Importance of Random Frequency Spacing in Ship Motion Simulation

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1. INTRODUCTION

The frequency-domain response amplitude operator (RAO) ship motion generation approach is commonly used to produce 'realistic' ship motion in low to moderate sea conditions because the motion can be generated analytically. Established methods and corresponding computer programs are available for the first step in the process which is calculating RAOs based on a description of the ship's geometrical and inertial properties and the operating environment[1, 2]. The resulting RAOs are the frequency-dependent amplitudes and phases of sinusoidal ship response solution components. In the second step, the RAOs are multiplied by the applicable seaway wave spectrum resulting in a frequency-domain ship response spectrum[3]. This process is then repeated for each combination of ship heading, ship speed, and sea state to completely characterize the ship response to the sea. From these spectra it is possible to quantify the severity of individual ship degree of freedom responses statistically. However, for many applications, such as dynamic interface analysis where transient dynamic aircraft responses to ship motion are of interest, it is necessary to evaluate time histories of ship motion, not simply statistical characteristics.

To achieve this, for each of the ship linear and angular displacements q_i, the motion is generated by creating a time series having the same spectral characteristics as the original ship motion spectrum. This is accomplished by summing the contributions of a large but finite number of solution components

$$q_i(t) = \sum_{j=1}^{M} A_{ij} \sin(\omega_{eij} t + \theta_{ij} + \theta_{RNDj}) \qquad (1)$$

where M is the number of solution components contributing to the motion, A_{ij} is the amplitude of solution component j contributing to motion i, ω_{eij} are encounter frequencies, θ_{ij} are phase angles, and θ_{RNDj} are random phase angles uniformly distributed on the interval $[0, 2\pi]$. By prescribing ship displacements in this way, reasonable ship motion can be obtained and long sequences of ship motion can be generated very efficiently. Ship velocities and accelerations can be obtained by differentiating Equation 1 with respect to time.

2. PROBLEM STATEMENT

Replicating frequency-domain-calculated ship motion statistics from time-series data relies on the ability to generate representative 'random' ship motion time histories. As the number of ship motion cycles increases, so does the observed peak amplitude following the Rayleigh distribution[i]

$$q_{i\,max} = \sqrt{2}(\ln N)^{\frac{1}{2}}\sigma \qquad (2)$$

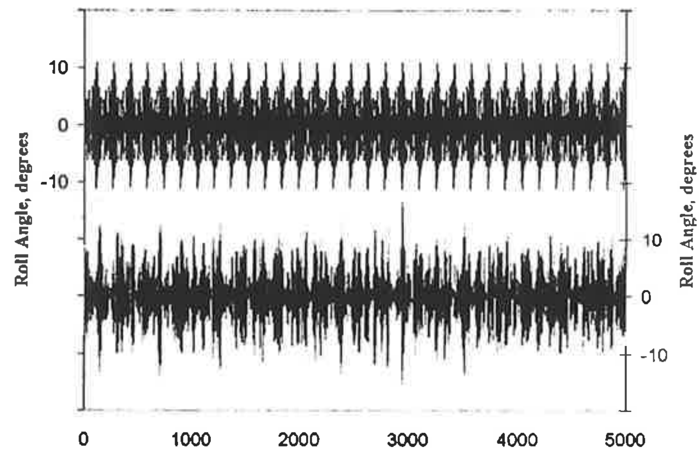

Figure 1. Variation of ship roll angle with time when generated using uniformly-spaced frequencies (upper) and randomized frequencies (lower).

where N is the number of successive amplitudes and σ is the root mean squared amplitude of the time series. For this relationship to be valid, it is essential that the time series data not repeat within the simulation duration. Consider, for example, the two plots in Figure 1 showing roll angle of a typical frigate operating in 4 metre beam seas. The lower trace shows representative ship motion whereas the upper trace is periodic with a period as low as 157 seconds. Clearly, irrespective of the simulation duration, the upper trace will never reach a ship roll angle larger than what is seen in the first 157 seconds.

It is generally recognized that random phase angles θ_{RNDj} are essential for obtaining realistic motion when using Equation 1 to simulate ship motion. However, the importance of the choice of solution component frequencies is much less widely recognized.

Hydrodynamics programs that are frequently used to generate RAOs often have preset output frequencies. These generally are either continuously spaced (for example 0.2, 0.4, 0.6, ... rad/sec) or are composed of blocks of frequencies with uniform spacing within the blocks. If such uniformly-spaced frequencies are used directly with Equation 1 to simulate ship motion, the period of repetition would be determined by the lowest common denominator of the periods associated with individual solution components. In practice, the overall repetition time can vary from less than several hundred seconds (as was the case in the upper trace in Figure 1) to many thousand seconds. This in turn limits the peak ship motion amplitudes that are observed in the time histories.

In practice, a beneficial effect exists. RAOs are functions of wave frequencies ω whereas Equation 1 requires encounter frequencies ω_e. The encounter frequencies combine the effects of ship speed and heading with the wave frequency to reflect the frequency at which wave components encounter the ship. The calculation of ω_e

alters the even frequency spacing to some extent because ω_e, given by

$$\omega_e = |\omega + (\omega^2 V \cos\mu)/g| \quad (3)$$

is a nonlinear function of ω where V is ship speed, μ is ship heading relative to the principle sea direction, and g is acceleration due to gravity. However, in the case of beam seas, where μ is either 90 deg or 270 deg, $\cos\mu$ becomes zero and $\omega_e = \omega$. Therefore, when using evenly-spaced frequencies, this leads to equally-spaced encounter frequencies, strong periodicity in the ship motion, and particularly low peak motion amplitudes observed for beam seas.

3. SOLUTION

The situation can be corrected by randomizing RAO frequencies prior to using them with Equation 1. The procedure consists of:

1. scanning the RAO phase response data and cleaning all 360 deg phase shifts from the data (to avoid evaluating erroneous phase angles along the jumps in subsequent steps);
2. spline fitting the amplitude and phase responses composing the RAOs for each ship degree of freedom;
3. selecting the number of frequencies to be used in evaluating ship motion with Equation 1 (this number can be different from the number of frequencies contained in the original RAO specifications);
4. evenly spacing the M frequencies over the frequency range of the input RAOs and determining the frequency increment $\Delta\omega$;
5. sequentially randomly shifting each frequency ω_i to a new frequency in the range $[\omega_i - \Delta\omega/2, \omega_i + \Delta\omega/2)$; and
6. evaluating the amplitude and phase responses from the spline-fitted data at the newly defined randomized frequencies.

This procedure has been automated in the computer program RAND_RAO.

A sample RAO for ship roll angle corresponding to beam seas is shown in Figure 3 before and after preprocessing. Amplitude and phase data at 40 input frequencies were spline fitted and reevaluated at 50 randomized output frequencies. Removal of the phase discontinuity at 180 deg was necessary before spline fitting the data. However, performance improvement is due to the randomized frequency increments and adequate frequency coverage provided by the method. The benefits of randomizing are clearly evident from Figures 1 and 2. The upper and lower traces shown in Figure 1 correspond to the same RAO with the lower trace generated following the frequency randomization process. Figure 2 compares the expected peak roll amplitudes derived in the frequency domain (left-most half polar plot), the time-domain results including frequency randomization (middle), and the erroneous time-domain results that do not include frequency randomization (right). The results show general agreement between the frequency-domain calculations and those derived from time histories when randomization is used. The error associated with not randomizing is evidenced by the unusual dip at 90 deg in the right-most plot.

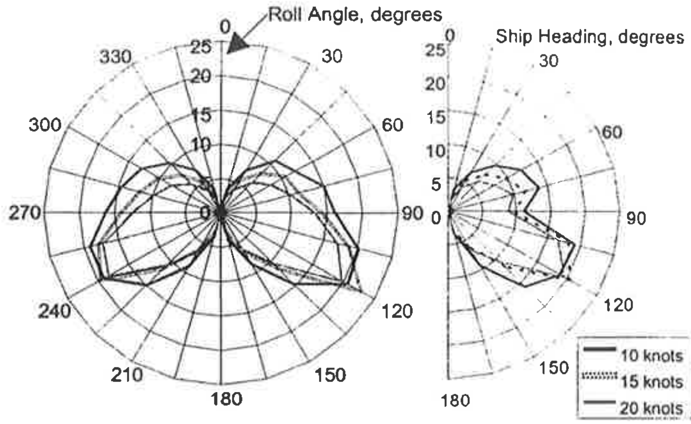

Figure 2. Variation of peak ship roll angle with ship heading for ship speeds of 10, 15, and 20 knots. Half polar plots, from left to right, correspond to frequency-domain statistics; time history data with randomized frequencies, and time history without randomized frequencies.

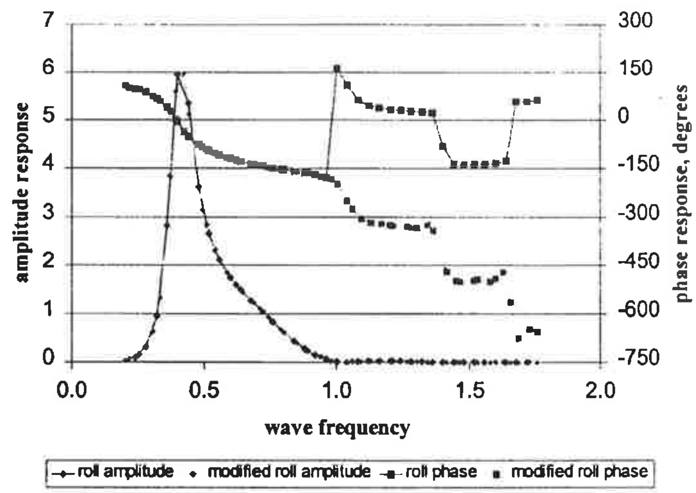

Figure 3. Response amplitude operator for roll angle prior to and following randomization of frequencies.

4. CONCLUSION

Ship motion time histories generated from RAOs must be developed such that appropriate 'randomness' is included in both the phase relationship between solution components *and* the frequencies used to evaluate motions to avoid unacceptable periodicity in the resulting ship motion time histories and misleading results.

ACKNOWLEDGEMENT

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