Some Problems in Predicting Low-Frequency Motion Damping and Response of Floating Offshore Structures

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Background

BMT took part in a comparative evaluation of computer programs, organised by the Royal Norwegian Council for Scientific and Industrial Research (NTNF). This project revealed a number of interesting problems, particularly those of estimating low-frequency motion damping and extreme responses. The present paper describes results from a follow-up study, showing how changes in the assumptions and procedures affect the results. Further details may be found in Ref. 1.

The problem posed by NTNF was to calculate wave forces on, and motions of, two vessels in regular and irregular waves; to estimate maximum responses in a storm of six hours duration for first- and second-order motions separately, and then for the combined process. The two vessels were a turret-moored production ship and a four-column deep-draft floater (DDF), the latter being a very large semi-submersible type structure of 150m draft. We shall limit discussion here to the DDF.

BMT's calculations were performed using the NMIWAVE computer program, which is based on first-order wave diffraction theory, using a conventional three-dimensional source/sink model at zero forward speed. NMIWAVE also computes mean and low-frequency, second-order wave forces and responses.

First- and Second-Order Forces and Moments

The first-order calculations were conventional. The results were fairly insensitive to facet discretisation, and will not be discussed further here.

The second-order forces were found to be more sensitive to the facet discretisation. There were also unexpectedly large differences (see Fig. 1) between second-order force spectra calculated using the quadratic transfer function (QTF) method and the Newman approximation. These discrepancies occurred at very low frequencies, and therefore seem to be due as much to numerical inaccuracy in the 'near-field' estimate of the QTF, as to differences between the two formulae. The Newman estimate was based on the alternative 'far-field' estimate of mean forces, which is less sensitive to numerical inaccuracy.

Which method is preferred will depend on whether the natural period of the motion is very long, on whether motions in the vertical plane are required, and (not least) on acceptable computer costs. The QTF and 'near-field' approach not only add to computer run time, but also seem to require a finer facet mesh in order to obtain comparable numerical accuracy.

The second-order response spectra (see Fig. 2) were typical of lightly-damped, resonant systems, and care had to be taken in order to make the frequency resolution δf fine enough to define the spectral shape: we require $\delta f < \min(\zeta f_o, 0.2 f_o)$, where ζ is the damping ratio, f_o is the natural frequency.

Low-Frequency Motion Damping

The estimation of low-frequency motion damping remains a major area of uncertainty in predicting responses of floating structures.

When estimating first-order responses it is often sufficient to use the wave radiation damping calculated by a standard diffraction-type program. At low frequencies, however, the wave radiation damping is very small, and other sources have to be considered, such as:

* drag forces, associated with flow separation and vortex shedding,
* skin friction, associated with viscous flow in the hull boundary layer,
* wave drift damping, associated with changes in the added resistance as the vessel surges backwards and forwards, and the encounter frequency varies.

The following notes discuss the relative importance of drag and skin friction forces for the DDF, and demonstrate the importance of current velocity. We use simple methods that would be readily available to the designer. Wave drift damping will not be considered here, though it is known to be important for low-frequency surge response of ships.

Estimates of damping and the associated responses are made, based on four alternative assumptions:

a) uses constant drag coefficients, and second-order velocities only in the drag force formula, ignoring the current,

b) represents increased drag due to first-order velocities,

c) also represents variations in C_d at low Keulegan-Carpenter numbers (K_c) associated with skin friction and vortex development,

d) uses constant drag coefficients, first- and second-order response velocities, and current drag is included.

NTNF specified a fairly strong current (0.5m/s for the operational sea-state, 1.0m/s for the design sea-state). A strong current greatly simplifies the analysis, dominating the damping, and making it almost independent of the structure's response. Constant, high K_c values of C_d may also be used.

The situation is much more complicated when there is no current present. In case (c) skin friction and drag may both be important, with complex changes in the effective C_d with K_c number. Estimates (a) and (b) are based on conventional drag coefficients (e.g. C_d = 0.7 for smooth circular cylinders). Recent experimental measurements (Refs. 2, 3) indicate that there are substantial variations in C_d at low values of K_c: an increase roughly proportional to $1/K_c$ due to skin friction, followed by development of instability and vortex shedding, leading towards the conventional value of C_d at high values of K_c. The experimental curves were idealised for use in a computer model for approach (c). Cases (a) to (c) use the standard Borgman linearisation of drag, which replaces the quadratic term $u|u|$ by $\sqrt{8/\pi}\,\sigma_u u$, where σ_u is the standard deviation of velocity u, with modifications to K_c and the β parameter to allow for irregular motions.

The following results demonstrate how the assumptions can affect the surge damping (in kN/ms^{-1}) and standard deviation of response σ_R (in m):

Assumption	$H_s = 6m$ Damping	σ_R	$H_s = 15.5m$ Damping	σ_R
a	517	1.6	737	2.2
b	798	1.3	3800	1.0
c	1036	1.1	6272	0.8
d	5840	0.5	11700	0.5

When current was ignored the inclusion of skin friction and first-order velocities both increased the amount of damping substantially, especially in the higher sea state. The 'naive' assumption (a) could result in a significant underestimate of damping, and overestimate of response.

The addition of a current (case d), greatly increased the damping and reduced the response. Current also caused a large increase in the damping of the TPS. These results confirm experimental and theoretical findings in studies on similar structures elsewhere.

These investigations demonstrated the importance of current forces, and the need for further research on the whole topic of low-frequency motion damping: on the sources of damping and their relative importance, on the development and validation of practical design procedures that take account of the random nature of the motion, and allow for combined first- and second-order effects. Further experimental data is needed on drag coefficients at low Keulegan-Carpenter numbers, particularly when the Reynolds number (or β parameter) is large, and on their functional relationships with K_c and β.

The usual cross-flow principle was used in calculating drag forces. This principle means that damping forces in the vertical (heave) direction are determined by the horizontal current velocity. One may question whether this assumption is reasonable.

Extreme response motions

BMT's investigation also included comparisons between two estimates of expected maximum second-order motions: one based on assuming a Rayleigh distribution of peaks; the other on an asymptotic distribution recently proposed by Naess (Ref. 4), which takes account of the second-order character of the forcing and correlation between successive peaks. The results indicate that the Rayleigh model is likely to underestimate extreme low-frequency motions. Further validation of Naess's formula is desirable, but it does appear to offer a practical way forward to the designer.

We also followed Naess's paper in combining extreme first- and second-order estimates. There were substantial differences between a 'square-root-of-sum-of-squares' (SRSS) estimate and a 'linear-sum' (LS) estimate. The first may be considered unconservative and the latter conservative. We propose a compromise formula which includes a 'correlation' parameter q:

$$(\tilde{Z}_1{}^2 + \tilde{Z}_2{}^2 + 2q\,\tilde{Z}_1\,\tilde{Z}_2)^{1/2} + \bar{Z}_2$$

where $\tilde{Z}_1$, $\tilde{Z}_2$ represent expected maximum first- and second-order oscillatory responses, and $\bar{Z}_2$ is the mean offset. The SRSS and LS estimates then represent the extremes q=0 and q=1. Comparing this formula with Naess's numerical examples, q=0.4 or 0.5 seems to be a reasonable compromise choice. Further validation of this approach is needed, however. Calculations on the DDF in the design sea state gave the following alternative estimates of expected maximum surge : 6.6m, 7.6m, 8.5m with q = 0, 0.5, 1.0 respectively.

References

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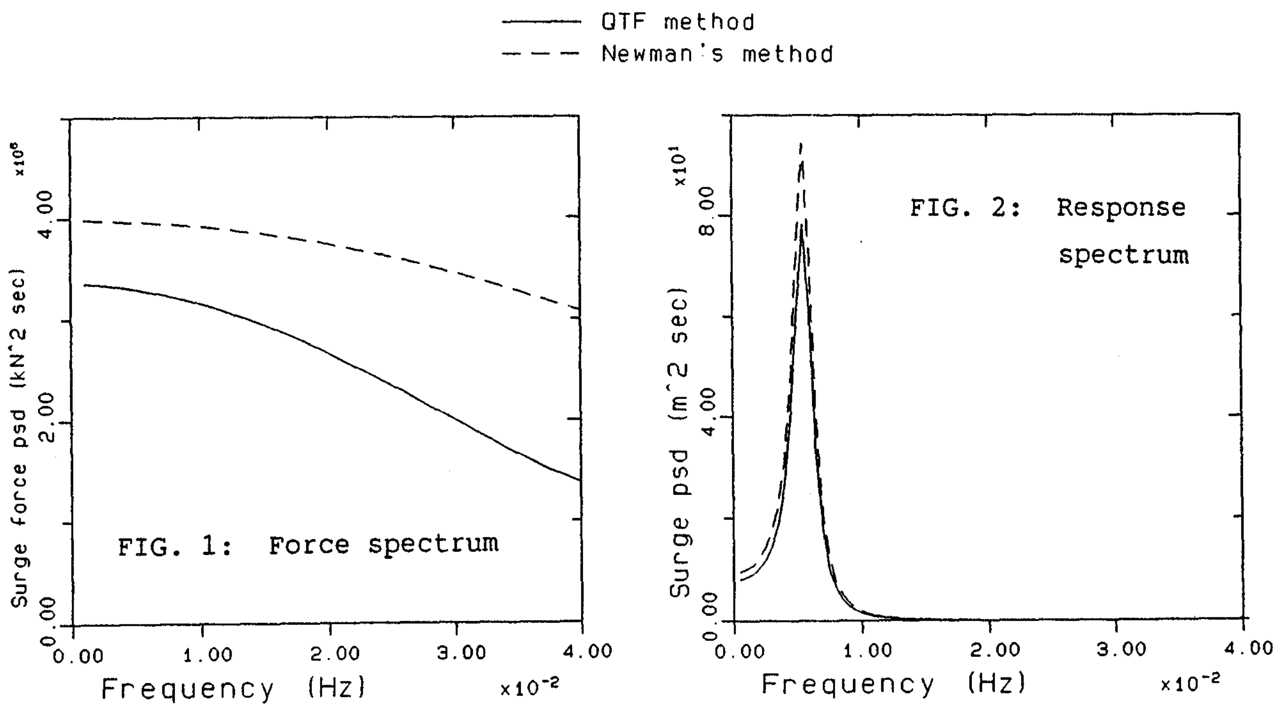

Spectral densities of second-order surge force and response:
Deep-Draft Floater, Hs = 6.0m.

DISCUSSION

McGregor: It is common in validating programs to use model rather than full-scale data. The heave response of a full-scale SWATH was modelled experimentally and theoretically but, of course, the cross-flow drag, which is effectively a damping force, has different effective values of C_d: $C_d \simeq 1.2$ by experiment but $C_d \simeq 0.6$ by computation. This had the effect that the theory showed an appreciable peak at the natural period whereas in the experiment it did not show up. The conclusion drawn by the experimentalist was that the theory was inadequate. However, if the model C_d is used, the agreement becomes good. This illustrates the intuitively obvious point that like must be compared with like, but as you have said, the available model test data is not in the appropriate parts of the Re-K_c space, and so variations are inevitable (Re is the Reynolds number). How to identify the proper combinations can be recognised by plotting iso-Re and iso-K_c lines on a chart with wave height and typical linear dimension as axes [1].

Standing: We have found similar difficulties in correlating model test data, full-scale measurements and theoretical calculations of semi-submersible low-frequency motions. Garrison's recent paper [2] presents C_m and C_d coefficients in the way that you suggest. His data starts, however, at a minimum K_c of 3. Several other experiments (e.g. Rodenbusch's large cylinder tests at SSPA), discussed in [2], have also provided limited data in the high Re, low K_c range. What is needed is systematic and detailed coverage of ranges of K_c around 1.0, and β around 10^5 to 10^6.

Thomas: In calculations of the first- and second-order forces on a submerged horizontal cylinder in water of finite depth using the Boundary Element Method, it was found that 20 sources were sufficient for the first-order forces but 60 sources were necessary to accurately determine the mean second-order force. Any comments?

Standing: This result agrees with our experience. First-order forces seem to be less sensitive to facet modelling because they contain a large Froude-Krylov component, due to incident wave pressures. This component is fairly insensitive to details of the model. First-order added masses and damping, as well as second-order forces, have no such component, and are much more sensitive. We have also found that second-order forces calculated by the 'near-field' or 'direct' method are much more sensitive than those calculated by the 'far-field' or 'momentum' method. There seem to be two main reasons:

(a) the near-field expression contains several terms, some of which are positive and some negative, and whose sum is often smaller than the individual components; and

(b) the waterline integral term is sensitive to the location of points around the waterline.

We found [3] that we needed twice as many waterline points as source points in the adjacent layer, and that these points should be placed symmetrically either side of the source point.

References

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