Comparison of open-source code Nemoh with Wamit for cargo ship motions in shallow water

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ABSTRACT

The resolution of linear hydrodynamic problems is often a basic subject to deal with for analysis and development of marine technologies. This paper presents comparison results in addition to the benchmarking study reported in Gourlay, von Graefe, Shigunov and Lataire (2015). The focus of this study is mainly on the validation of analytical results produced with the radiation-diffraction code Nemoh developed at Ecole Centrale de Nantes, against data results from commercial code Wamit. The Nemoh code is based on Boundary Element Methods (BEM), is open-source, and is described in Babarit and Delhommeau (2015). Three different ship models were used in the study: a post-panamax container ship, a panamax container ship and a panamax bulk-carrier, corresponding to the numerically identical geometries adopted for the Wamit computations in Gourlay et al. (2015). Hydrodynamic coefficients, excitation forces and motion RAOs are computed and compared in order to provide further evidence of the Nemoh code reliability solving shallow water hydrodynamic problems, for example the prediction of ship motions for a vessel sailing through ports or channels.

The analysis results presented in this memo show a good agreement between the code's computations across the different parameters observed. The study contributes to a number of positive verification cases already available for the open-source code, and remark the consistency and the compatibility of the output produced. The benefits of a robust, open-source BEM code for solving seakeeping problems are vast, and will certainly contribute to the exploration and the optimization of both existing and new marine technologies.

INTRODUCTION

Both software, Wamit and Nemoh, are designed to solve the three-dimensional radiation-diffraction problem using panel methods. Therefore, they allow to compute wave loads and hydrodynamic characteristics of bodies interacting with ocean surface waves.

A very brief description of the resolution of vessel motions in regular waves is given below, while a complete dissertation can be found in literature.

The solution of the hydrodynamic problem of a floating body subject to ocean waves can be obtained by applying linear potential theory to the fluid domain, treated as non-viscous, incompressible and homogeneous. The surface waves are assumed to be regular (harmonic) waves of small amplitude. Linear boundary conditions on the domain bottom-floor, fluid free-surface and body-surface are also applied. The set of differential equations with boundary conditions is known as Boundary Value Problem (BVP). Eventually, the computation of the velocity potential as solution of the BVP allows to derive hydrodynamic coefficients and excitation forces caused by the waves on the geometry surface. Ship motions are subsequently derived applying linear equations for floating body's responses in regular waves.

VESSEL DESCRIPTION

Hull meshes, namely Ship D, Ship F and Ship G, were obtained from the earlier Wamit analysis. Those *gdf* files were re-arranged in a Nemoh format, which is described in Nemoh (2016). No manipulation or modification of the actual mesh points was performed for consistency with the input data and comparison purposes. Table 1 summarises main particulars of the considered vessels.

The coordinate system is set to have origin in longitudinal centre of gravity, centreline and free-surface (~waterplane). The x-axis is positive toward bow, y-axis is positive to port and z-axis pointing upward.

Table 1 - Vessel main particulars

Item	Ship D	Ship F	Ship G
Length between perp. [m]	291.13	190.00	180.00
Beam at WL [m]	40.25	32.00	33.00
Design draft [m]	15.00	11.60	11.60
Modelled draft [m]	11.60		
Displacement (computed) [m^3]	75169	42274	57724
Radii of inertia (x, y, z) [m]	13.3, 72.8, 72.8	11.7, 47.5, 47.5	14.8, 45.0, 45.0
Number of panels [-]	2160	2160	2192

Note that the number of panels is relative to half breadth only. A detailed description of the ship geometries is found in *Gourlay et al. (2015), pp.3-4.*

SOLVER SETTINGS

Analysis cases were computed for each of the three vessel shapes. Table 2 presents common parameters that were adopted in the study. Further settings are detailed for each code, separately.

Table 2: Solver settings adopted for both codes

Item	Value
Gravity	9.81 m/s^2
Water density	1000 kg/m^3
Water depth*	14.0, 13.6, 13.6
Wave direction**	0, 90, 180deg
Wave (circular) frequency	0.1 to 1 rad/s with step of 0.02 rad/s

*) Water depth is given for ship D, ship F and ship G, respectively.

**) Wave direction of 180deg means waves coming from ship bow.

Mainly, two sets of analysis cases were compared following the methodology described in *Gourlay et al. (2015)*. A first set considered six degrees of freedom (DoF) for the “free” floating body. A second set consisted in a system restrained at the centre of gravity for the surge, sway and yaw motions. Thus, those models had three DoF only (i.e. heave, roll and pitch).

For Wamit, the radiation potential and diffraction components were solved for all six DoF for the free method, with setting both IRAD and IDIFF to 1, as well as IMODE array, in the *POT* input file. For the fixed methodology, radiation/diffraction components where set to 0, while IMODE was set to “0 0 1 1 1 0” resulting in computed heave, roll and pitch only. No *config* file was passed as input, so all default values applied. As output, Wamit produces non-dimensional data. Following prescribed definition of quantities (*Wamit, 2013*), appropriate dimensions were assigned to the results in accordance to the units adopted in ULEN and GRAV parameters of the geometry (*gdf*) file.

For Nemoh, all six DoF and excitation forces were requested in the *Nemoh.cal* file for the free method. And, similarly to the Wamit input, the fixed methodology input consisted in specifying three DoFs and relative excitation forces only. Iterative solver GMRES was used in the *input.txt* file, with TOL_GMRES of 1.0E-07. The *input.txt* file information were derived from examples provided on the Nemoh website.

VALIDATION OF MOTION RAO SUB-ROUTINE

Wamit does provide Response Amplitude Operators for the analysis cases when setting the IOPTN(4) to 1 (one) in the *FRC* input file. The resulting output is found in the *frc.4* file, where RAO magnitude, phase, real and imaginary part are listed for each wave period, wave direction and degree of freedom, *Wamit (2013)*.

Since Nemoh does not directly provide ship motion RAOs, those were obtained applying the equations of motion for a floating body in regular waves. From Newman (1977), eq.(187):

$$\sum_{i=1}^{6} \xi_j \left[-\omega^2 \left(M_{ij} + a_{ij}\right) + i\omega b_{ij} + c_{ij}\right] = AX_i$$

where:

- ω is the wave circular frequency
- ξ_j is the body motion
- a_{ij}, b_{ij}, c_{ij} are added mass, damping and restoring term, respectively.
- X_i is the wave excitation force per unit wave amplitude
- A is the wave amplitude

The equation is solved for the body motion ξ_j, and the complex Response Amplitude Operator for the jth mode is obtained (Newman, 1977):

$$Z_j(\omega,\theta) \equiv \frac{\xi_j}{A} = \sum_{i=1}^{6} \left[C_{ij}\right]^{-1} X_i$$

where $[C_{ij}]^{-1}$ indicates the inverse matrix of the member between brackets in the equation of motion. Note that the RAOs are given for each wave frequency (ω) and direction (θ), considered.

An independent sub-routine was written and developed in Python in order to implement the motion equation. Please note that, there are Matlab scripts available for this on the Nemoh website.

The motion RAOs are computed after running the code solver, when added mass, damping, restoring term and excitation force data are collected.
A test run was performed on the Wamit output only in order to validate the sub-routine itself. Initially, hydrodynamic coefficients and excitation forces were read from output files *frc.1* and *frc.3*, respectively. Then, body-mass and restoring terms matrices were built using the Wamit output-data. Those quantities were passed to the sub-routine which returned the computed RAOs. Figure 1 presents a comparison between output RAOs and re-computed ones for ship G with: pitch in head seas (top) and roll in beam seas (bottom).

There is a difference in the complex notation adopted between the two codes. From *Wamit (2013) eq(3.1)*:

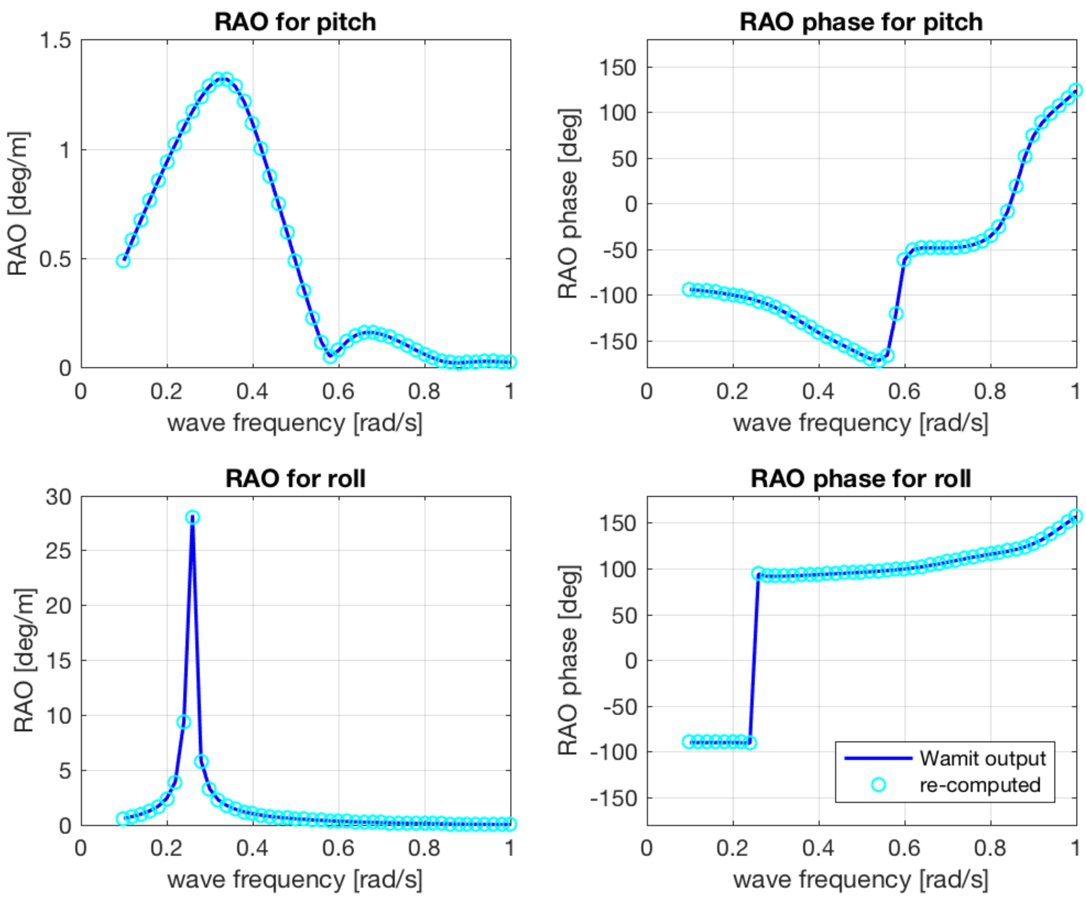
$$\Re\left((U+iV)e^{i\omega t}\right)=W\cos(\omega t+\delta)$$

where W = |U + iV|. While *Delhommeau (1993)* indicates the complex notation as:

$$A=A^{(1)}\cos(\omega t)+A^{(2)}\sin(\omega t)=\Re\left(\tilde{A}e^{-i\omega t}\right)$$

where $\tilde{A} = A^{(1)} + iA^{(2)}$. Hence, the harmonic motion defined in Delhommeau (1993) is complex conjugate to the Wamit one, having an opposite-sign imaginary part. In other words, for a similar argument, Wamit output would have phase *lead* while Nemoh would have a phase *lag* relatively to each other. Therefore, for comparison purposes, the phases were “aligned” during the output post-processing in accordance to the Wamit representation.

Figure 1 - RAOs sub-routine validation for Ship G (Wamit only)



There is very good agreement between the two sources for both RAO amplitude and phase. Therefore, the sub-routine is found suitable for its scope.

ANALYSIS RESULTS

The following quantities were obtained as analysis output:

- added mass and damping coefficients
- excitation (wave) forces
- motion RAOs

Although the codes are capable of producing further output variables, only the mentioned output was available for comparison, since the Wamit results were gathered from the previous study.

For comparison purposes, the same 3x3 matrix containing radii of gyration assigned in Wamit via the XPRDCT was imposed to the Nemoh RAO calculation. Note that Nemoh does provide a mass-matrix assuming that "the mass of the body is equal to its displacement and that the mass is distributed on the surface of the body.", Nemoh (2016). The hydrodynamic stiffness matrix (restoring term) was read from "mesh" results, with no modifications.

Figure 2 shows the motion output for ship D in beam (top) and head (bottom) waves.

Figure 2 - Ship D characteristic motions

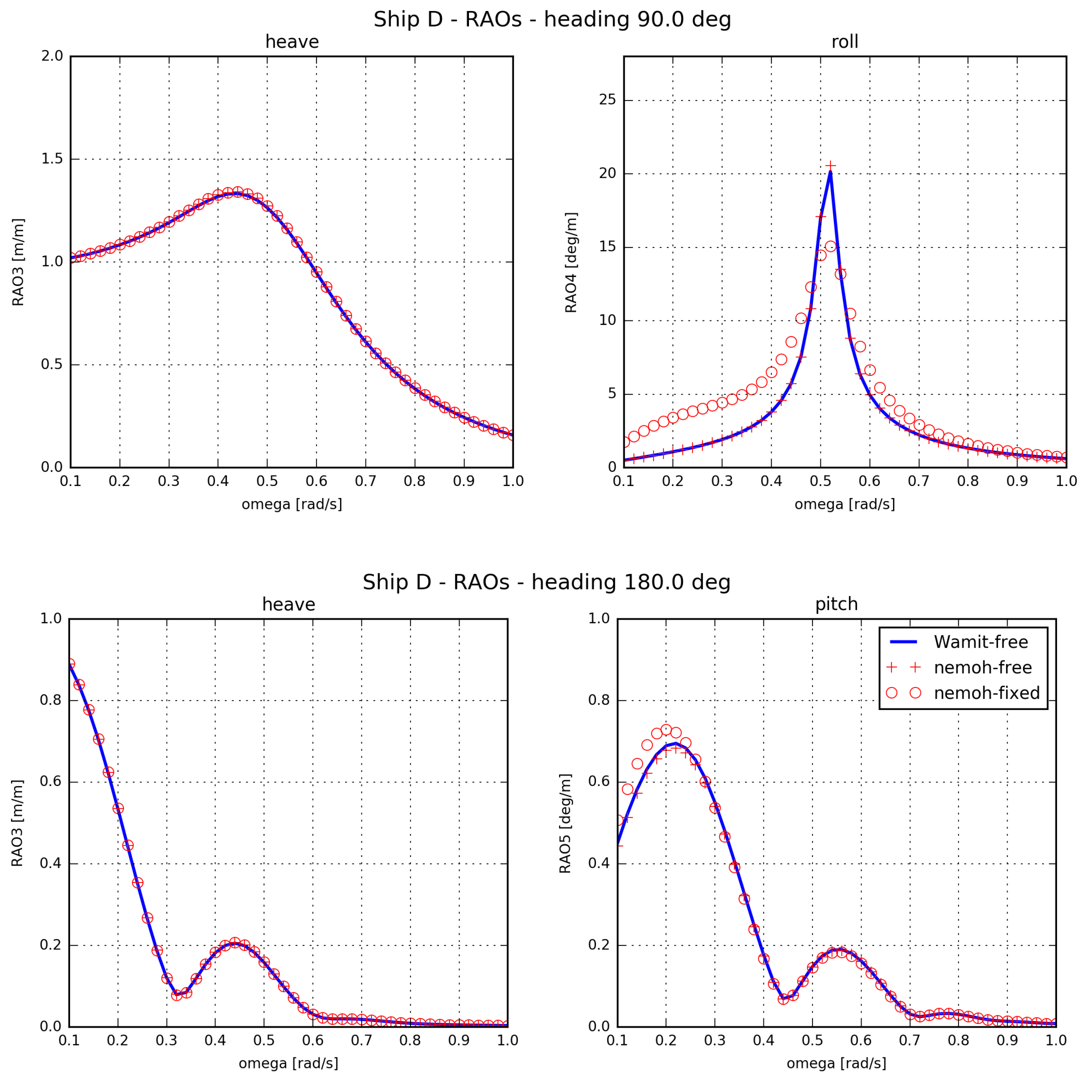


Figure 3 shows the motion output for ship F in beam (top) and head (bottom) waves. This figure also presents available Wamit data for Ship F in "fixed" mode.

Figure 3 - Ship F characteristic motions

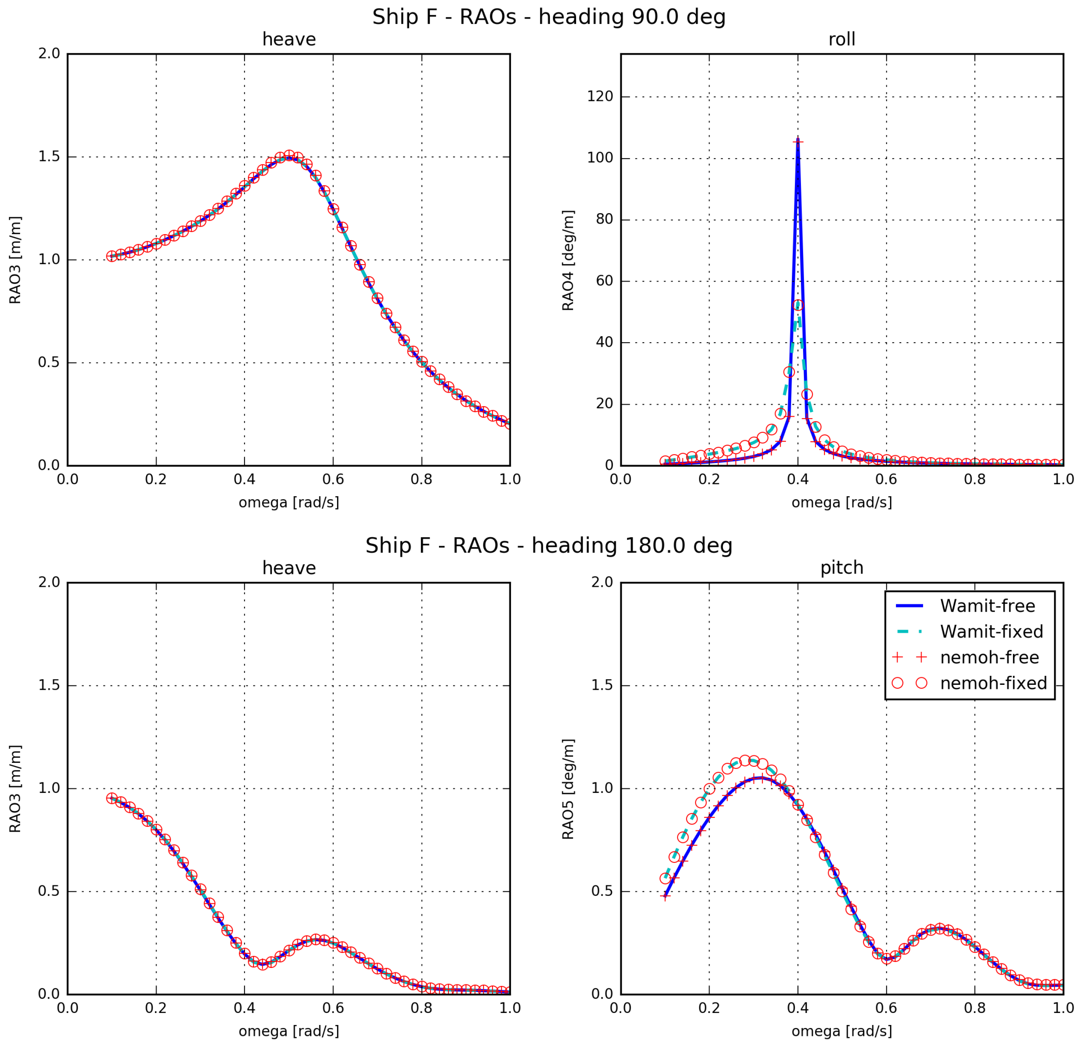
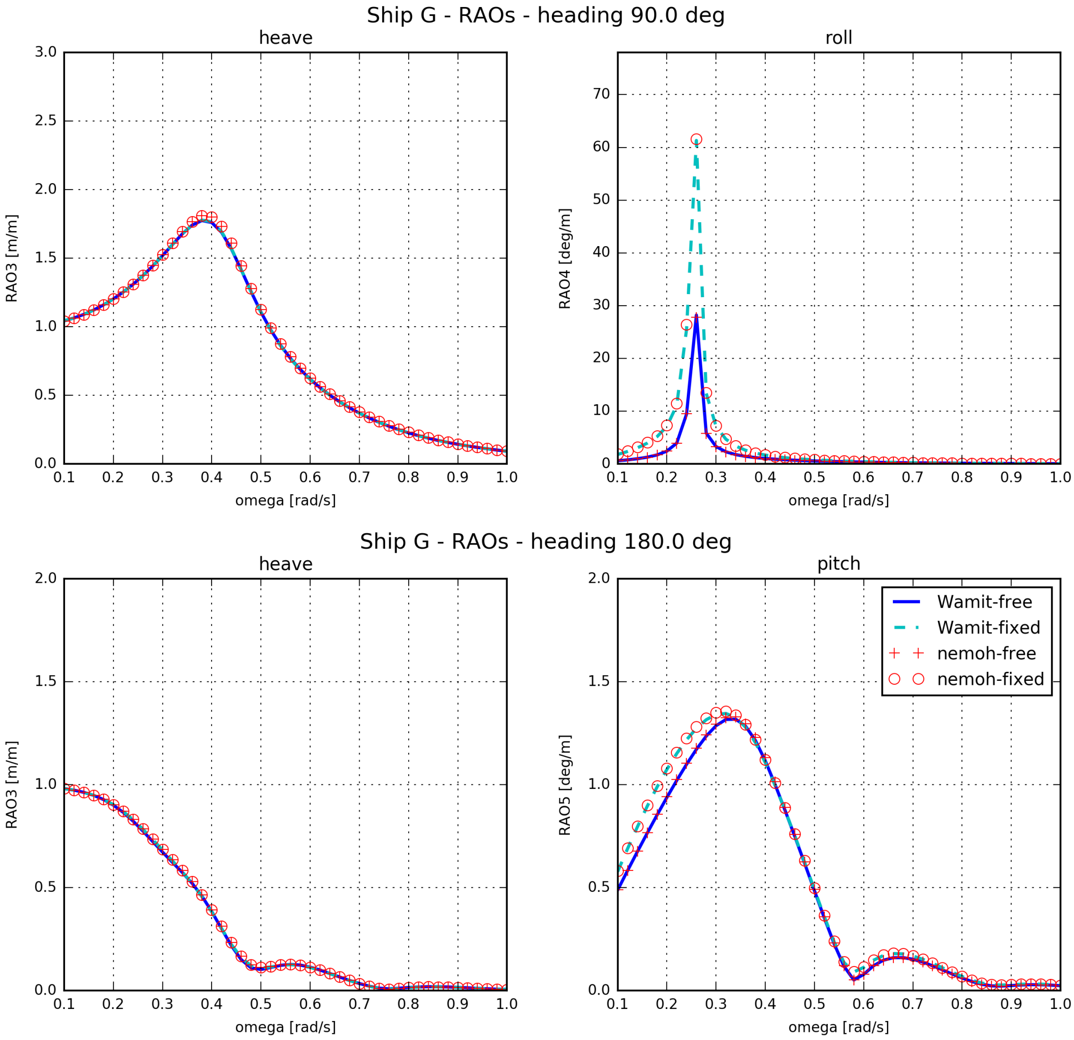


Figure 4 shows the motion output for ship F in beam (top) and head (bottom) waves. This figure also presents available Wamit data for Ship F in "fixed" mode.

Figure 4 - Ship G characteristic motions



Detailed output figures are found in Appendix 1.

Hydrodynamic coefficients, excitation forces and RAOs are in good agreement between Wamit and Nemoh output throughout different cases and conditions compared.

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APPENDIX – DETAILED OUTPUT

The following output is included in this appendix:

- Ship D results
  - hydrodynamic coefficients
  - Excitation forces for wave heading 0, 90, 180deg
  - RAOs for wave heading 0, 90, 180deg
- Ship F results
  - hydrodynamic coefficients
  - Excitation forces for wave heading 0, 90, 180deg
  - RAOs for wave heading 0, 90, 180deg
- Ship G results
  - hydrodynamic coefficients
  - Excitation forces for wave heading 0, 90, 180deg
  - RAOs for wave heading 0, 90, 180deg

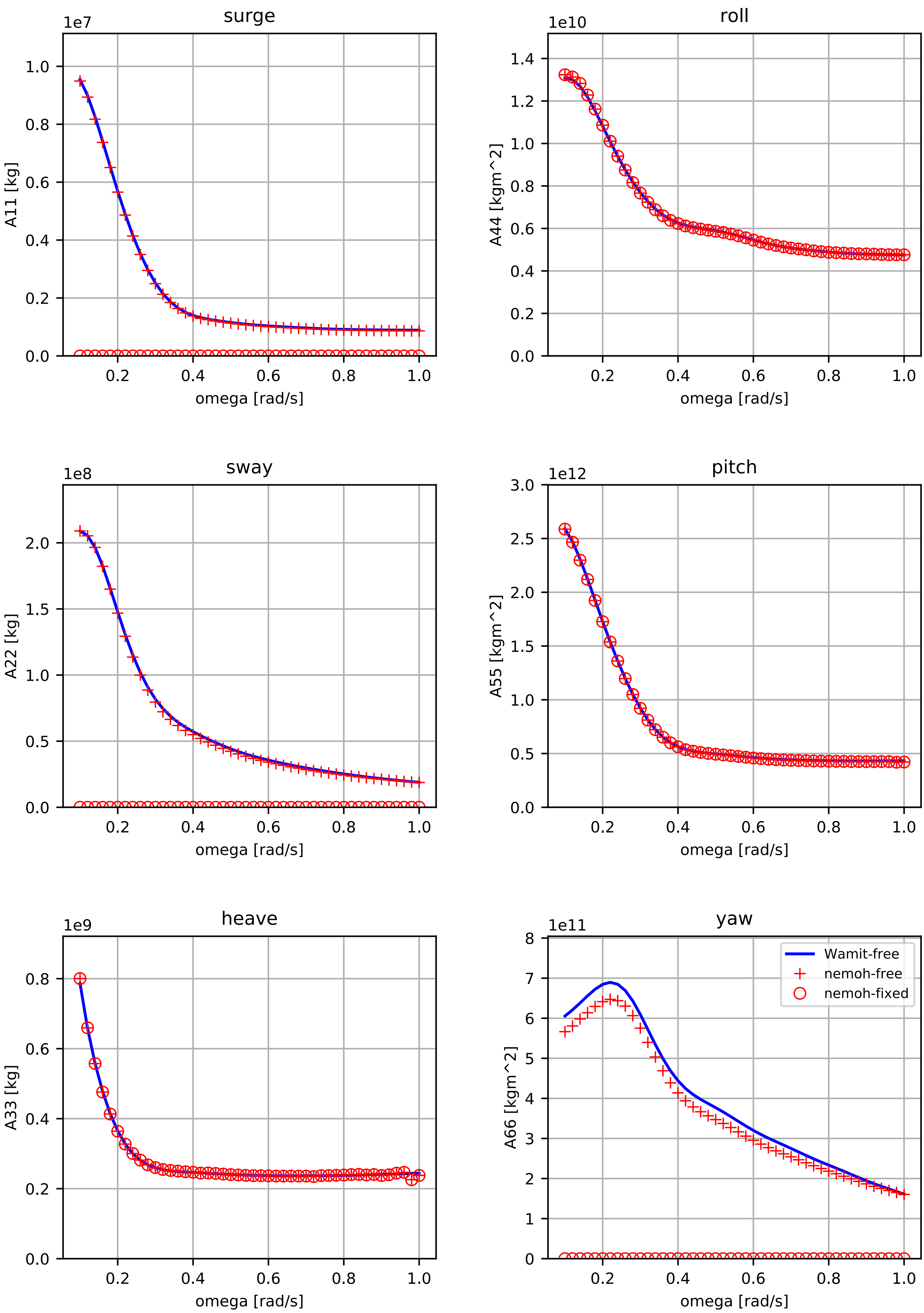
Corrigenda

Please note that the following items have been corrected:

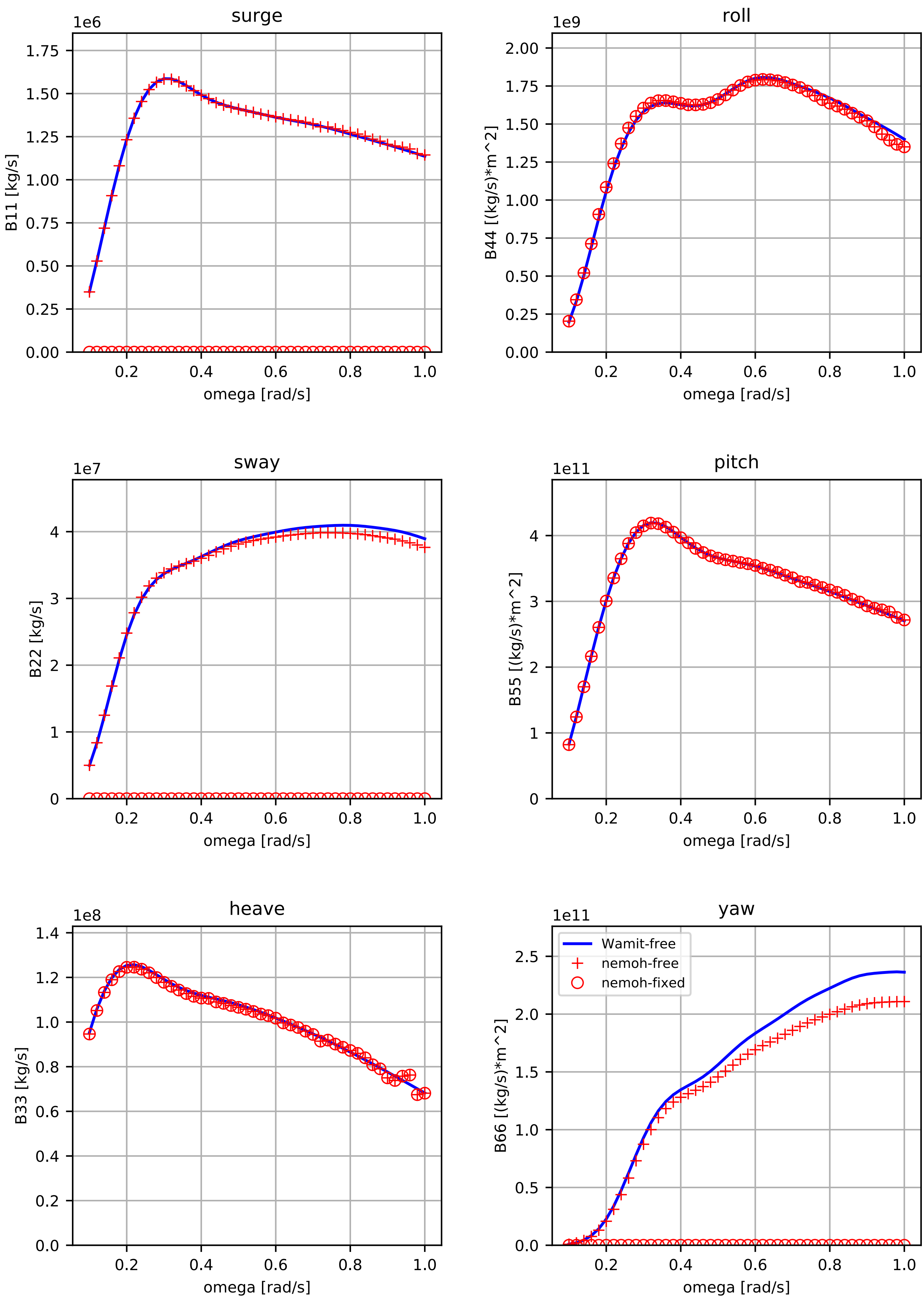
Correction: "Hence, the harmonic motion defined in Delhommeau (1993) is complex conjugate to the Wamit one, having an opposite-sign imaginary part. In other words, for a similar argument, Wamit output would have phase *lead* while Nemoh would have a phase *lag* relatively to each other." in page 4.
Original: "Further, the motion equation (Delhommeau, 1993) presents a minus sign for the radiation/diffraction terms. This would results in a phase shift of π (180deg) with reference to the Wamit definition.".

Correction: added mass units [kg] and [kgm^2], damping units [kg/s] and [kg/s*m^2], excitation force [N/m] and [Nm/m] through data plots labels.
Original: added mass units [N] and [Nm^2], damping units [Ns/m] and [(Ns/rad)*m], excitation force [N] and [Nm].

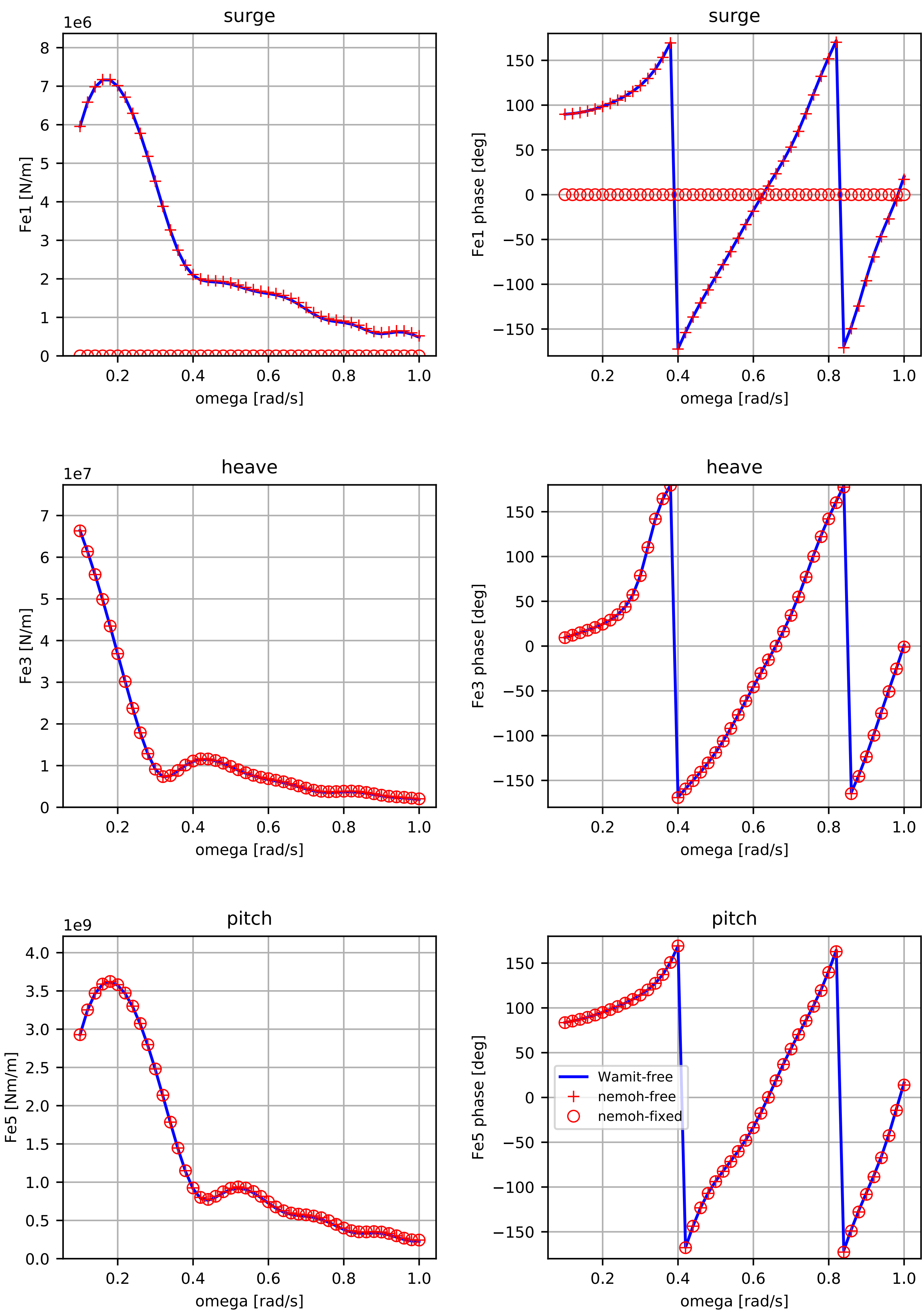
Ship D - Added mass



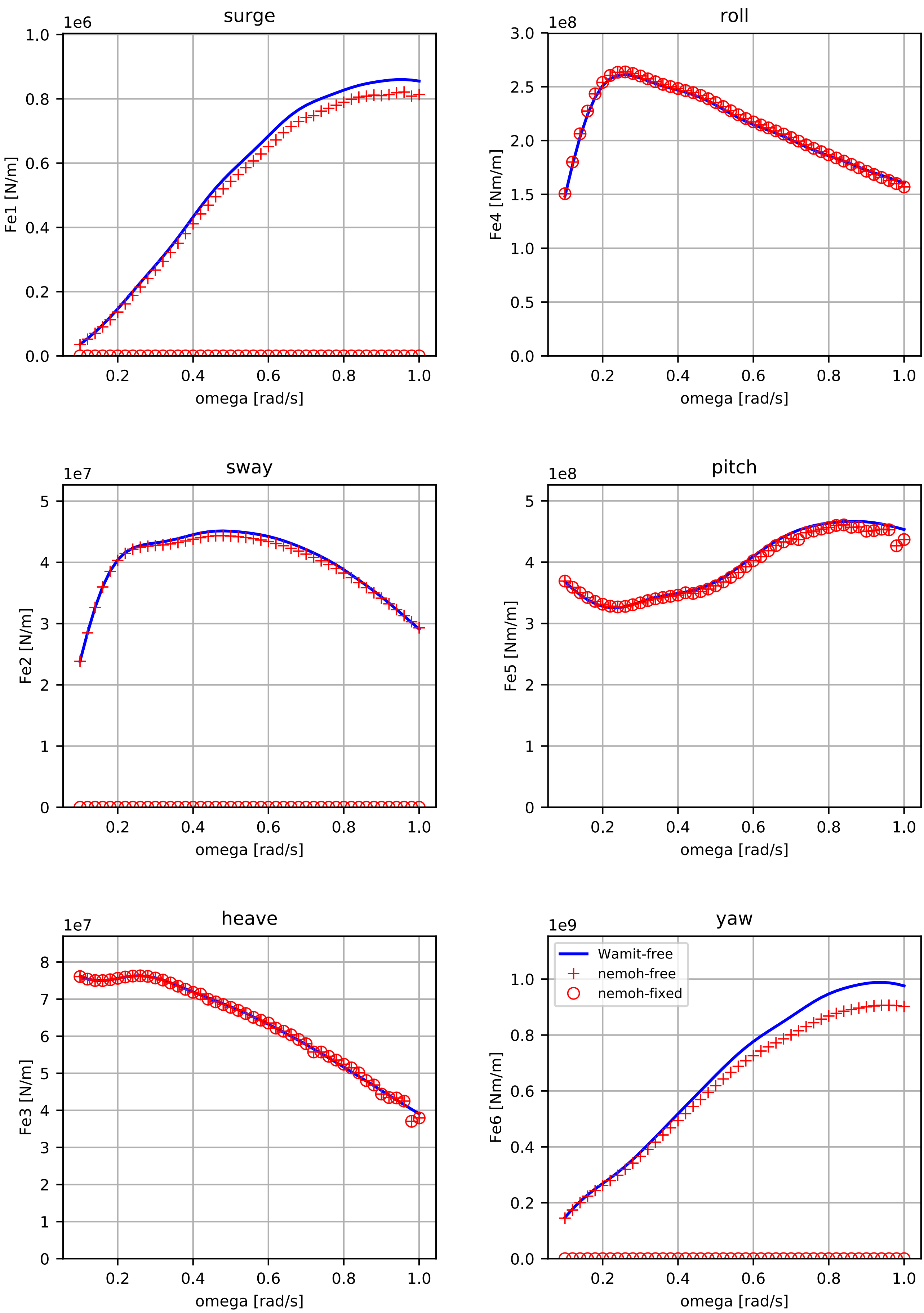
Ship D - (potential) Damping

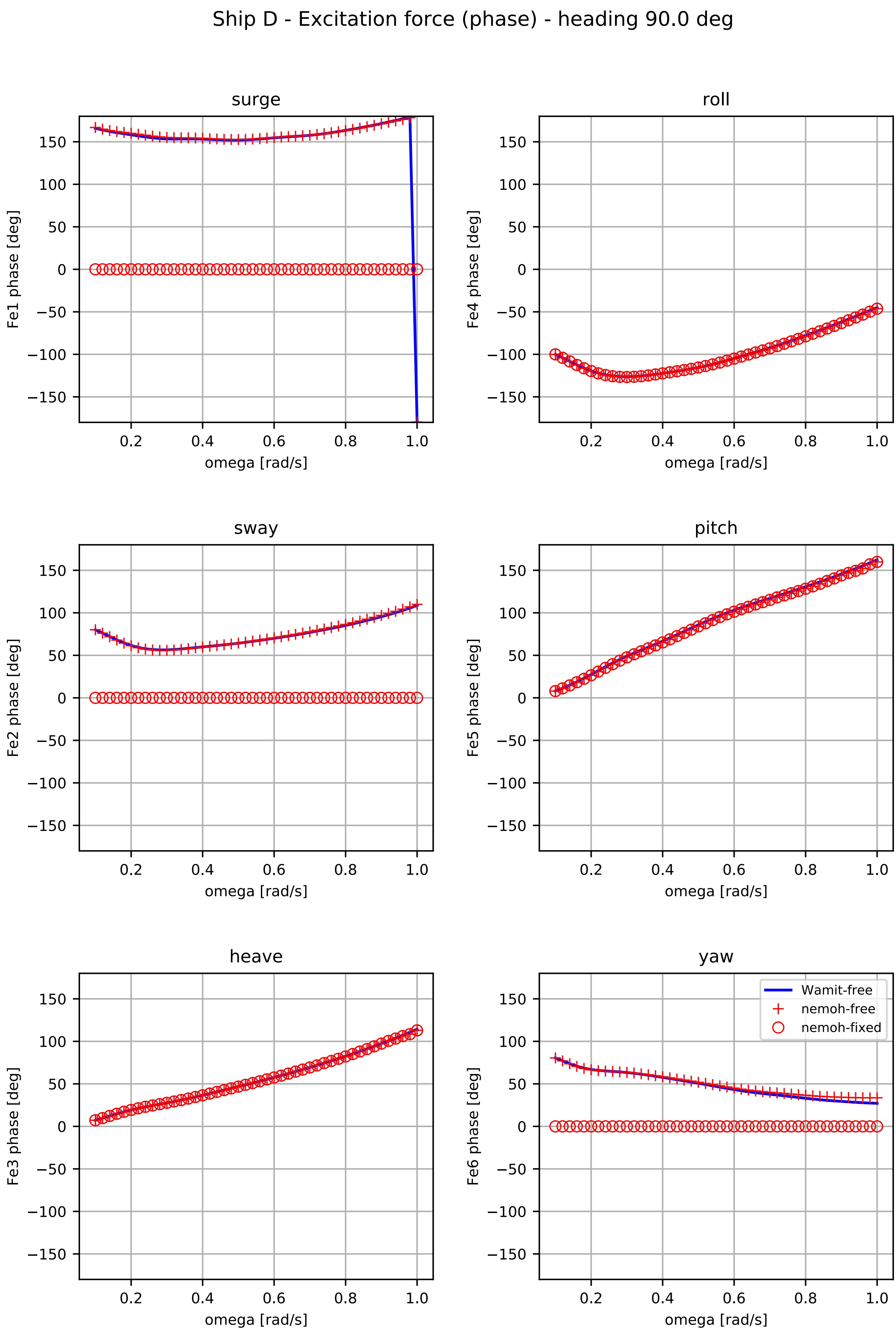


Ship D - Excitation force (with phase) - heading 0.0 deg



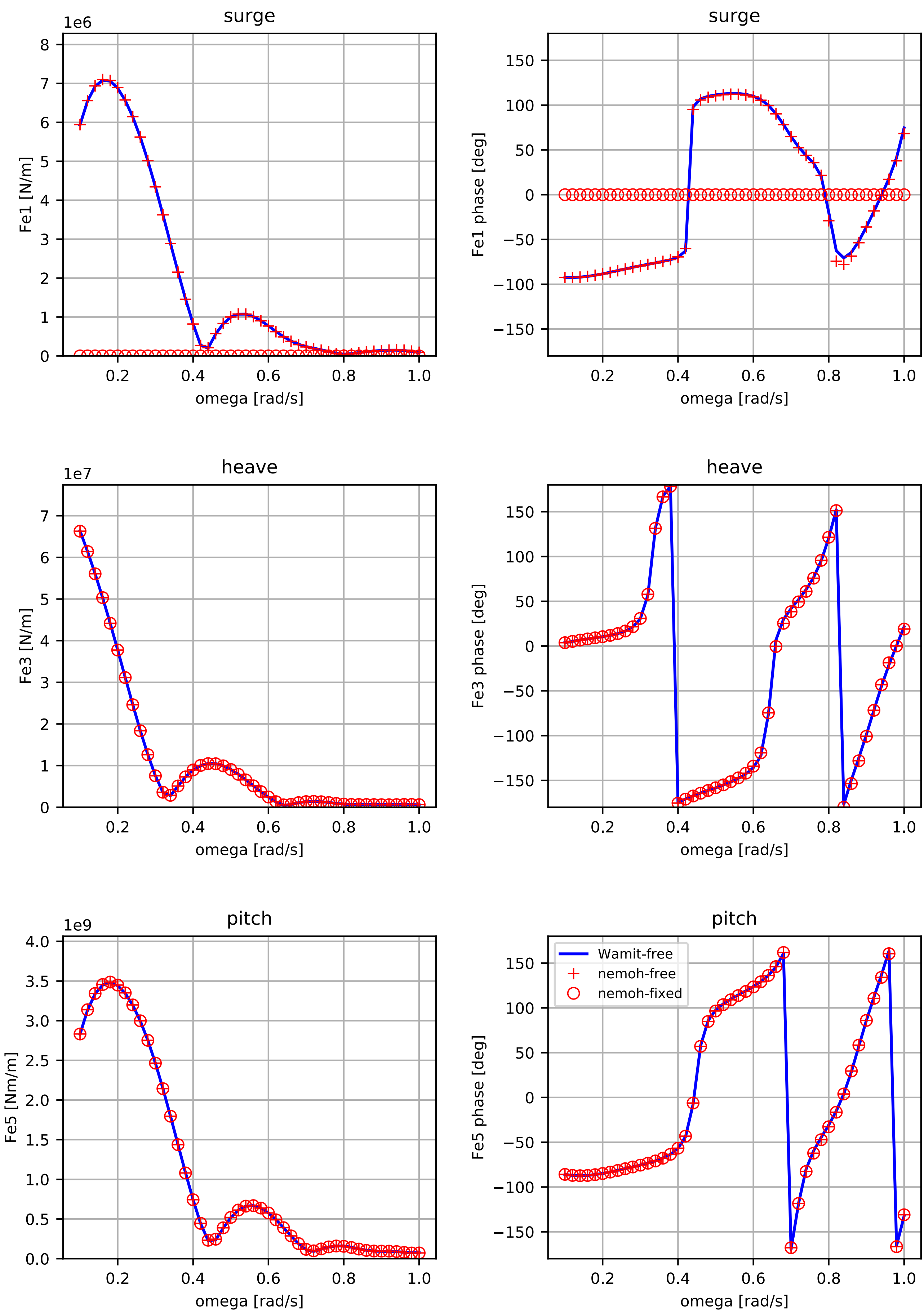
Ship D - Excitation force (magnitude) - heading 90.0 deg

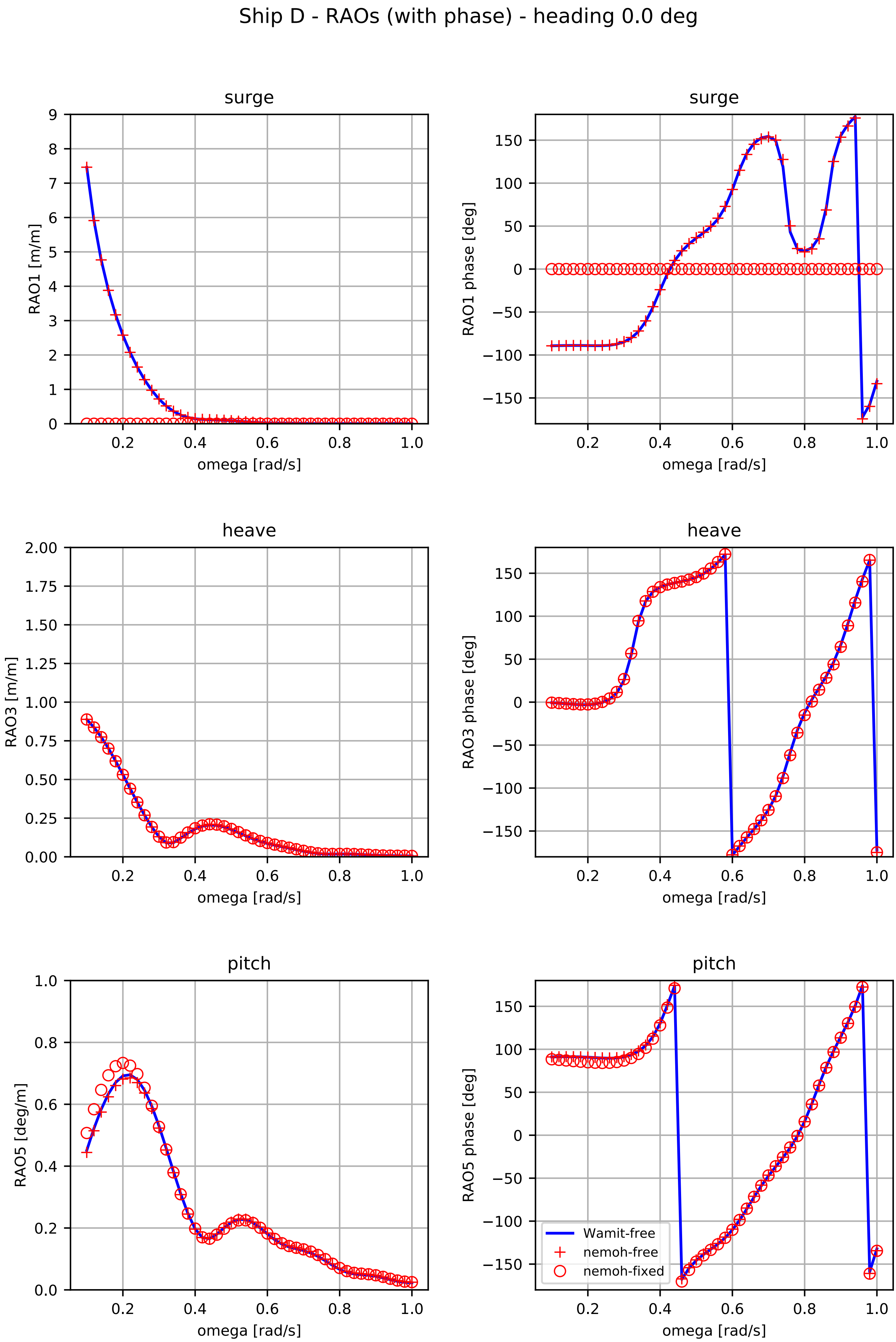


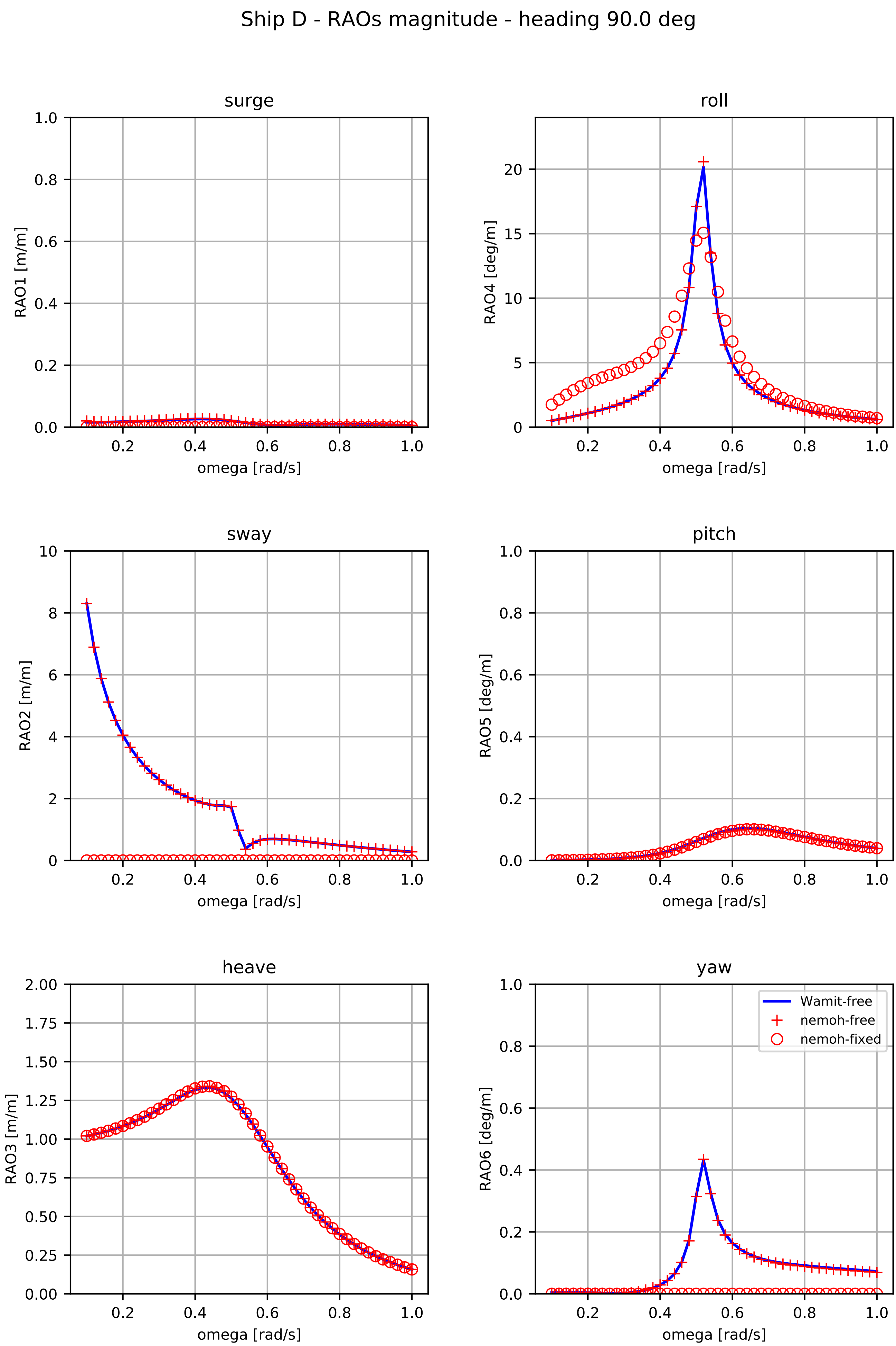


Ship D - Excitation force (phase) - heading 90.0 deg
surge
roll
sway
pitch
heave
yaw
Fe1 phase [deg]
Fe2 phase [deg]
Fe3 phase [deg]
Fe4 phase [deg]
Fe5 phase [deg]
Fe6 phase [deg]
omega [rad/s]
Wamit-free
nemoh-free
nemoh-fixed

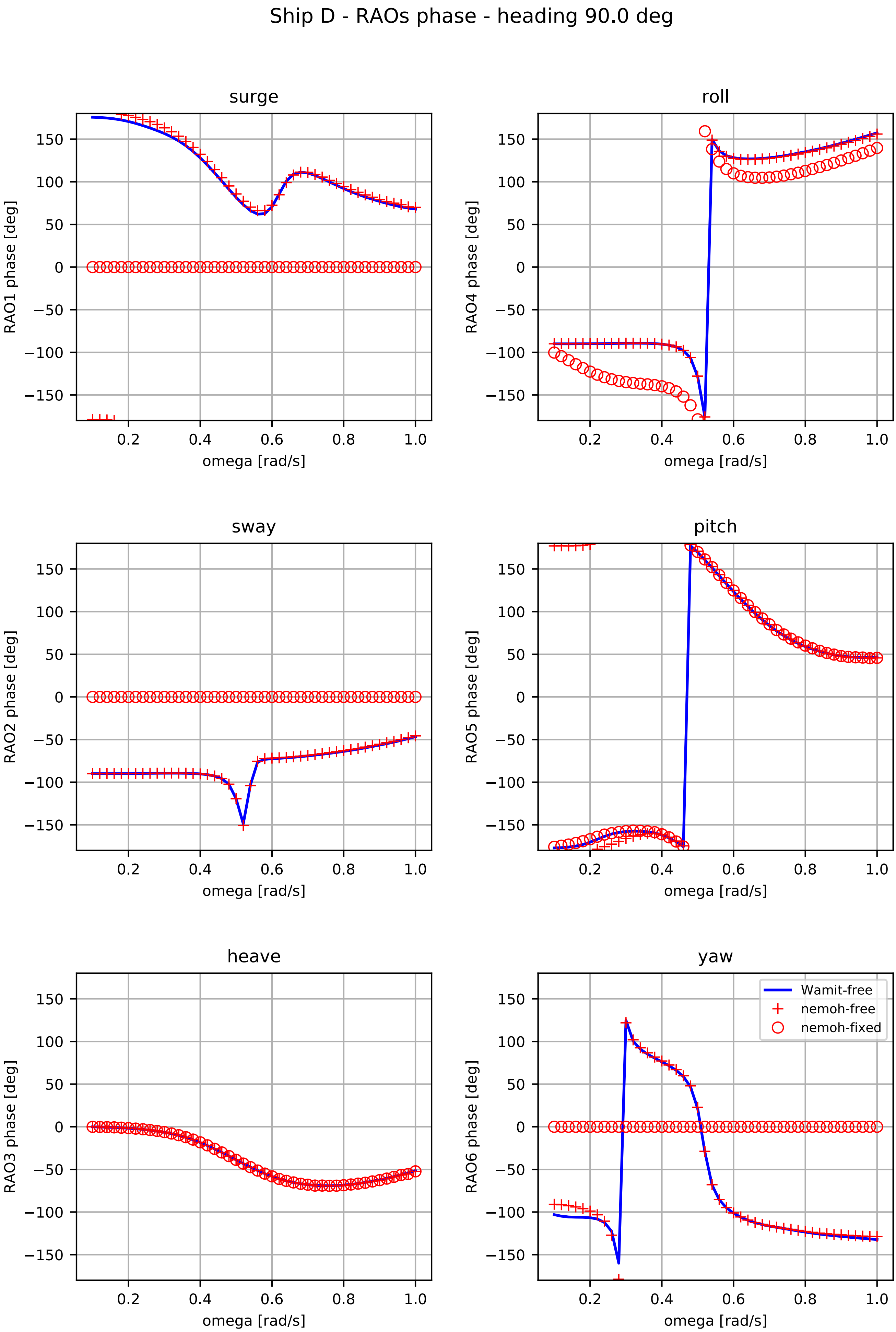
Ship D - Excitation force (with phase) - heading 180.0 deg




Ship D - RAOs (with phase) - heading 0.0 deg
surge
RAO1 [m/m]
RAO1 phase [deg]
heave
RAO3 [m/m]
RAO3 phase [deg]
pitch
RAO5 [deg/m]
RAO5 phase [deg]
omega [rad/s]
Wamit-free
nemoh-free
nemoh-fixed

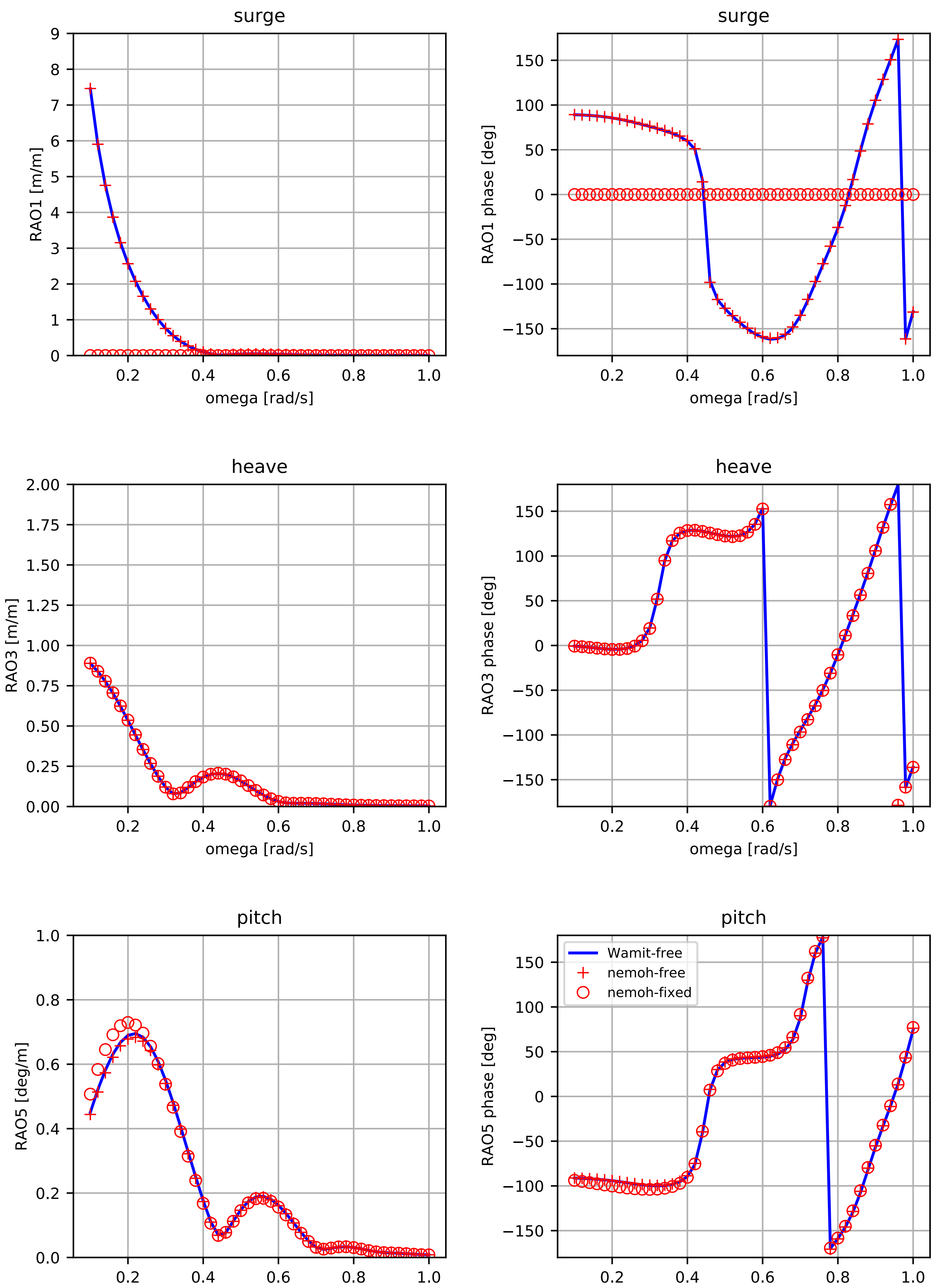


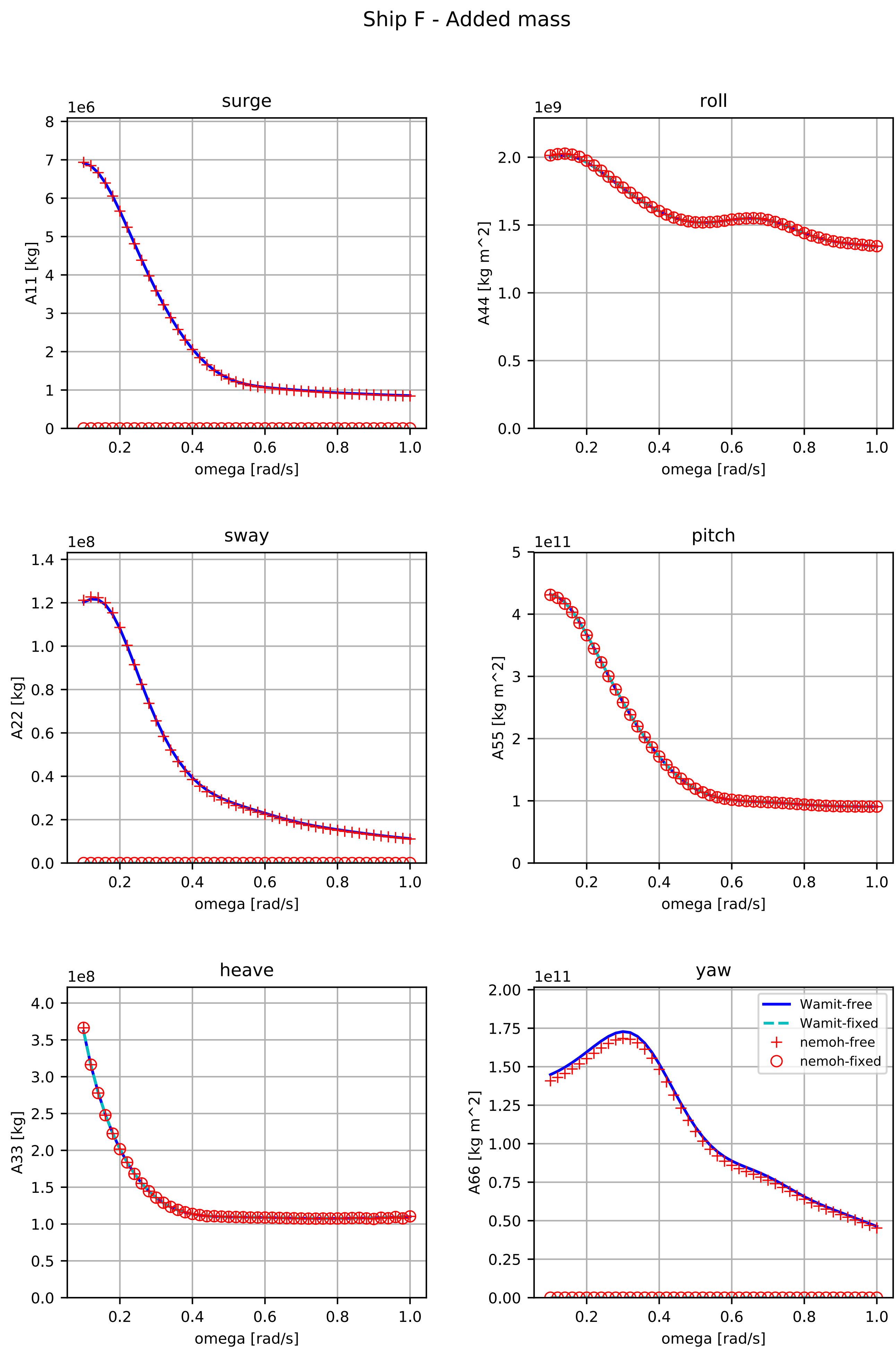
Ship D - RAOs magnitude - heading 90.0 deg
surge
RAO1 [m/m]
roll
RAO4 [deg/m]
sway
RAO2 [m/m]
pitch
RAO5 [deg/m]
heave
RAO3 [m/m]
yaw
RAO6 [deg/m]
omega [rad/s]
Wamit-free
nemoh-free
nemoh-fixed



Ship D - RAOs phase - heading 90.0 deg
surge
roll
sway
pitch
heave
yaw
RAO1 phase [deg]
RAO2 phase [deg]
RAO3 phase [deg]
RAO4 phase [deg]
RAO5 phase [deg]
RAO6 phase [deg]
omega [rad/s]
Wamit-free
nemoh-free
nemoh-fixed

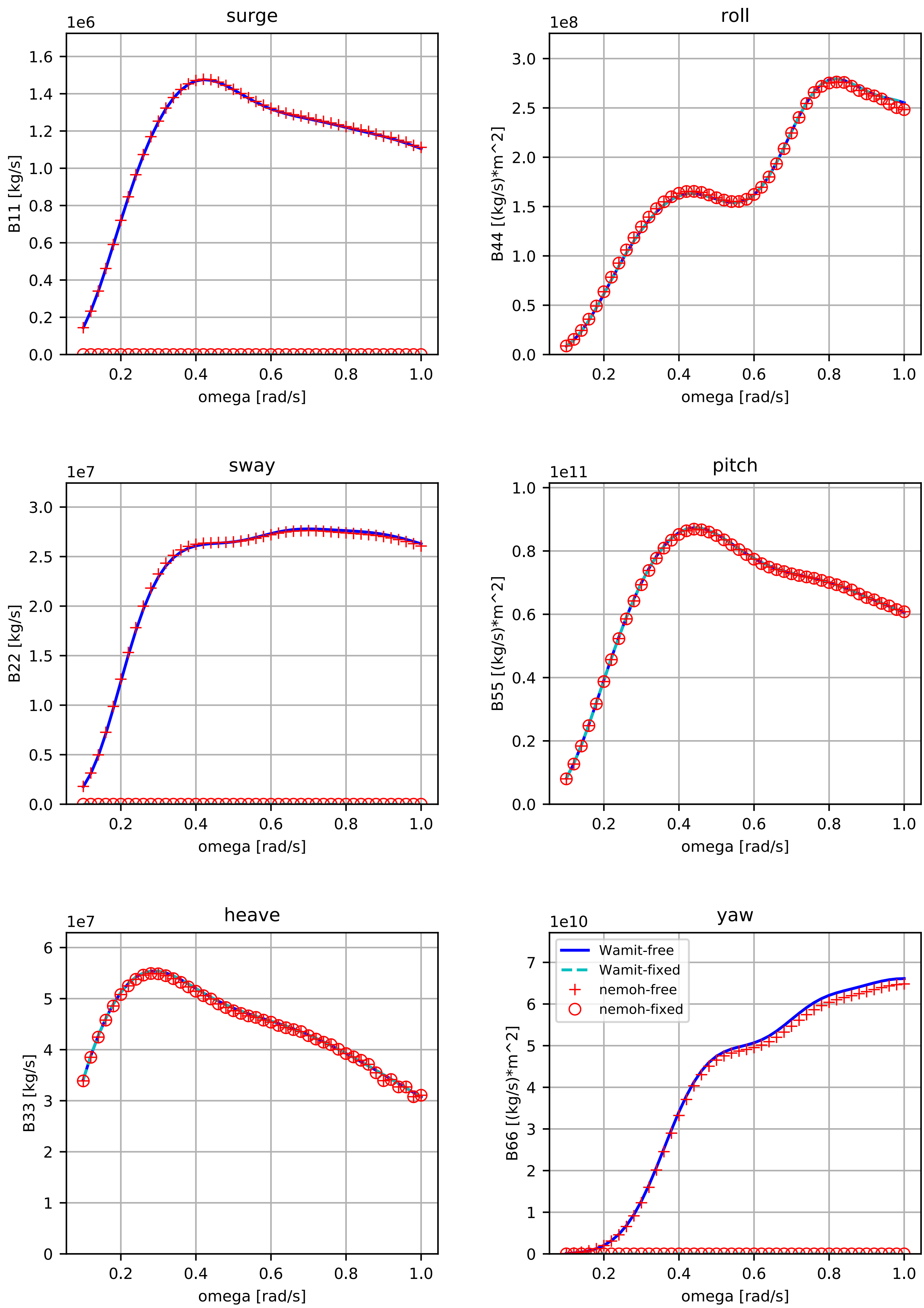
Ship D - RAOs (with phase) - heading 180.0 deg

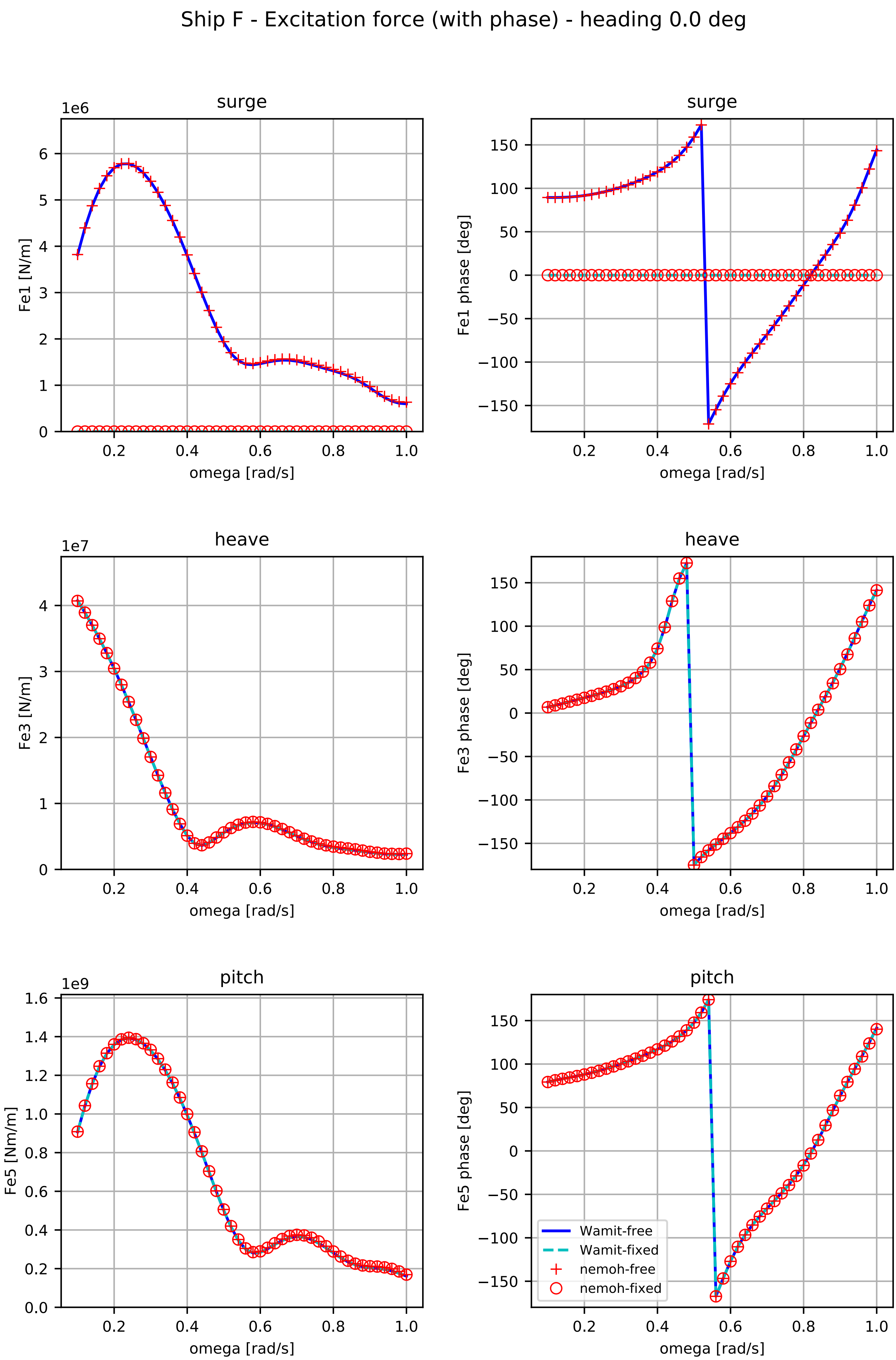




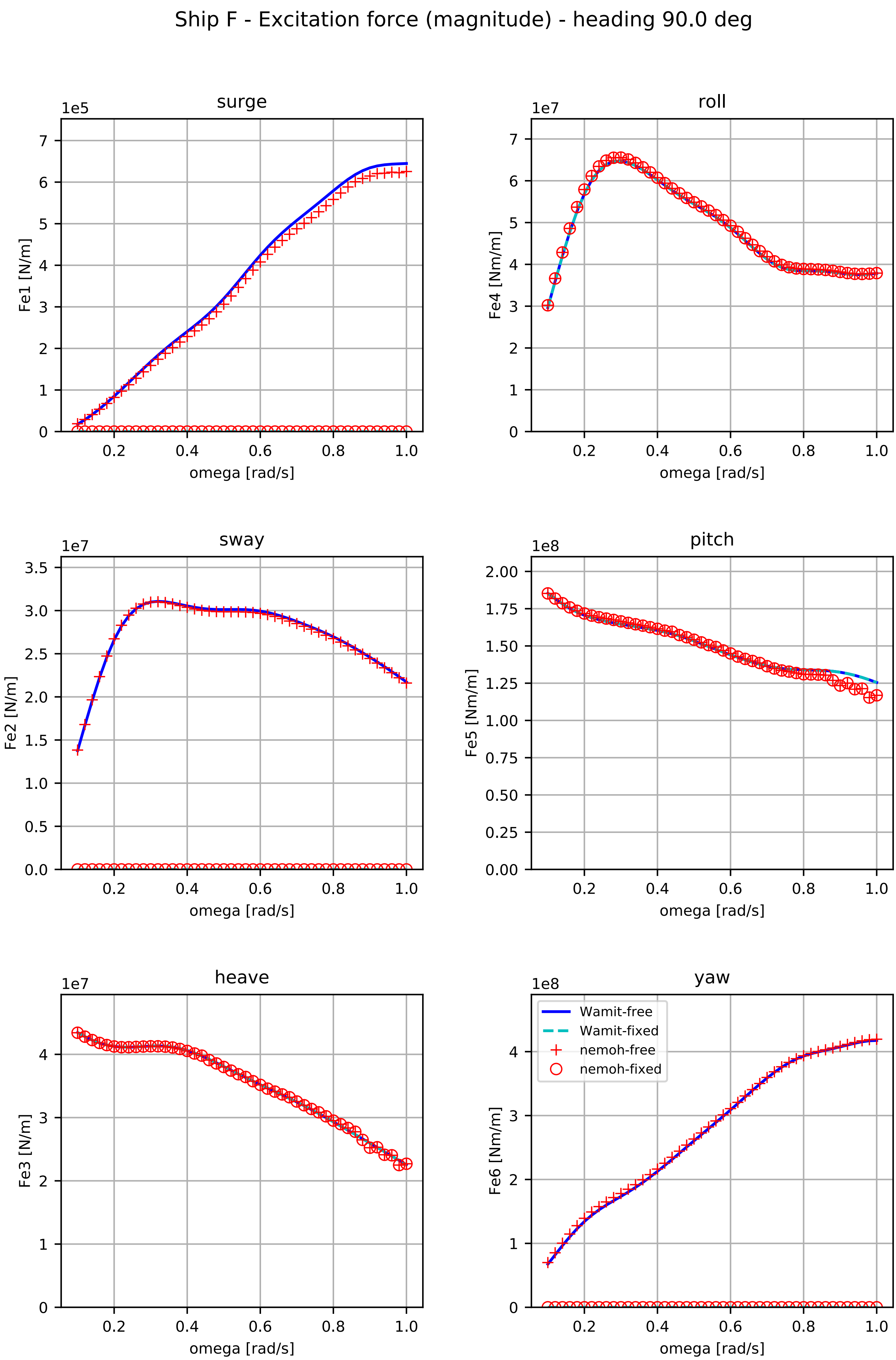
Ship F - Added mass
surge
1e6
A11 [kg]
omega [rad/s]
roll
1e9
A44 [kg m^2]
omega [rad/s]
sway
1e8
A22 [kg]
omega [rad/s]
pitch
1e11
A55 [kg m^2]
omega [rad/s]
heave
1e8
A33 [kg]
omega [rad/s]
yaw
1e11
A66 [kg m^2]
omega [rad/s]
Wamit-free
Wamit-fixed
nemoh-free
nemoh-fixed

Ship F - (potential) Damping

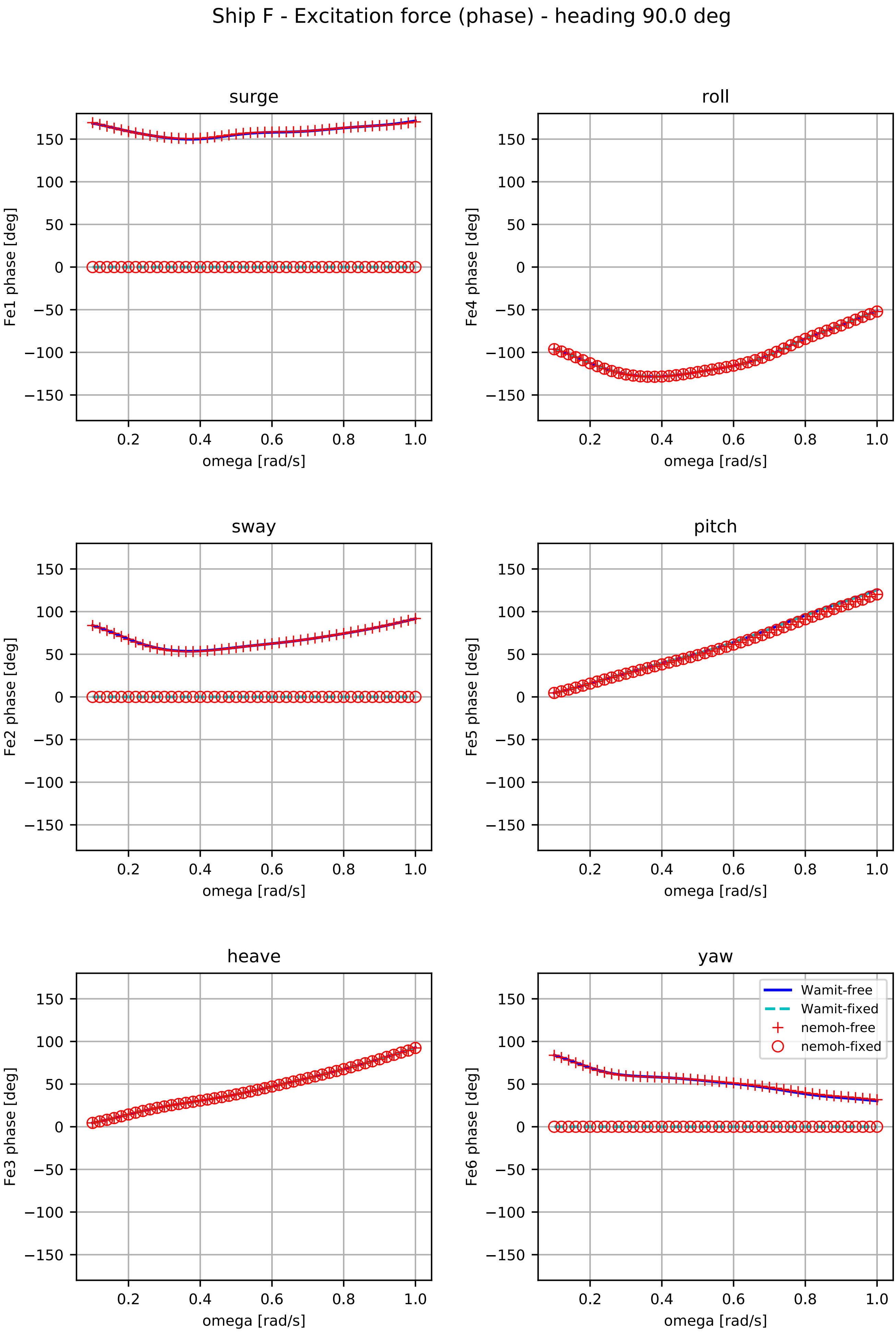


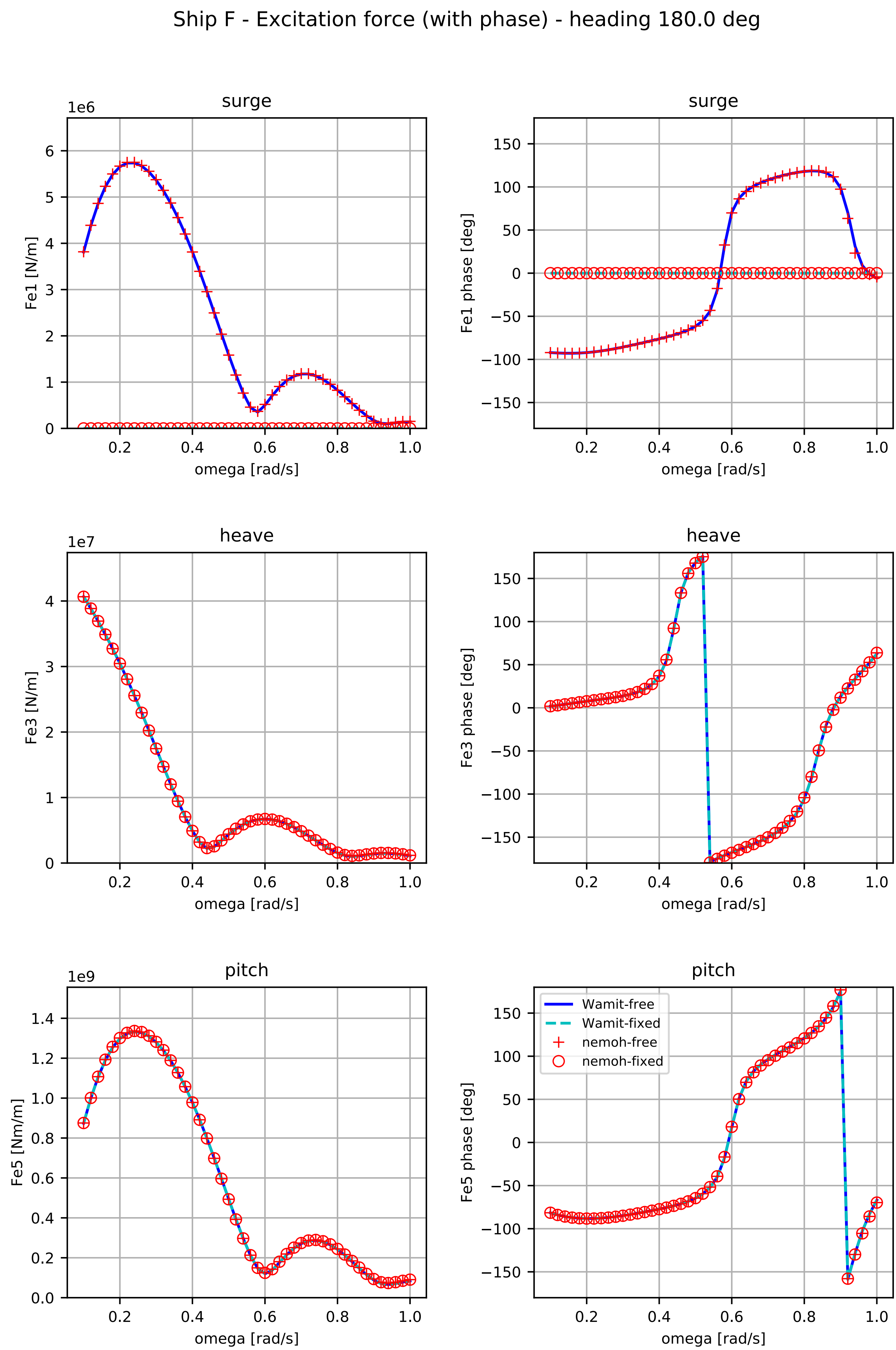


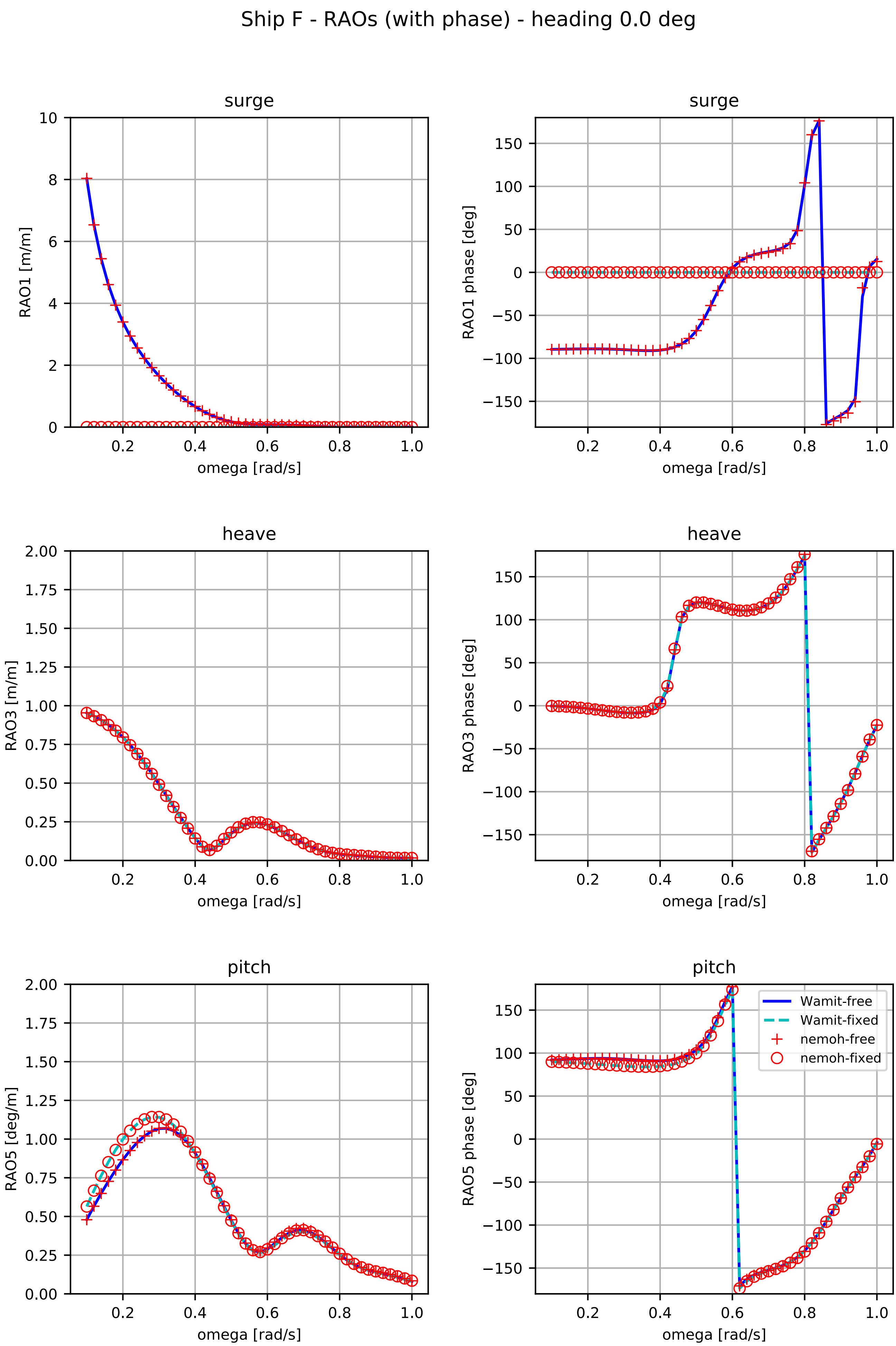
Ship F - Excitation force (with phase) - heading 0.0 deg
surge
1e6
Fe1 [N/m]
omega [rad/s]
surge
Fe1 phase [deg]
omega [rad/s]
heave
1e7
Fe3 [N/m]
omega [rad/s]
heave
Fe3 phase [deg]
omega [rad/s]
pitch
1e9
Fe5 [Nm/m]
omega [rad/s]
pitch
Fe5 phase [deg]
omega [rad/s]
Wamit-free
Wamit-fixed
nemoh-free
nemoh-fixed



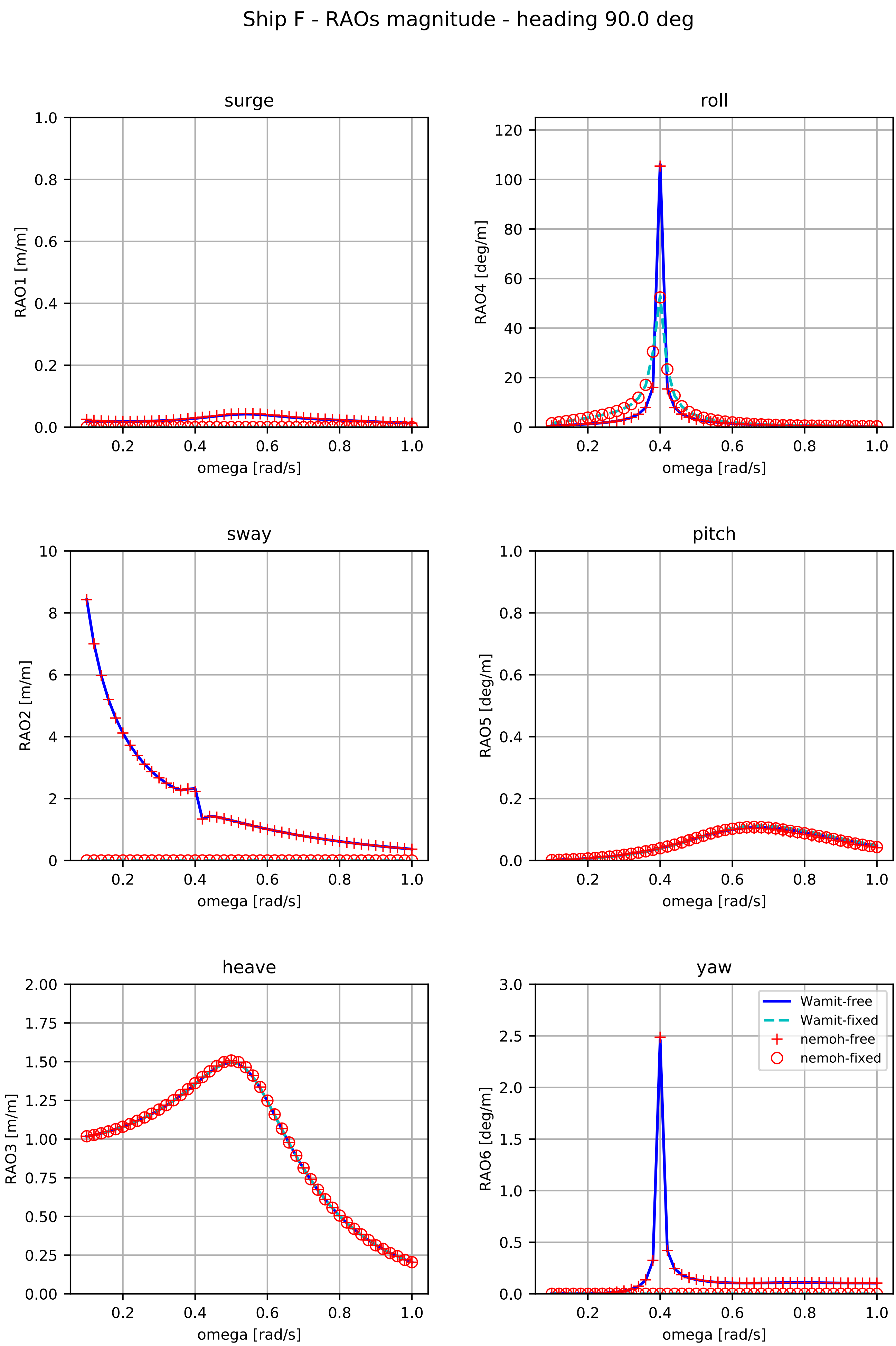
Ship F - Excitation force (magnitude) - heading 90.0 deg
surge
1e5
Fe1 [N/m]
omega [rad/s]
roll
1e7
Fe4 [Nm/m]
omega [rad/s]
sway
1e7
Fe2 [N/m]
omega [rad/s]
pitch
1e8
Fe5 [Nm/m]
omega [rad/s]
heave
1e7
Fe3 [N/m]
omega [rad/s]
yaw
1e8
Fe6 [Nm/m]
omega [rad/s]
Wamit-free
Wamit-fixed
nemoh-free
nemoh-fixed


Ship F - Excitation force (phase) - heading 90.0 deg
surge
roll
sway
pitch
heave
yaw
Fe1 phase [deg]
Fe2 phase [deg]
Fe3 phase [deg]
Fe4 phase [deg]
Fe5 phase [deg]
Fe6 phase [deg]
omega [rad/s]
Wamit-free
Wamit-fixed
nemoh-free
nemoh-fixed

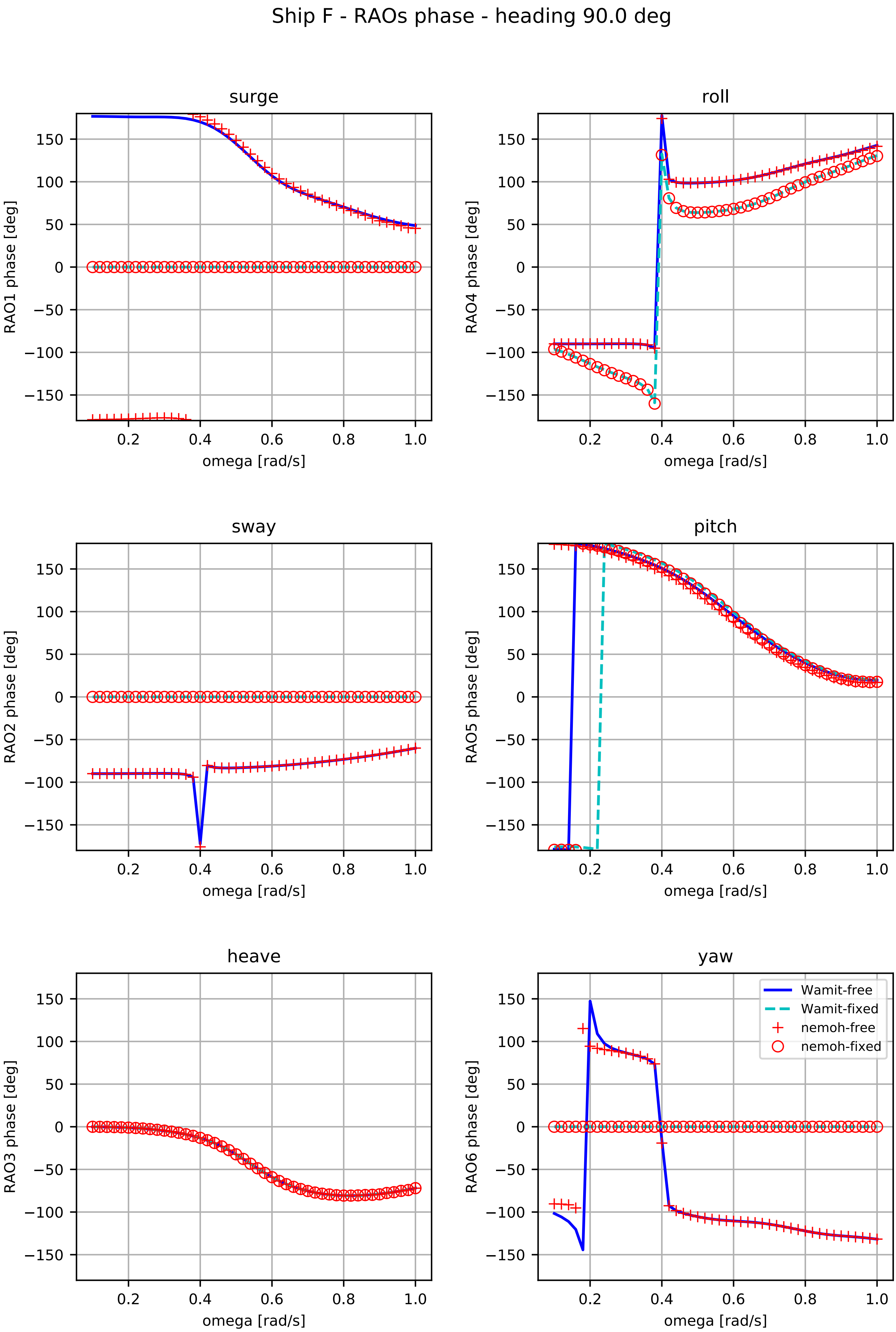

Ship F - Excitation force (with phase) - heading 180.0 deg
surge
1e6
Fe1 [N/m]
Fe1 phase [deg]
heave
1e7
Fe3 [N/m]
Fe3 phase [deg]
pitch
1e9
Fe5 [Nm/m]
Fe5 phase [deg]
omega [rad/s]
Wamit-free
Wamit-fixed
nemoh-free
nemoh-fixed



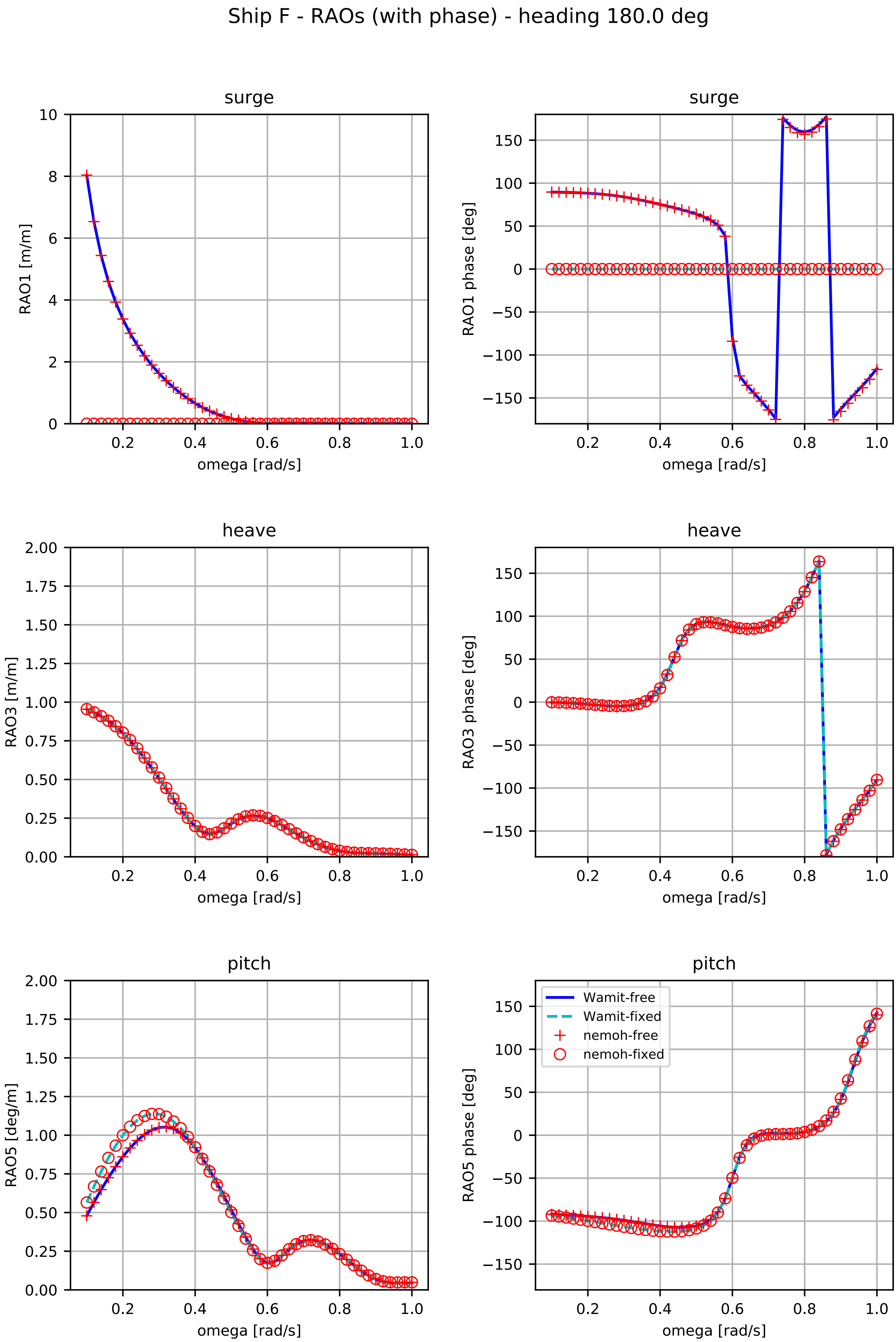
Ship F - RAOs (with phase) - heading 0.0 deg
surge
RAO1 [m/m]
RAO1 phase [deg]
heave
RAO3 [m/m]
RAO3 phase [deg]
pitch
RAO5 [deg/m]
RAO5 phase [deg]
omega [rad/s]
Wamit-free
Wamit-fixed
nemoh-free
nemoh-fixed

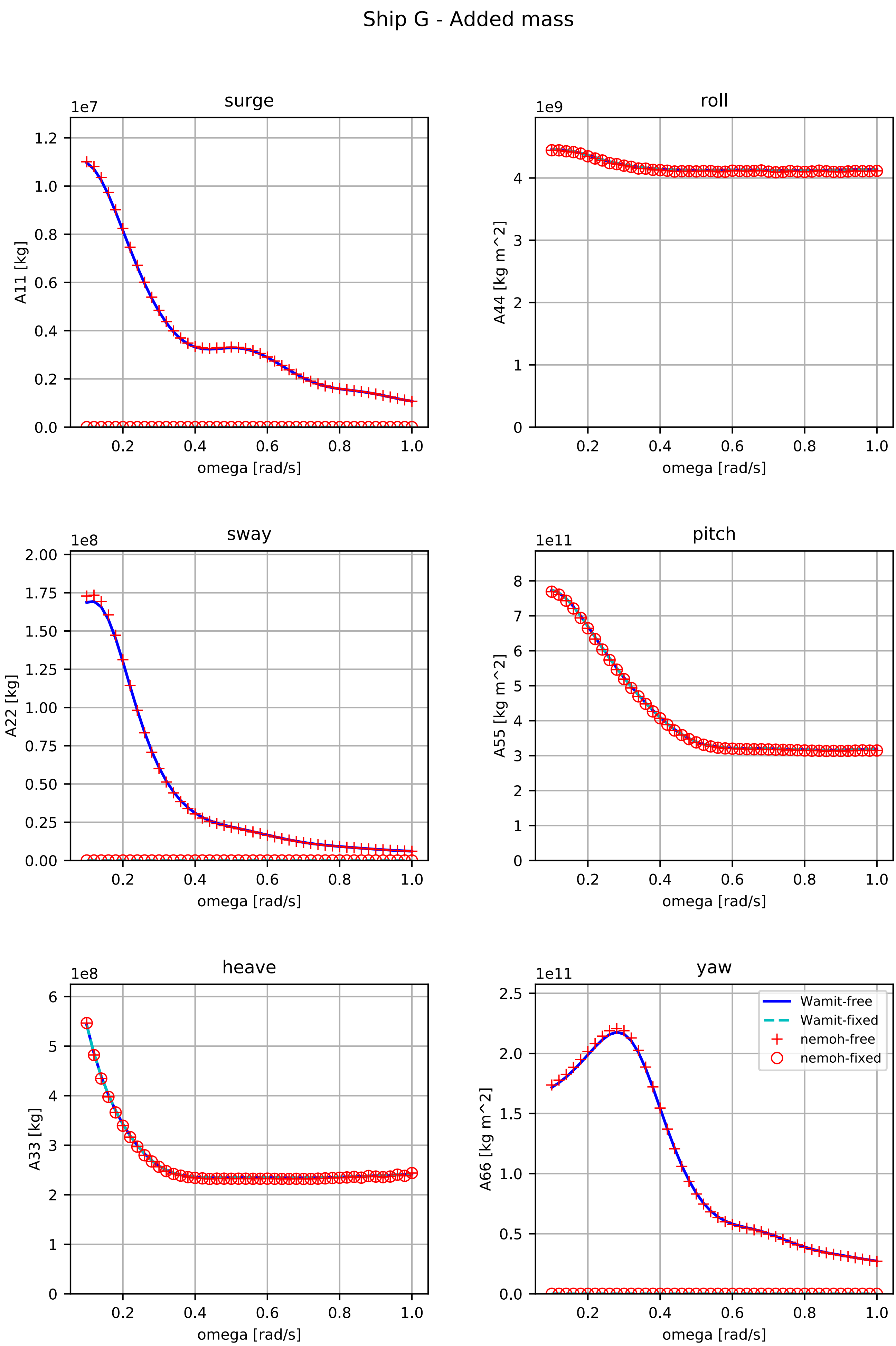


Ship F - RAOs magnitude - heading 90.0 deg
surge
RAO1 [m/m]
roll
RAO4 [deg/m]
sway
RAO2 [m/m]
pitch
RAO5 [deg/m]
heave
RAO3 [m/m]
yaw
RAO6 [deg/m]
omega [rad/s]
Wamit-free
Wamit-fixed
nemoh-free
nemoh-fixed

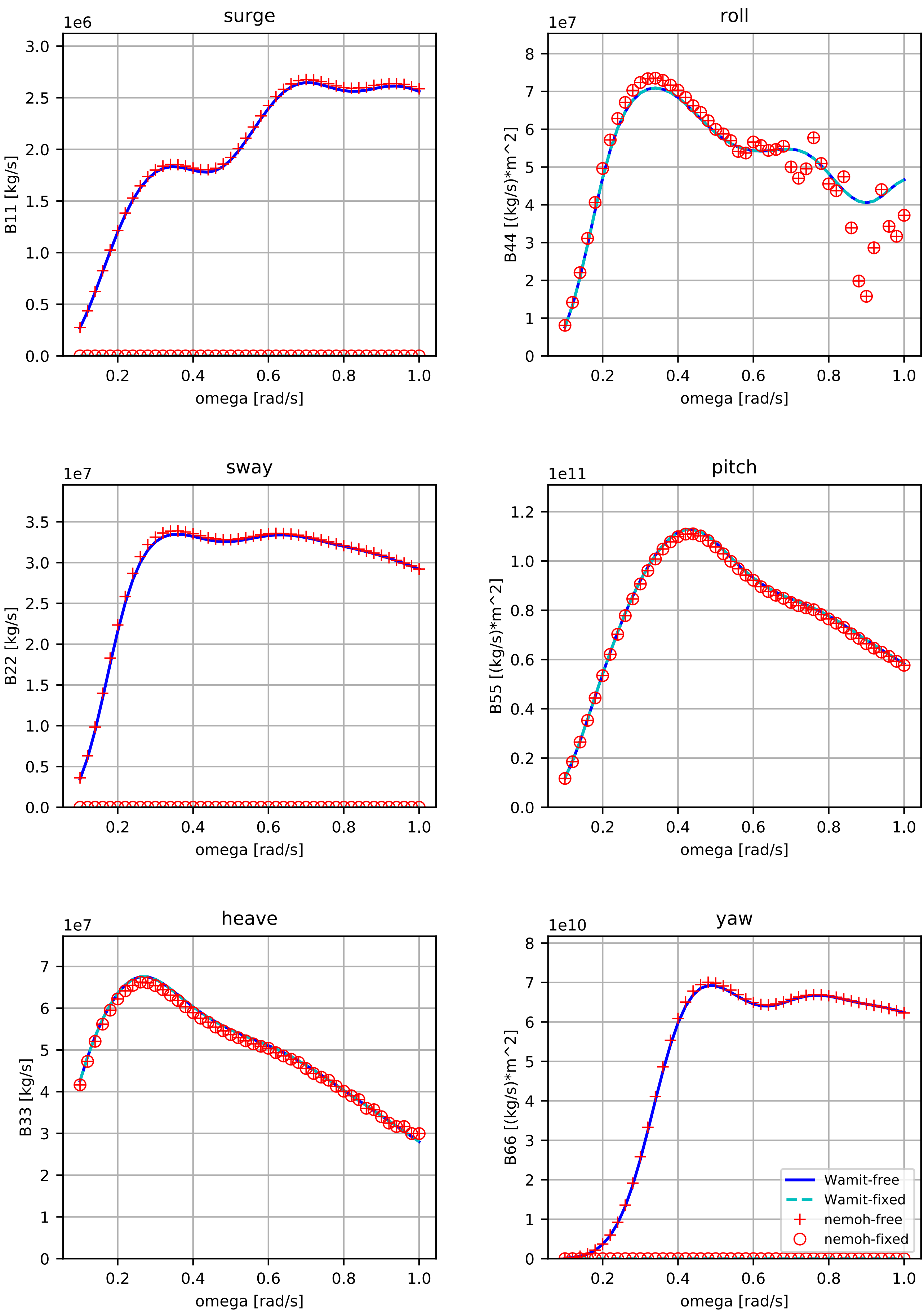


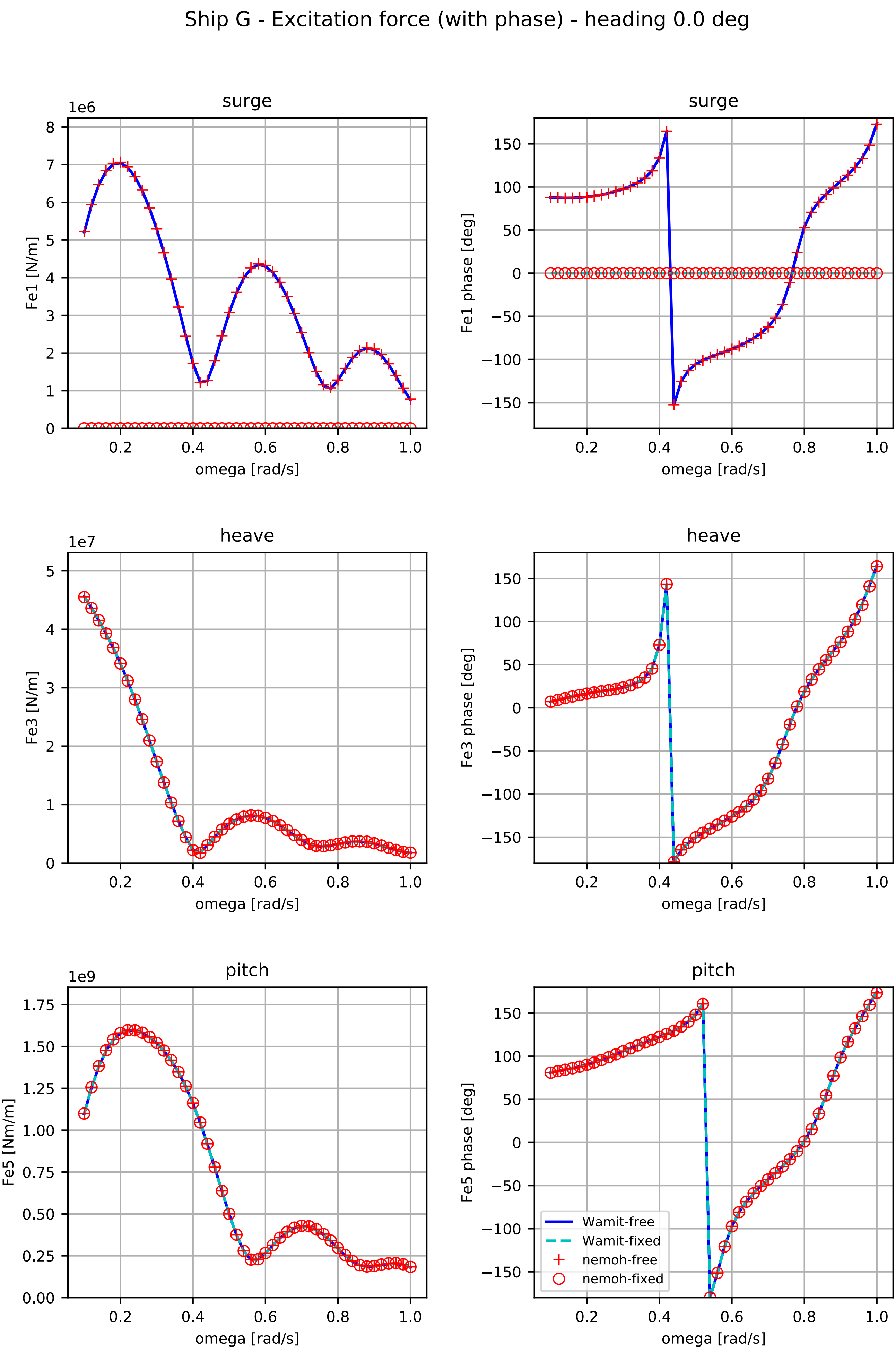
Ship F - RAOs phase - heading 90.0 deg
surge
roll
sway
pitch
heave
yaw
RAO1 phase [deg]
RAO2 phase [deg]
RAO3 phase [deg]
RAO4 phase [deg]
RAO5 phase [deg]
RAO6 phase [deg]
omega [rad/s]
Wamit-free
Wamit-fixed
nemoh-free
nemoh-fixed


Ship F - RAOs (with phase) - heading 180.0 deg
surge
RAO1 [m/m]
RAO1 phase [deg]
heave
RAO3 [m/m]
RAO3 phase [deg]
pitch
RAO5 [deg/m]
RAO5 phase [deg]
omega [rad/s]
Wamit-free
Wamit-fixed
nemoh-free
nemoh-fixed


Ship G - Added mass
surge
1e7
A11 [kg]
omega [rad/s]
roll
1e9
A44 [kg m^2]
omega [rad/s]
sway
1e8
A22 [kg]
omega [rad/s]
pitch
1e11
A55 [kg m^2]
omega [rad/s]
heave
1e8
A33 [kg]
omega [rad/s]
yaw
1e11
A66 [kg m^2]
omega [rad/s]
Wamit-free
Wamit-fixed
nemoh-free
nemoh-fixed

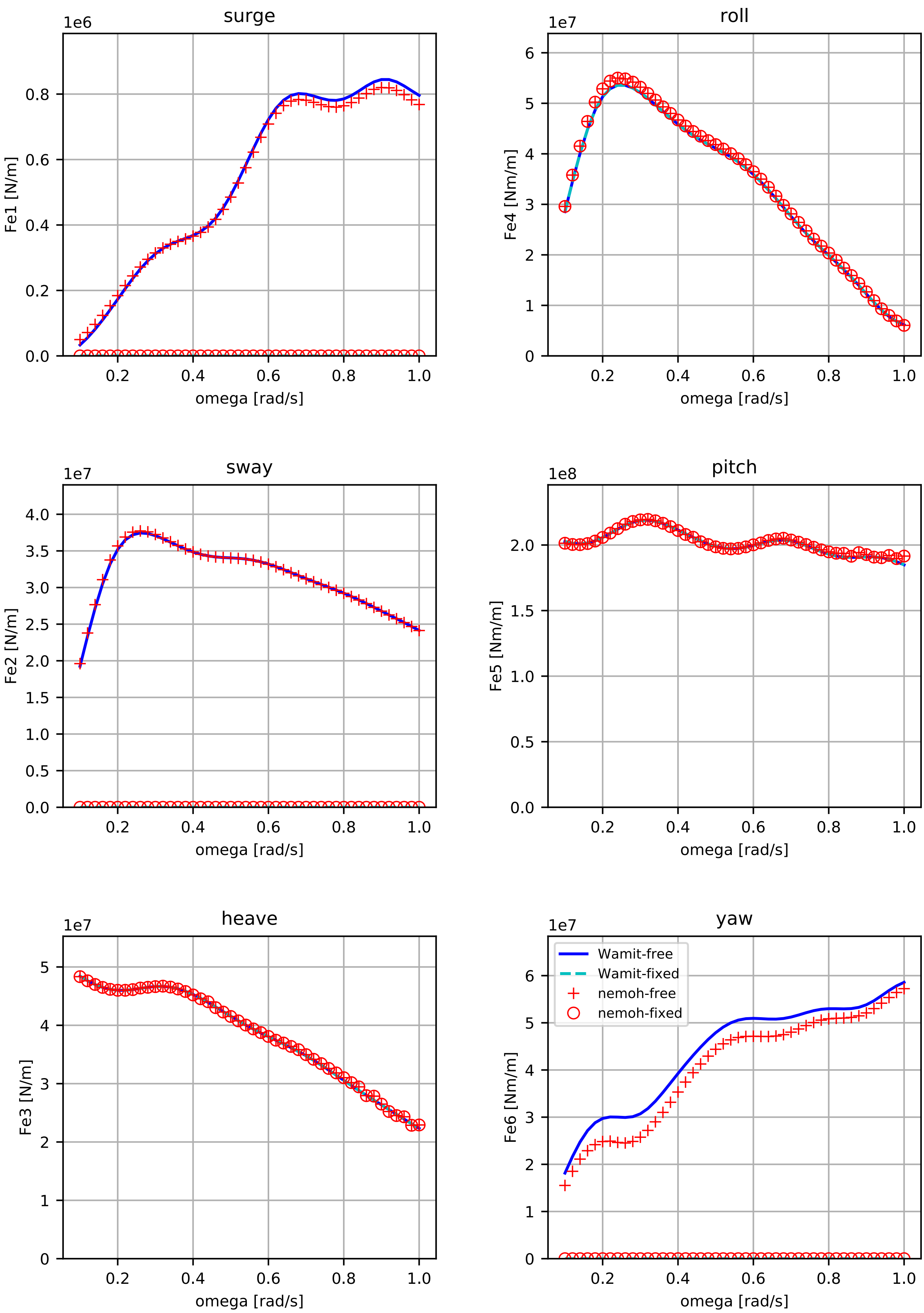
Ship G - (potential) Damping

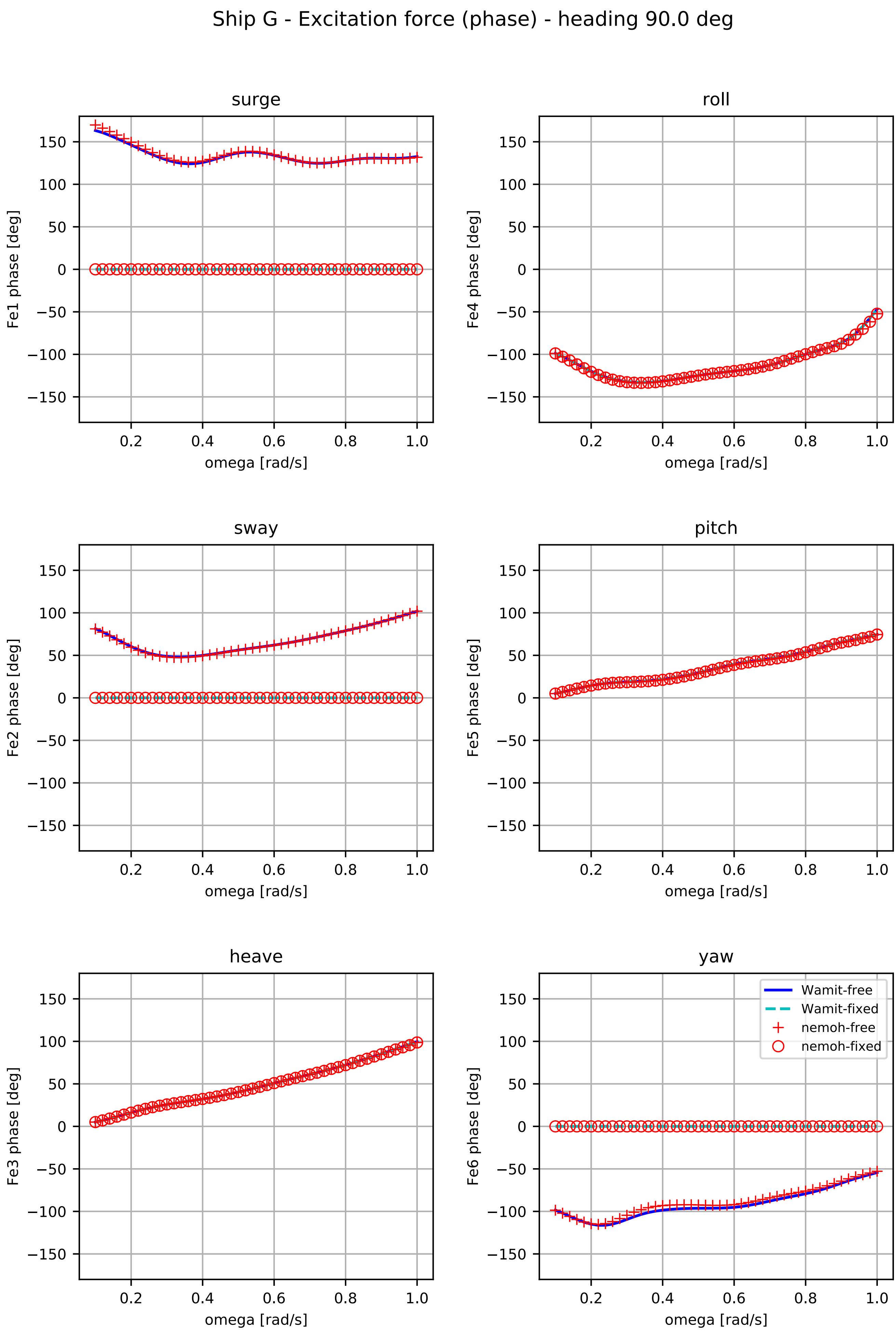




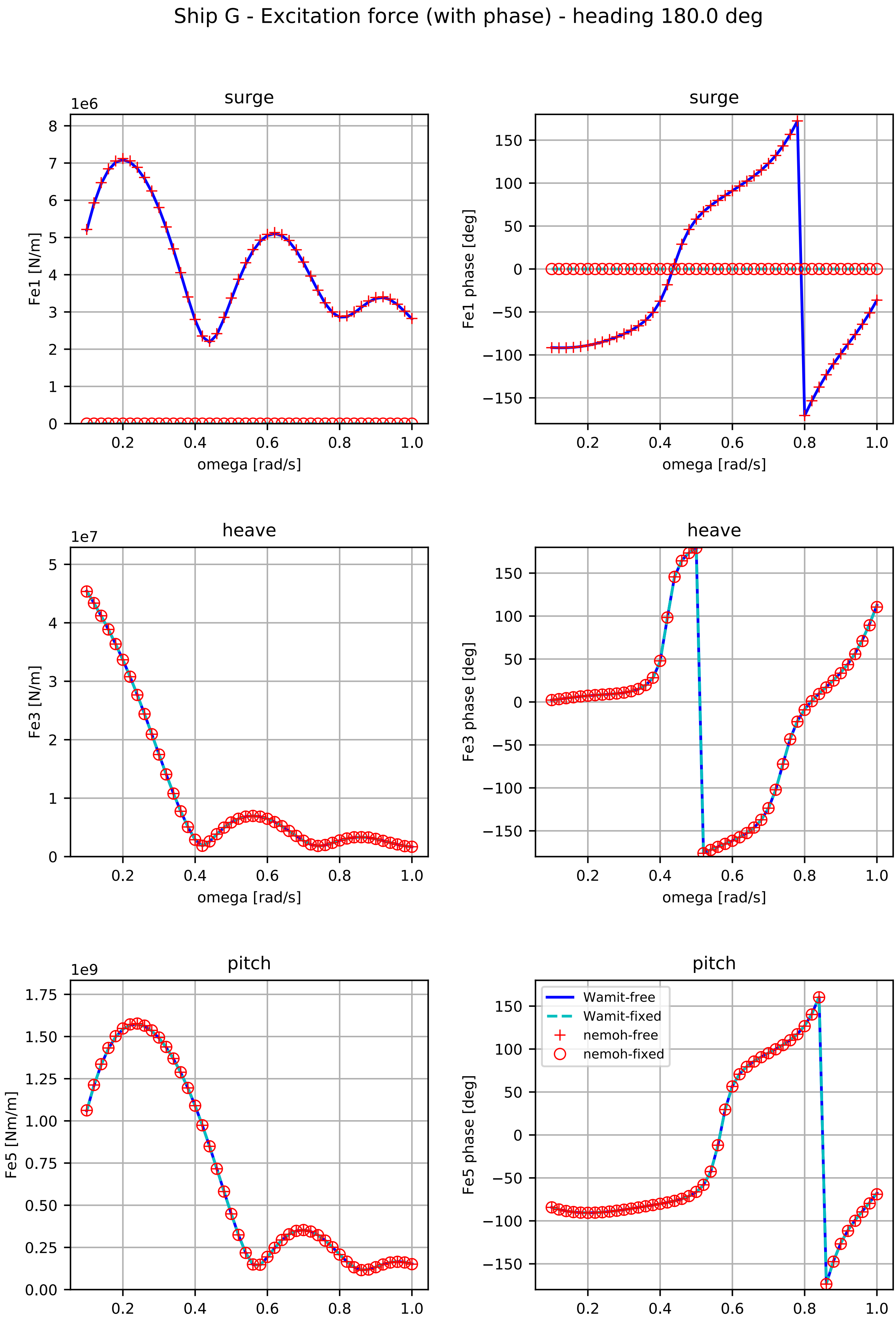
Ship G - Excitation force (with phase) - heading 0.0 deg
surge
1e6
Fe1 [N/m]
omega [rad/s]
surge
Fe1 phase [deg]
omega [rad/s]
heave
1e7
Fe3 [N/m]
omega [rad/s]
heave
Fe3 phase [deg]
omega [rad/s]
pitch
1e9
Fe5 [Nm/m]
omega [rad/s]
pitch
Fe5 phase [deg]
omega [rad/s]
Wamit-free
Wamit-fixed
nemoh-free
nemoh-fixed

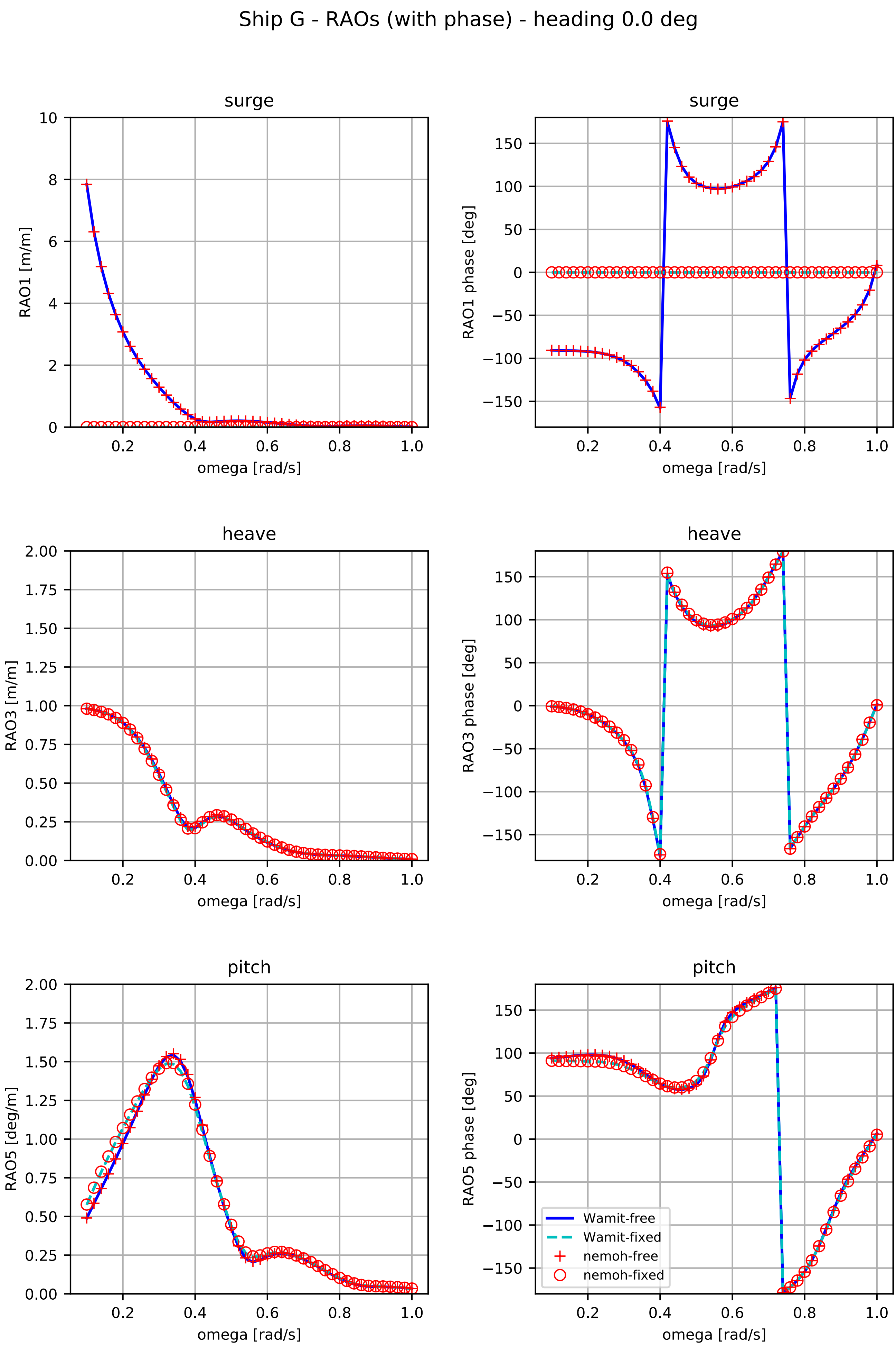
Ship G - Excitation force (magnitude) - heading 90.0 deg

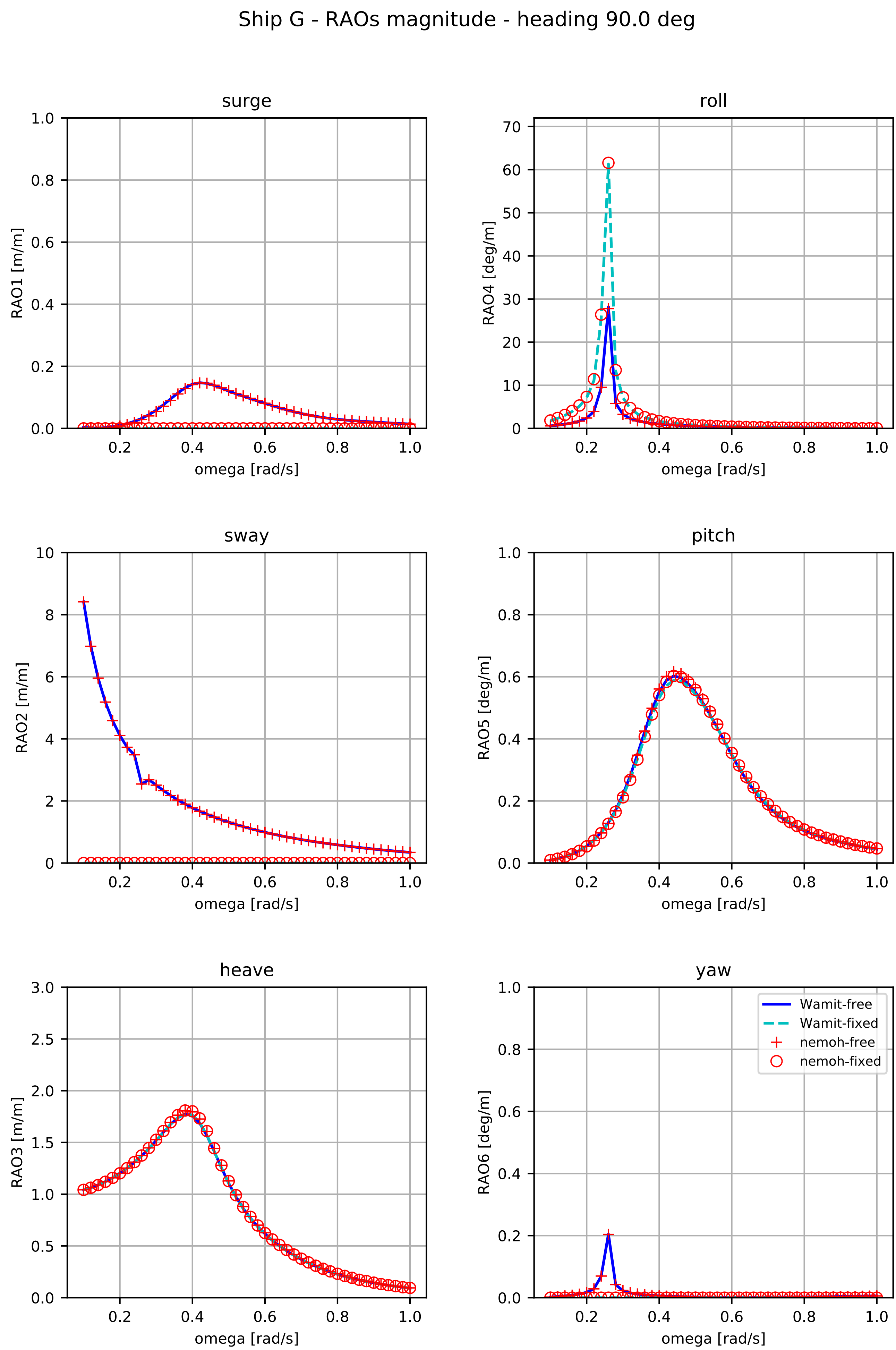




Ship G - Excitation force (phase) - heading 90.0 deg
surge
roll
sway
pitch
heave
yaw
Fe1 phase [deg]
Fe2 phase [deg]
Fe3 phase [deg]
Fe4 phase [deg]
Fe5 phase [deg]
Fe6 phase [deg]
omega [rad/s]
Wamit-free
Wamit-fixed
nemoh-free
nemoh-fixed

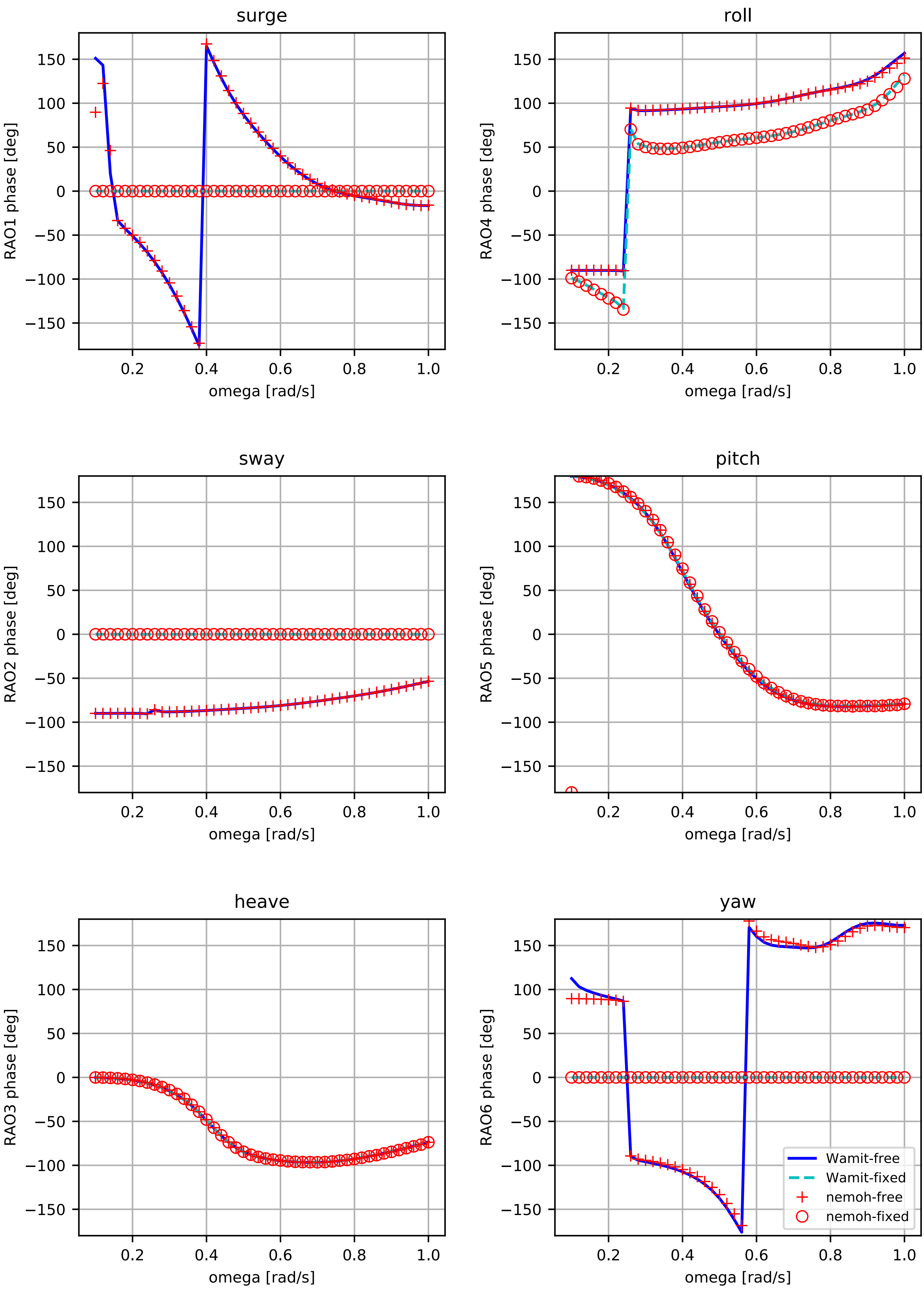

Ship G - Excitation force (with phase) - heading 180.0 deg
surge
1e6
Fe1 [N/m]
omega [rad/s]
surge
Fe1 phase [deg]
omega [rad/s]
heave
1e7
Fe3 [N/m]
omega [rad/s]
heave
Fe3 phase [deg]
omega [rad/s]
pitch
1e9
Fe5 [Nm/m]
omega [rad/s]
pitch
Fe5 phase [deg]
omega [rad/s]
Wamit-free
Wamit-fixed
nemoh-free
nemoh-fixed


Ship G - RAOs (with phase) - heading 0.0 deg
surge
RAO1 [m/m]
RAO1 phase [deg]
heave
RAO3 [m/m]
RAO3 phase [deg]
pitch
RAO5 [deg/m]
RAO5 phase [deg]
omega [rad/s]
Wamit-free
Wamit-fixed
nemoh-free
nemoh-fixed



Ship G - RAOs magnitude - heading 90.0 deg
surge
RAO1 [m/m]
omega [rad/s]
roll
RAO4 [deg/m]
omega [rad/s]
sway
RAO2 [m/m]
omega [rad/s]
pitch
RAO5 [deg/m]
omega [rad/s]
heave
RAO3 [m/m]
omega [rad/s]
yaw
RAO6 [deg/m]
omega [rad/s]
Wamit-free
Wamit-fixed
nemoh-free
nemoh-fixed

Ship G - RAOs phase - heading 90.0 deg



Ship G - RAOs (with phase) - heading 180.0 deg