LOW FREQUENCY MOTIONS OF LNG CARRIERS MOORED IN SHALLOW WATER

Mamoun Naciri
Member ASME
Single Buoy Moorings Inc.
24 Avenue de Fontvieille, PO Box 199
MC98007 Monaco Cedex
T: +377 92 05 17 96, F: +377 92 05 85 44
Email: mamoun.naciri@singlebuoy.com

Bas Buchner, Tim Bunnik & René Huijsmans MARIN
2, Haagsteeg, P.O. Box 28
6700 AA
T: +31 317 493 333, F: +31 317 493 245
Email: b.buchner@marin.nl

Jerome Andrews
Single Buoy Moorings Inc.
24 Avenue de Fontvieille, PO Box 199
MC98007 Monaco Cedex
T: +377 92 05 84 82, F: +377 92 05 44 94
Email: jerome.andrews@singlebuoy.com

Key words: FPSO, LNG, mooring, model testing, shallow water.

ABSTRACT

With the LNG market booming, the need for reliable and safe means of transferring LNG from a producing, floating facility to an LNG carrier and from this carrier to a nearshore terminal is becoming acute. The Soft Yoke Mooring and Offloading (SYMO®) system has recently been model tested in MARIN’s offshore basin. Results of these tests are presented.

Insight has been gained, from these model tests and from the calibration of numerical tools performed thereafter, on the following issues:

- The inherent weakly damped nature of a moored LNG carrier,
- Shallow water effects in wave drift forces,
- The effect of current on drift forces,
- The structure of low frequency long waves in a shallow water basin.

These issues will be discussed and guidance regarding their importance will be provided. Consequences in terms of system design, mooring analysis methodology and model test program will be discussed.

1. INTRODUCTION

For many years, new challenges in the oil industry and in the hydrodynamics of moored structures have been associated with deep water. As a result, a large body of literature associated with shallow water hydrodynamics of floating bodies dating from the seventies and eighties (for instance [1]) may not be known or fully digested by younger engineers and designers. With the pioneers of shallow water system design nearing retirement, there is a clear risk of loss of this expertise. The booming LNG market however, has brought back the focus on shallow water and sparked renewed interest in coastal engineering.

Most LNG Import/Export terminals have in common with the well known soft yoke system (see Figure 1.1), the absence of underwater moorings and flow lines. Furthermore, standard LNG carriers have much smaller fully loaded drafts (less than 12m) compared to crude oil tankers and therefore reduced resistance in current. Last but not least, these carriers have more slender hull forms and significantly smaller block coefficients as compared to converted tankers, not to mention purpose built
barges (see Figure 1.1). The above means that a moored LNG carrier has, perhaps, the least amount of damping of all ship shaped moored structures.

The number crunching power available with today's desktop computers is incomensurable with that existing two or three decades ago when the first shallow water systems were being designed. Today's computing capabilities make it possible to perform sophisticated and detailed hydrodynamic analyses to design LNG Import/Export terminals and shallow water systems in general.

The dynamics of a moored LNG carrier in surge are discussed in §2. The model tests performed in 2003 for a moored LNG carrier in 30m water depths are presented in §3. Time domain simulation tools are discussed in §4 and their results compared to the experiments. Interesting aspects of wave generation in shallow water basins are discussed in §5. Recommendations about analysis methods and model testing are provided before drawing conclusions in §6.

2. DYNAMICS OF MOORED LNG CARRIERS

2.1 General

This paper concentrates on the surge response of moored LNG carriers. A standard 135,000m³ capacity LNG carrier is moored via a soft yoke system (SYMÖ°) to a crane revolving on a fixed jacket in 30m water depth (See Figure 2.1). A more detailed description of the SYMÖ° system can be found in [2] - [5].

The mooring force time series shown in Figure 2.2 has been obtained for the following in-line environment:

- Waves: Hₚ=3m, Tₚ=10.3s and Pierson-Moskowitz spectrum,
- Wind: Uₕ=15m/s,
- Current: Uᵦ=0.7m/s.

The mooring force signal is clearly monochromatic with low frequency amplitude modulation. The natural period in surge is about 125s.

2.2 Damping

To understand the origin of this monochromatic behavior, one can investigate the Dynamic Amplification Factor (DAF) for a Single Degree Of Freedom system (SDOF). The DAF represents the amplification in the motion response for a harmonic excitation, at a given frequency, as compared to the static response. The value of the DAF at resonance (normalized frequency of unity) is 1/(2δ) where δ represents the relative damping.

One observes in Figure 2.3 for large values of relative damping a relatively broad-banded response yielding in the time domain to irregular time series. In contrast, when the relative damping is small, the DAF becomes very narrow banded meaning an almost monochromatic response. Assessing the relative damping in the moored LNG carrier system is thus important.
Dynamic Amplification Factors (DAF)

The following sources of damping are identified:

- Current drag on wetted hull (relative velocity effect). The associated damping force can be estimated as \(2F_{\text{cur}}/V_{\text{cur}}\), where \(F_{\text{cur}}\) refers to the mean current force on the hull and \(V_{\text{cur}}\) to the current velocity averaged over the LNG carrier draft.
- Current drag on any other component of the system located under water.
- Wind drag on LNG carrier (relative velocity effect). The associated damping force can be estimated as \(2F_{\text{wind}}/V_{\text{wind}}\), where \(F_{\text{wind}}\) refers to the mean wind force on the vessel and \(V_{\text{wind}}\) to the mean wind velocity measured 10m above mean sea level and averaged over an appropriate time scale.
- Wave drift damping. This damping originates from the dependency of wave drift forces on the slow drift speed of the vessel.
- Wave radiation damping.
- Friction in articulations (soft yoke).

The magnitude of each source of damping is assessed. In Figure 2.4a, the current and wind relative velocity damping are plotted as a function of current and wind speed respectively. When estimating these contributions, a water depth of 30m and a Moss type containment system have been assumed respectively. It is seen that wind contributes very little whereas current contributes significantly more. Wave drift damping for head waves with \(H_s = 3\) m and a Pierson-Moskowitz spectrum has been calculated using the Aranha formulation ([6] - [9]) and plotted for different spectral peak periods in Figure 2.4b. The above damping has been normalized by the critical damping \(2(m+n)\omega_c\) with \(\omega_c\) the surge natural frequency. The wave radiation damping is plotted as well in Figure 2.4b as a function of the system natural frequency. One observes that at \(\omega_c = 0.05\) rad/s, radiation damping contributes about 0.2%. However, if the system surge natural frequency were increased so would this contribution.

### Figure 2.3 – Dynamic Amplification Factor (DAF) as a function of relative damping.

### Figure 2.4a – Current and wind relative velocity damping.

For the environment listed at the beginning of the section, the following damping contributions have been evaluated:

- Current: 0.64%
- Wind: 0.27%
- Wave Drift Damping: 0.20%
- Radiation Damping: 0.18%

This amounts to a total relative damping of 1.3%.
2.3 Wave forcing

After addressing the issue of damping, wave forcing is discussed. Diffraction calculations have been performed using three independent programs: AQWA-LINE maintained by Century Dynamics, DIFFRAC developed in MARIN and HYDROSTAR developed by Bureau Veritas. The first calculation was performed in-house prior to the model tests. MARIN performed the second calculation during the test campaign. As both AQWA-LINE and DIFFRAC have an approximate solution of the second order potential contribution (see Ref [1]), a third calculation was contracted out to Bureau Veritas to have a full second order solution. Up to three meshes have been considered to assess with each software convergence of the pressure integration. In Figure 2.5, the mean surge drift force coefficients for head waves are shown. HYDROSTAR predicts larger drift forces throughout the frequency range and therefore larger mean forces regardless to the wave spectrum. DIFFRAC predicts the smallest drift forces almost throughout the frequency range.

The slowly varying drift forces can either be estimated in the time domain, using the Newman approximation [10] based on the mean wave drift coefficients, or using a direct double summation over the entire P and Q quadratic transfer functions (QTF). The latter method is more labor intensive. The P and Q matrices concern the in-phase and quadrature parts of the quadratic transfer function T (T=P+iQ).

In order to quickly assess the performance of the Newman approximation, one can estimate the spectral density of surge wave drift force using this approximation first:

\[ S_f(\mu) = 8 \sum_{a} S_a(\omega) S_a(\omega) \left| P(\frac{\omega + \mu}{2}) \right|^2 d\omega \]

and then assuming the full matrix summation:

\[ S_f(\mu) = 8 \sum_{a} S_a(\omega) S_a(\omega) \left| T(\omega + \mu, \omega) \right|^2 d\omega \]

where \( T = \sqrt{P^2 + Q^2} \) and \( S_a \) stands for the wave spectrum.

In Figure 2.6, the two expressions are plotted as a function of the system natural frequency \( \omega_0 \) assuming \( H_s=3m, T_p=10.3s \) and a Pierson-Moskowitz spectrum. The P, Q and T matrices come from AQWA-LINE. It is clear that the two approaches are equivalent near the system natural frequency \( \omega_0=0.05rad/s \). This is an indication that shallow water effects are not large for this spectral peak period and water depth. Had the spectrum peak period been 13s, the Newman approximation would have underestimated the drift force spectral density at 0.05rad/s. Had the water depth been say 20m, the Newman approximation would have been too optimistic as well.
Finally, the off-diagonal term of matrix T at difference frequency 0.05rad/s, as predicted by the three programs, is compared in Figure 2.7. One observes that DIFFRAC and HYDROSTAR agree very well up to about 1 rad/s. AQWA underestimates the coefficients for low frequencies and yields the second largest coefficients for frequencies above 1 rad/s. The forces due to the complete second order potential diffraction effects calculated by HYDROSTAR and the forces calculated using the approximations on the second order diffraction made in DIFFRAC do not differ too much under these circumstances.

![Figure 2.7 - Surge T QTF off-diagonal term at 0.05rad/s for head waves.](image)

### 3. MODEL TEST DESCRIPTION

#### 3.1 General

Model tests were performed in 2003 to validate the SYMO© concept focusing on the connected/moored situation but also looking at the yoke connection and disconnection in 30m water depth.

The scale adopted was 1:35 to ease the visualization during the connection/disconnection operations and to improve the accuracy of free surface elevation measurements for the benign environment considered.

The main particulars of the LNG carrier scale model are listed in Table 3.1 below:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length (m)</td>
<td>274</td>
</tr>
<tr>
<td>Breadth (m)</td>
<td>44.2</td>
</tr>
<tr>
<td>Draft (m)</td>
<td>11.0</td>
</tr>
<tr>
<td>Displacement (ton)</td>
<td>96,970</td>
</tr>
<tr>
<td>COG above keel (m)</td>
<td>15.7</td>
</tr>
<tr>
<td>Transverse radius of gyration (m)</td>
<td>15.1</td>
</tr>
<tr>
<td>Transverse metacentric height (m)</td>
<td>4.8</td>
</tr>
</tbody>
</table>

Table 3.1 – Main particulars of standard LNG carrier.

The following tests were performed:

- Static tests,
- Decay tests in calm water, current and monochromatic waves,
- Monochromatic wave tests with and without current. These tests were used to estimate the mean surge drift force coefficients experimentally,
- Irregular wave tests.

#### 3.2 Static tests

The LNG carrier was first pulled away and then towards the import terminal in order to check the mooring force induced by the yoke system against theoretical predictions.

#### 3.3 Decay tests

Standard free-floating decay tests in calm water were performed to derive the LNG carrier natural periods. Once moored, surge decay tests were carried out both in calm water and in current with a view to establishing the natural period and damping levels. This period was found to be 125s. The linear surge damping was estimated at about 0.5%-0.6% of critical. These values are consistent with the estimate of current damping in §2. Decay tests were also performed in
monochromatic waves with a view to estimating wave drift damping experimentally with and without current.

### 3.4 Monochromatic wave tests

The main purpose of these waves was to obtain an estimate of the main diagonal of the Q wave drift force QTF matrix. Three wave frequencies have been selected centered about the peak of the surge mean drift force transfer function in head waves: 0.50, 0.65 and 0.80 rad/s. Three series of tests were performed:

- **Series 1**: $H=3m$, no current,
- **Series 2**: $H=6m$, no current,
- **Series 3**: $H=3m$, 0.7m/s collinear current.

Comparison of series 1 and 2 will provide information regarding non-linear effects while series 1 and 3 will illustrate the effect of current.

For each test, the asymptotic mean drift force was measured once the transient effects have died out. This mean force is then divided by the square of the undisturbed wave amplitude to obtain the surge QTF at the given frequency.

In figure 3.1, the three series of experimental surge QTF have been plotted along with the AQWA-LINE QTF modified to account for the presence of a 0.7m/s current [6]-[9].

Series 1 shows that one can expect a minimum surge QTF of about $-100 \text{ kN/m}^2$ i.e. in excess of AQWA-LINE and DIFFRAC predictions but smaller than HYDROSTAR predictions.

Comparison of Series 1 and 2 shows non-linear effects: a higher wave results in a lower QTF. This can be due to non-linear effects in the drift forces which are neglected in linear theory. In linear theory only the wave loads below the still waterline are considered and above the waterline a "wall-sided" ship is assumed. The waterline is very thin. In reality, the hull shape of the LNG carrier is changing significantly in waves and with a moving vessel: the bulbous bow is coming out of the water and the flaring bow is submerged in the waves regularly. Linear assumptions can be questioned in this case.

Note that the AQWA-LINE drift forces corrected to account for current effects [9] agree well with the Series 3 test for 0.65rad/s.

The significant wave heights generated were in the range 2.1m to 4.5m. Only one peak period was considered $T_p=10.3s$. Wind speeds between 15 and 17m/s were generated and the current speed was 0.7m/s. Both in-line and transverse conditions were tested.

### 3.5 Irregular wave tests

For the sake of brevity, in-line environments only are considered in this paper. The focus will be on the following three tests:

- **Test 106003**: $H_s=3m$, $T_p=10.3s$, PM spectrum, $U_w=17m/s$, $U_c=0.7m/s$.
- **Test 906002**: $H_s=3m$, $T_p=10.3s$, PM spectrum, $U_c=0.7m/s$.
- **Test 903002**: $H_s=3m$, $T_p=10.3s$, PM spectrum.

In irregular wave testing, the standard practice is to apply, step by step, each component of the environment. In particular, an hour full-scale data acquisition is performed with wind and current only before the 3-hour full test 106003.

The response of the LNG carrier to wind and current is shown in Figure 3.2. The standard deviation of the measured surge motion is 0.29m for this wind and current test. This can be compared to 2.62m in the presence of wind, waves and current (test 106003). Figure 3.2 clearly shows a response at the natural frequency of the moored LNG carrier.

Note that the AQWA-LINE drift forces corrected to account for current effects [9] agree well with the Series 3 test for 0.65rad/s.

The significant wave heights generated were in the range 2.1m to 4.5m. Only one peak period was considered $T_p=10.3s$. Wind speeds between 15 and 17m/s were generated and the current speed was 0.7m/s. Both in-line and transverse conditions were tested.
4. CALIBRATION OF NUMERICAL TOOLS

4.1 General

Calibration of numerical tools against model tests is essential to gain confidence in their ability to capture the behavior of a floating system.

The ultimate goal of a calibration exercise is to recover through a 3-hour time domain simulation the results of an irregular wave test (or at least its main statistical parameters: mean, standard deviation). In general, the free surface elevation time series generated in the simulation is not identical to the free surface elevation measured during the wave calibration process, though both time series may have the same significant wave height, peak period and spectral density. Consequently, the wave group structure will be different and so will the low frequency response. If N simulations are performed with N different free surface realizations, each simulation will yield a different result.

For a single degree of freedom subjected to white noise, it can be shown [11] that the variance of the response variance $\sigma^2$ is inversely proportional to the simulation duration $T$, to the resonant wave frequency $\omega_0$, and to the relative damping $\delta$:

$$\sigma^2 = \frac{1}{T \omega_0 \delta}$$

Assimilating the response of a moored LNGC subjected to an in-line environment to a single degree of freedom (surge) system, it is clear from the above that the scatter in surge rms will be large when the relative damping is small.

Consequently, the only way to achieve a meaningful agreement between tests and simulation is to use in the latter the time series measured in the basin.

Calibration of the model tests was performed with MARIN's LIFSIM program [12]. The main features of this programme are discussed next.

4.2 LIFSIM features

The following features have been implemented in LIFSIM for this calibration exercise:

- Potential damping: this linear contribution is included in the retardation functions;
- Viscous damping: this linear damping is determined from the calibration of decay tests in calm water;
- Wave drift damping: this linear damping coefficient is derived from decay tests in monochromatic waves or alternatively through the Aranha formula [8];
- Current relative velocity damping. The current coefficient $C_l$ has been derived from tests in current only.

The current force is computed as follows:

$$F_{\text{current}} = \frac{1}{2} \rho_w l_w T C_d (U_c - U)(U_c - U)$$

where $\rho_w$, $l_w$, $T$, $C_d$, $U_c$, and $U$ respectively stand for water density, length between perpendicular, drag coefficient, current speed and surge velocity.

4.2.2 Wave force model

The free surface elevation $\zeta(t)$ is described as the linear superposition of harmonic components whose amplitude $a_i$ are related to the wave spectrum $S(\omega)$:

$$\zeta(t) = \sum_{i=1}^{N} a_i \cos(\omega_i t + \theta_i)$$

where $\omega_i$ and $\theta_i$ are respectively the wave frequency and phase angle of harmonic component $i$.

The first and second order wave forces are computed through first and second order convolution of the measured wave trains in the basin.

The effect of the undisturbed second order wave potential on the wave drift forces on shallow water has been described by [13]. The part of the wave drift forces due to the second order undisturbed wave potential can be estimated using the bound wave profile also called wave set-down. This wave set-down can also be calculated using second order transfer functions as shown in [14]. It is shown in [15] that this set-down can have a significant effect on drift forces.

The free surface elevation time series imported from the basin is measured in the absence of structure at the future location of the floating structure COG. In shallow water, this time series will include the abovementioned low frequency set-down.

To avoid double accounting of the set-down effect, the measured free surface elevation is high pass filtered before import in LIFSIM.
The calibration work has been focused on a test in waves only (903002) and secondly on a test with collinear waves and current (902001). The DIFFRAC hydrodynamic database has been used in both cases.

### 4.3 Test 903002: Waves only

Figure 4.1 illustrates the measured and calculated surge motion responses. The calculation generally follows the group structure measured during the tests. Note that the velocity at the start of the simulation is identical to the test. Note however that this initial condition seems to overshoot the test at the start. The statistical results in surge are listed in Table 4.1 below:

![Image](image.png)

Table 4.1 – Surge statistics in waves only.

<table>
<thead>
<tr>
<th></th>
<th>Mean [m]</th>
<th>RMS [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>MARIN Test 903002</td>
<td>-0.45</td>
<td>2.29</td>
</tr>
<tr>
<td>Simulation 903002</td>
<td>-0.27</td>
<td>2.00</td>
</tr>
</tbody>
</table>

The mean surge is underestimated by 40%. From Figure 2.5, it appears clearly that should the HYDROSTAR results be used, a sizable improvement in the mean surge motion would occur.

The standard deviation, on the other hand, is underestimated only by 13%. From Figure 2.6, we do not expect any improvement in using HYDROSTAR diffraction results.

### 4.4 Test 906002: Waves and collinear current

Figure 4.2 illustrates the measured and calculated surge motion responses. The calculation underestimates the group strength during most of the 3-hour simulation. The statistical results in surge (simulation 906002) are listed in Table 4.2 below:

![Image](image.png)

Table 4.2 – Surge statistics in waves and collinear current.

The mean (absolute value) and RMS surge motions are both underestimated by about 20%. Examination of Figure 2.6 shows that shallow water effects are not so important since the Newman approximation of the drift force spectral density at \( \omega_0 = 0.05 \) rad/s agrees very well to the direct estimate from the relevant off-diagonal terms. From Figure 3.1, it appears clearly that the surge mean drift force QTF in the presence of a 0.7 m/s current is significantly increased compared to the zero current situation. This is shown not only by the monochromatic tests in current but also by the Aranha prediction based on AQWA-LINE results. Consequently, an increase of the P and Q drift force QTF matrices has been implemented (+25%) and a new simulation has been run (9060021). Statistical results are clearly much better with the mean value within 2% of the target and the standard deviation within 4% of target.
5. WAVE GENERATION IN SHALLOW WATER BASINS

5.1 Motivations

Differences between the calculated and measured surge motion statistics have been reduced in the test with current by multiplying the P and Q drift force QT matrices by 1.25. Arguments, both theoretical and experimental, have been presented to justify an increase in the quadratic transfer functions.

Another possibility worth investigating is the presence in the basin of excitation sources not accounted for in the numerical simulation. In particular, it was mentioned in §4.2.2 that the measured free surface elevation time series was first high-pass filtered before import in LIFSIM. The main reason was to avoid accounting twice for the set-down effect. However, the low frequency content of the free surface elevation may not be limited to this set-down component and, in that case, the high pass filter eliminates unduly a source of excitation.

The purpose of this section is to shed some light on the structure of the low frequency content of irregular waves in shallow water basins, to propose a methodology to analyze model tests of moored LNG carriers and, finally to outline the way forward.

5.2 Free surface elevation low frequency content

It is well known (see [16]) that the application of a bi-chromatic signal (at frequencies $\omega_1$ and $\omega_2$) to a flap or piston wave maker will give rise in the basin to waves at the above two frequencies but also to so-called bound waves. These waves are the product of non-linearity and can exist only in the presence of first order waves i.e. here the waves at frequency $\omega_1$ and $\omega_2$. The bound waves do not meet the dispersion relation:

$$\left(\omega_1 - \omega_2\right)^2 = \frac{g}{(k_1 - k_2)\tanh\left(k_1 - k_2\right)}$$

The water depth is not shallow enough for the waves to meet the linear dispersion relation:

$$\omega_1 - \omega_2 = \sqrt{gh(k_1 - k_2)}$$

It is well known that a freely propagating wave is also generated. This wave therefore satisfies the dispersion relation:

$$\left(\omega_1 - \omega_2\right)^2 = \frac{g}{k_1h}$$

and is referred to as a free wave. Modern test facilities as MARIN’s offshore basin are equipped with a second order flap correction that essentially adds to the flap motion a signal opposite to the second order free wave. In practice, cancellation is never perfect and a fraction of the original free wave remains. Furthermore, this free wave being very long is hardly absorbed by the beach at the opposite end of the wave basin. It is then reflected and then propagates towards the wave maker where it is reflected again. The presence of this reflected free wave compromises to some extent the second order correction (where no knowledge about the surface elevation at the flap is used).

Also other aspects in the inflow and outflow of model basins can play a role. MARIN’s offshore basin for instance is 10.5m deep and has a movable floor to accommodate shallow water combined to the generation of high quality current. The cross section of the movable floor is shown in Figure 5.1. As shown in [17]-[18] this transition between the water depth at the wave maker and the nominal water depth may also generate free propagating waves.

Figure 5.1 - Cross section of basin movable floor near wave maker.

Finally, when the first order waves reach the beach at the opposite end of the basin, they get partly reflected. The reflected first order waves have also in principle bound waves associated with them. Estimates of reflection coefficients (amplitude-wise) are shown in Figure 5.2. It is seen that reflection is below 10%. As the set-down is proportional to the squared wave amplitude, the magnitude of the reflected bound waves will be approximately 1% of the incident bound waves.

![Figure 5.2 - Reflection coefficient for waves of test 903002](image)

In summary, the low frequency end of an irregular free surface elevation time series includes the following components:

- Incident bound waves,
Reflected bound waves (this component is small in principle),
Incident free waves,
Reflected free waves.

The incident and reflected free waves if at or near the surge natural frequency will induce a harmonic excitation of the LNG carrier. The amplitude and phase of this excitation are readily obtained from the 1st order wave force RAOs at the relevant low frequency.

### 5.3 Methodology for free surface analysis

*The proposed methodology to be applied for shallow water wave tests with weakly damped moored vessels is outlined in the flowchart of Figure 5.3.*

The measured free surface elevation time series is first low and high pass filtered to obtain the low frequency (LF) and wave frequency (WF) surface elevation time series. This split is possible only if there is no energy overlap.

#### 5.3.1 LF wave

This wave component is separated in the four components listed in §5.2. The incident bound waves are accounted for in the second order drift force QTF.

The surge response of the moored structure to the incident and/or reflected free waves can be estimated directly from the relevant time series and the first order force RAOs. The standard deviation of this response can be compared to the measured surge response to assess the importance of these wave components.

#### 5.3.2 WF wave

This wave component is decomposed in incident and reflected waves. The following calculations are then performed for the incident waves and optionally for the reflected waves:

- Wave group spectrum,
- Set-down spectrum,
- Spectral density of wave drift force with Newman approximation,
- Spectral density of wave drift force with full P & Q QTF matrices,

Comparison of the spectral densities (as shown in Figure 2.6) will give indication of the importance of shallow water effects and the need to use or not the Newman approximation in the time domain. This approach is useful regardless to the level of damping.

Another approach not shown in the flow chart is to work in the time domain. The following calculations are performed:

- Force time series ignoring the contribution of the second order potential (shallow water effects) i.e. based on pressure integration with the following terms (see [1]):
  - Relative wave elevation (Term I),
  - Quadratic velocity contribution (Term II),
  - Pressure gradient (Term III),
  - Angular acceleration (Term IV).
- Force time series including only the contribution of second order potential (Term V in Ref [1]) or, alternately, derive this force time series with all five terms.

With the above steps, it is possible to assess the relative importance of shallow water effects directly in the time domain.

#### 5.3.3 Relative importance of low and wave frequency

The response due to the low and wave frequency components can be compared to assess their relative importance on a case by case basis i.e. depending on water depth, wave spectrum parameters and wave basin geometry.

Based on the above comparison, a strategy can be selected for the calibration of the numerical tools.

#### 5.4 Future Investigations

The following issues deserve further attention:

- Decomposition of incident & reflected first order waves.
- The development and testing of these procedures will be completed and applied to a large number of seastates to gain confidence in their performance.
- Decomposition of bound, free, incident and reflected low frequency waves. The development and testing of these procedures will be completed and applied to a large number of seastates to gain confidence in their performance.
- Identification of the flow chart range of applicability (water depth, spectrum shape, peak period, relative damping).
- Implementation in time domain analysis programs of incident and reflected free waves.
- Accuracy of wave probes. For the benign environments considered today for offloading to an LNG carrier (Hₗ < 3m), the long waves components have very small amplitudes. The accuracy with which the wave probes deliver the free surface elevation is therefore critical. From this point of view as well, the choice of 1:35 scale was particularly well suited.

Most of these items are well underway. In particular, a comprehensive model test campaign is scheduled in March 2004 to test the LNG carrier behavior in a wide range of seastates. The methodology described above will be checked against the model test data.

### 6. CONCLUSIONS

From the model tests performed on an LNG carrier moored via the SYMÖ system to a tower jacket and the calibration of
numerical tools thereafter, the following conclusions can be drawn:

1) Moored LNG carriers are generally weakly damped. This implies a larger sensitivity to the environmental conditions (wave group structure, low frequency fluctuations in the wind and current fields). This feature is not restricted to shallow water.

2) Model testing in shallow water basin of weakly damped moored LNG carriers requires particular attention to the low frequency content of the generated irregular waves. These long waves must be isolated and quantify in relative terms the basin specific components from the set-down.

3) Calibration of numerical time domain programs against irregular wave tests must be performed with the measured free surface time series and the appropriate pre-processing. Results of the LIFSIM simulations agree well with measurement for the wave only test. When current is present, the agreement is not as good. QTF must be increased to match the measured surge response.

4) A methodology has been laid out for the exploitation of model tests (see Figure 5.3). This methodology applies primarily to weakly damped moored vessels in shallow water. Its range of application will be more precisely understood after it is applied to the results of the model test campaign scheduled in March 2004.

The following recommendations can be made for model testing of moored LNG carriers:

- Use large number of wave gauges at appropriate locations to perform the wave separation,
- Perform also wave only tests,
- Perform calibration of wind and current over the test duration,
- Start data acquisition from rest and stop it well after the wave makers are turned off,
- Perform tests of long duration to improve the statistics of the response,
- Use as large a scale as possible to improve the accuracy of the free surface elevation.

The effects, described in this paper, should be considered in the evaluation of model tests and simulations of these types of systems before drawing conclusions on thresholds of connections, disconnection and offloading.

ACKNOWLEDGMENTS

The authors would like to acknowledge MARIN’s Arjan Voogt for his contribution to the wave analysis and MARIN’s Radboud van Dijk for the interesting flowchart in Figure 5.3.

REFERENCES


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Figure 5.3 – Methodology for free surface elevation analysis.