex. Interestingly we see the vessel yaw back and forth at a frequency similar to the suspected surge resonance discussed earlier.

Initially we see reasonable agreement when comparing models using Newman and full QTFs. However, as the simulation develops, the motion reported in the two models begins to diverge. Figure 9 highlights an example of differences between Newman and full QTF loads. Those differences lead to the change in the reported vessel response seen in Figure 13.

One final point to consider is run time. Modelling wave drift loads using Newman's approximation resulted in a 75% decrease in the run time of the dynamic simulation. When combined with the decreased workload during diffraction analysis, this makes Newman's approximation an attractive simplification provided the loss of accuracy can be tolerated.

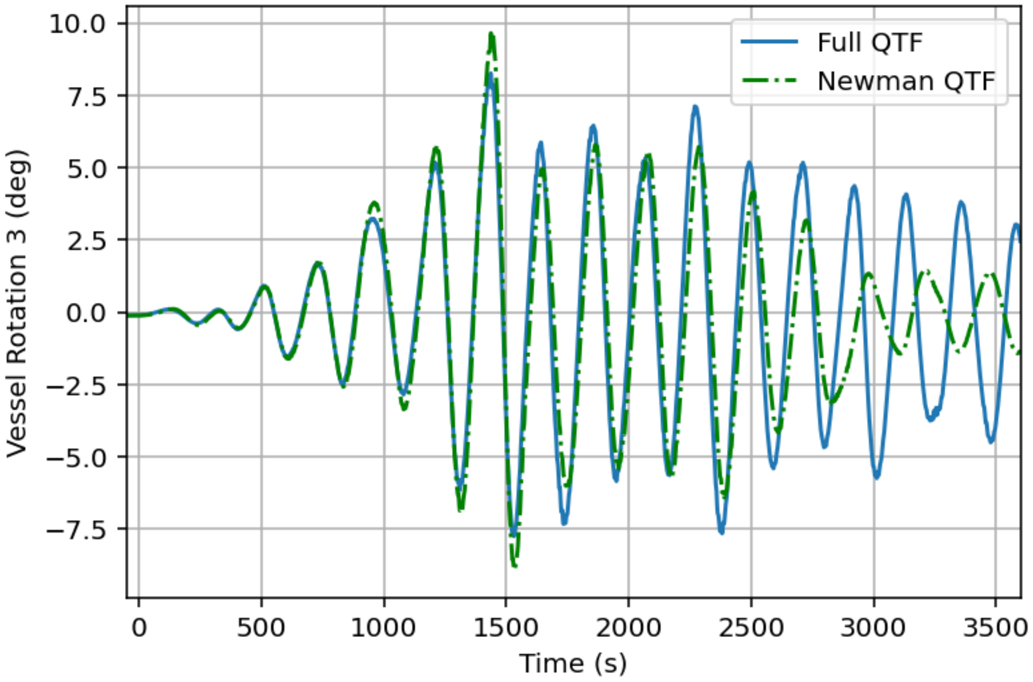


Figure 13: A time history of vessel Rotation 3 when modelling wave drift loads via Newman's and full QTF data.