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Correlation between Time-domain Calculations of Helicopter Securing Probe Forces and Frequency-domain Calculations of Ship Flight Deck Motions towards Determining the Effect of Multidirectional Waves

ABSTRACT

Launch and recovery of shipboard aircraft is facilitated and, in elevated sea conditions, enabled by mechanical aircraft securing and handling equipment. Detailed calculations of helicopter securing probe forces and loads can be made using advanced time-domain methods; however, the ship motion generation capability currently implemented in this methodology is not able to model "multidirectional" seaways, which often occur when local wind-generated waves are combined with swells from remote weather systems. This paper examines correlation between time-domain calculations of helicopter securing probe forces and frequency-domain calculations of ship flight deck motions. Specifically, it examines the relationship between time-domain securing probe maximum radial forces and the "generalized lateral force estimator" (F_{LAT}*) calculated in the frequency-domain. The correlation between pitch angle and flight deck vertical acceleration calculated using the time-domain and the frequency-domain methodologies were examined to determine if frequency-domain calculations can be used to provide insight on the effects of multidirectional seaways on securing probe vertical forces. These vertical forces are highly non-linear due to the way the helicopter probe is secured to the ship, and the helicopter landing gear suspension design. The correlation study shows very good agreement between time-domain and frequency-domain calculations for lateral forces, and for lateral and vertical motions, for parametric variation of ship speed, significant wave height, and ship heading relative to unidirectional waves. Subsequently, a parametric study of flight deck motions and accelerations for unidirectional and multidirectional seaways was performed in the frequency-domain to determine which seaway characteristics would produce the highest maximum probe forces, and so establish a procedure for determining securing probe design loads.

INTRODUCTION

Conventional dynamic interface analysis aimed at determining securing requirements for the case where the aircraft is on the ship flight deck during launch and recovery operations is performed using a variety of engineering analysis software. The following computational approach was adopted to benchmark Canadian operations of Sea King helicopters aboard the Canadian Forces HALIFAX Class frigates, for Existing the Project Management Office of the Canadian Maritime Helicopter (MH) Project [1]. This methodology also provides a consistent process for evaluating new MH candidates, and to support their subsequent integration into the Canadian Forces. The frequency-domain hydrodynamics computer program *SHIPMO* [2], developed by DRDC Atlantic, was used to calculate ship hydrodynamic coefficients and motions for parametric variation of significant wave height, wave peak period, ship headings relative to the wave direction, and ship speeds. *SHIPSIM* [3], a program developed by Curtiss-Wright Controls, Engineered Systems – Marine Defense that calculates prescribed ship motion time histories from linear frequency-domain response amplitude operators (RAOs) generated by a hydrodynamics code such as *SHIPMO*, was run to evaluate time histories of flight deck motion. Next, *DYNAFACE* [4], a nonlinear transient dynamic simulation of the response of a shipboard helicopter to deck motion and wind, developed by Curtiss-Wright Controls, Engineered Systems – Marine Defense, was run to determined helicopter securing forces. Although widely used, this methodology is limited to the simulation of unidirectional seas due to the use of linear frequency-domain methods for characterizing and generating time responses of the ship motion in *SHIPSIM*. Recognizing the need to identify the potentially most-severe cases, the study reported in this paper was performed to determine if an analysis of unidirectional seaways was a reasonable and conservative approach, or whether a more complex analysis methodology for multidirectional seas had to be developed.

To accomplish this, a study comprised of the following three parts was undertaken.

1. Correlations between ship motions generated by *SHIPSIM* in the time domain and those generated by *SHIPMO* in the frequency domain were investigated.
2. Correlations between lateral and vertical force estimators based on *SHIPMO* frequency-domain ship motions and securing forces developed using *DYNAFACE* in the time domain were investigated.
3. Based on what was supported by the previous two analyses, an investigation of the relative severity of uni- and multidirectional seas was performed in the frequency domain. The basis for this approach was that if high correlation exists between *DYNAFACE* and *SHIPMO* calculations for unidirectional waves, then *SHIPMO* calculations for multidirectional waves can provide insight on the effects of multidirectional waves on helicopter probe forces.

All ship motions considered in this paper are calculated for the HALIFAX Class frigate at a nominal operating displacement. Location-dependent forces and accelerations are calculated at the hauldown bell-mouth on the flight deck. This is the location where the helicopter hauldown, rapid securing device (HHRSD) "captures" the helicopter by clamping the helicopter securing probe that projects downward from the helicopter fuselage, at a location roughly coincident with the helicopter centre of mass. The main purpose for this correlation study is to determine if *SHIPMO* can be used to extend analysis of helicopter securing probe forces using *DYNAFACE* to include 'multidirectional' seas with swells and wind-waves from different directions. In Canadian operating areas of the western North Atlantic, multidirectional seaways occur more than 40 percent of the time.

The first section of this paper examines correlation for ship motions, by comparing roll angle, pitch angle and flight deck vertical acceleration (FDVA) from *SHIPSIM* time-domain calculations with *SHIPMO* frequency-domain calculations. This provides an indirect link with forces calculated by *DYNAFACE*, in an attempt to examine likely effects of multidirectional seas on main probe vertical force, and on tail probe radial and vertical forces. The next section examines correlation for directly calculated forces, comparing *DYNAFACE*'s main probe maximum radial force, $F_{R(MP)}$, with *SHIPMO*'s 'generalized lateral force estimator', F_{LAT}* (a force-per-unit-mass parameter). The following section, considers the relative magnitudes of uni- and multidirectional sea environments. The paper concludes with key observations and associated implications.

SHIP MOTION CORRELATION

This section examines correlations between *SHIPSIM* time-domain ship motion calculations with *SHIPMO* frequency-domain calculations.

A parametric simulation study was run using both *SHIPMO* and *SHIPSIM* for significant wave heights, H_{SIG} , of 4, 5, and 6 metres; ship headings relative to the principle wave direction from zero through 360 degrees in 15 degree increments; and, ship speeds from 5 through 25 knots, in 5 knot increments. *SHIPSIM* runs generated 30,000 seconds of simulated ship motion. In the case of *SHIPMO*, RMS motions were extrapolated using the Rayleigh distribution to maximum expected values in 30,000 seconds (consistent with the time base used for *SHIPSIM* calculations), using a factor of 4.0, corresponding to 3,000 wave encounters in beam seas for a wave peak period, T_P, of 10 seconds, which is representative of a 4 metre significant wave height. Varying this parameter to consider a wider range of peak periods does not have a large effect on the extrapolation factor. For example, for peak periods from 11 to 13.6 seconds, the factor for expected maxima in 30,000 seconds varies from 3.98 to 3.92.

The premise for examining ship motion correlation is that if high correlation exists for unidirectional waves between motions used as input to *DYNAFACE* (i.e. from *SHIPSIM*) and those calculated by *SHIPMO*, then *SHIPMO* calculations for motions in multidirectional waves may provide insight into the forces experienced in these multidirectional seaway conditions. A cursory examination shows that the relationship between ship motions (i.e. the forcing function) and securing probe force, incorporating the helicopter reaction, is highly non-linear for main probe vertical force, and for tail probe radial and vertical forces. Conversely, the high correlation between $F_{R(MP)}$ and F_{LAT} shown subsequently suggests that non-linear effects are small for the main probe lateral forces. If multidirectional motions are higher than unidirectional, then one might expect that the probe forces would also be higher, but this is not certain.

Figure 1 compares *SHIPMO* and *SHIPSIM* calculations for flight deck vertical acceleration (FDVA), which is of particular importance for vertical probe force calculations. This figure shows *SHIPMO* data on the Left Hand Side (LHS), and *SHIPSIM* on the RHS, with both maximum and minimum accelerations (i.e. upwards and downwards). The maximum values are all greater than 1.0 (g), and minimum values are all less than 1.0 (g).

Tables 1, 2 and 3 show correlation coefficients (Pearson 'r' values) and "variance explained" (r^2) for roll angle, pitch angle and FDVA, for significant wave heights of H_{SIG} = 4, 5, and 6 metres, with ship speeds of 5, 10, 15, 20, and 25 knots, and for ship headings of 0 through 180 degrees relative to the waves.

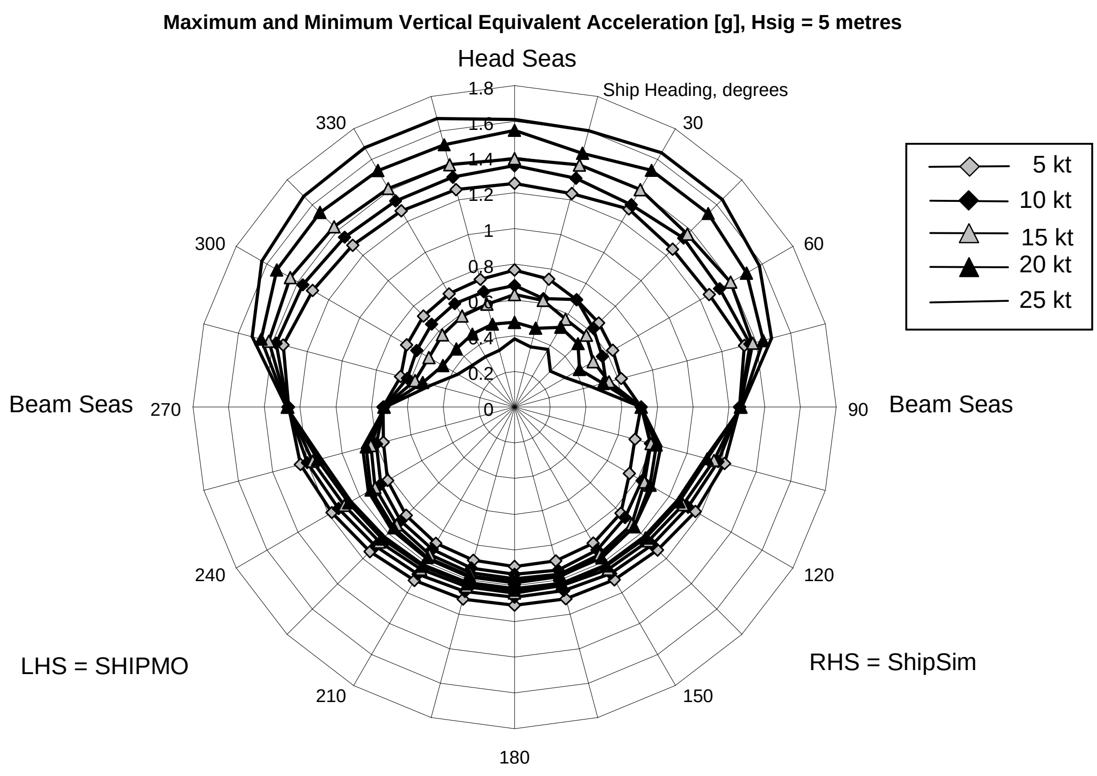

FIGURE 1 SHIPMO FDVA (LHS) vs. ShipSim FDVA (RHS), H_{SIG} = 5 m

TABLE 1 Correlation for Roll Angle, ϕ, (deg), for ship headings from 0 to 180 degrees.

Hsig (m)	ϕ Correlation (r)					ϕ Variance Explained (r^2)				
	5 kt	10	15	20	25	5 kt	10	15	20	25
4	1.00	1.00	0.99	1.00	1.00	0.99	0.99	0.99	0.99	1.00
5	1.00	1.00	0.99	1.00	1.00	0.99	0.99	0.98	0.99	1.00
6	1.00	1.00	0.99	0.99	1.00	0.99	0.99	0.98	0.99	0.99

TABLE 2 Correlation for Pitch Angle, θ, (deg), for ship headings from 0 to 180 degrees.

Hsig (m)	θ Correlation (r)					θ Variance Explained (r^2)				
	5 kt	10	15	20	25	5 kt	10	15	20	25
4	0.97	0.98	0.98	0.98	0.98	0.94	0.96	0.96	0.97	0.97
5	0.97	0.98	0.98	0.98	0.98	0.95	0.95	0.96	0.96	0.96
6	0.97	0.98	0.98	0.98	0.98	0.95	0.96	0.96	0.96	0.96

TABLE 3 Correlation for Flight Deck Vertical Acceleration (g), for headings from 0 to 180 degrees.

Hsig (m)	FDVA Correlation (r)					FDVA Variance Explained (r^2)				
	5 kt	10	15	20	25	5 kt	10	15	20	25
4	0.99	0.99	1.00	1.00	1.00	0.98	0.99	0.99	1.00	1.00
5	0.98	0.99	0.99	1.00	1.00	0.96	0.98	0.99	0.99	1.00
6	0.98	0.99	0.99	0.99	1.00	0.96	0.99	0.99	0.98	1.00

Figure 2 compares general trends for roll angle (deg), pitch angle (deg) and FDVA (g), for ship speeds of 5 and 20 knots, in 5 metre waves, and Figure 3 shows all data and linear regression curves for these motions.

For unidirectional waves, there is high correlation between *SHIPSIM* and *SHIPMO* motion calculations for roll angle, pitch angle and flight deck vertical acceleration (FDVA). For ship speeds of 5 through 25 knots, significant wave heights, H_{SIG}, of 4, 5, and 6 metres, and ship headings from zero through 180 degrees, the correlation coefficients vary from 0.97 to 1.00. These very high correlations validate that the *SHIPSIM* time-domain code is producing ship motions with the same characteristics as those calculated by *SHIPMO* in the frequency domain.

SECURING FORCE CORRELATION

The generalized lateral force estimator, F_{LAT}, is the ship-referenced lateral force (per unit mass) acting on an object, incorporating the effects of both lateral (dominant) and vertical (secondary) accelerations. If one assumes that F_{LAT} is proportional to the forces acting on the helicopter probe which secures the aircraft in the HHRSD, then there should be high, positive correlation between F_{LAT} and radial force on the probe. In this case, the main probe maximum radial force, $F_{R(MP)}$, calculated by *DYNAFACE* is the parameter of interest for comparison with the F_{LAT} calculated by *SHIPMO*.

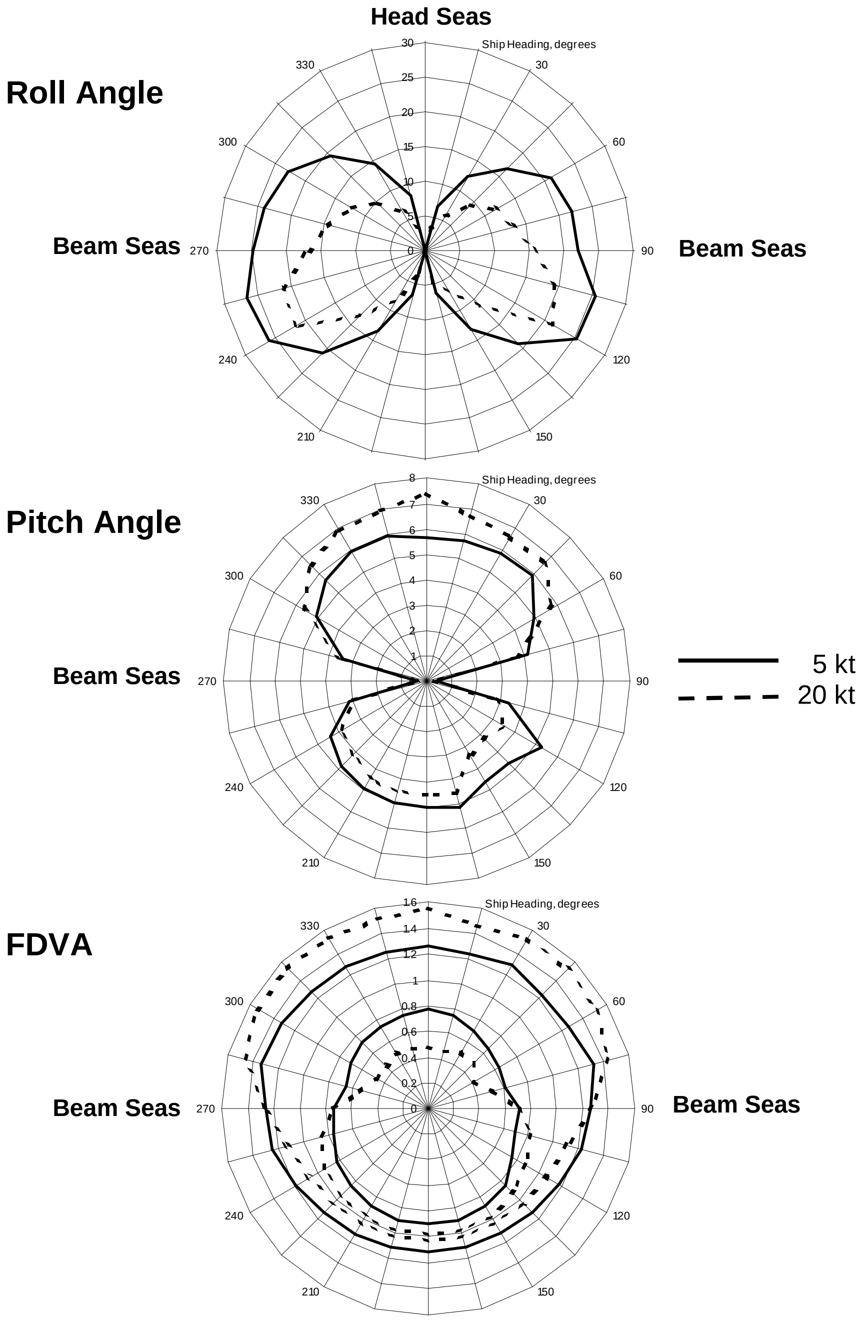

FIGURE 2 Ship motions - SHIPMO (LHS) and ShipSim (RHS), H_{SIG} = 5 meters

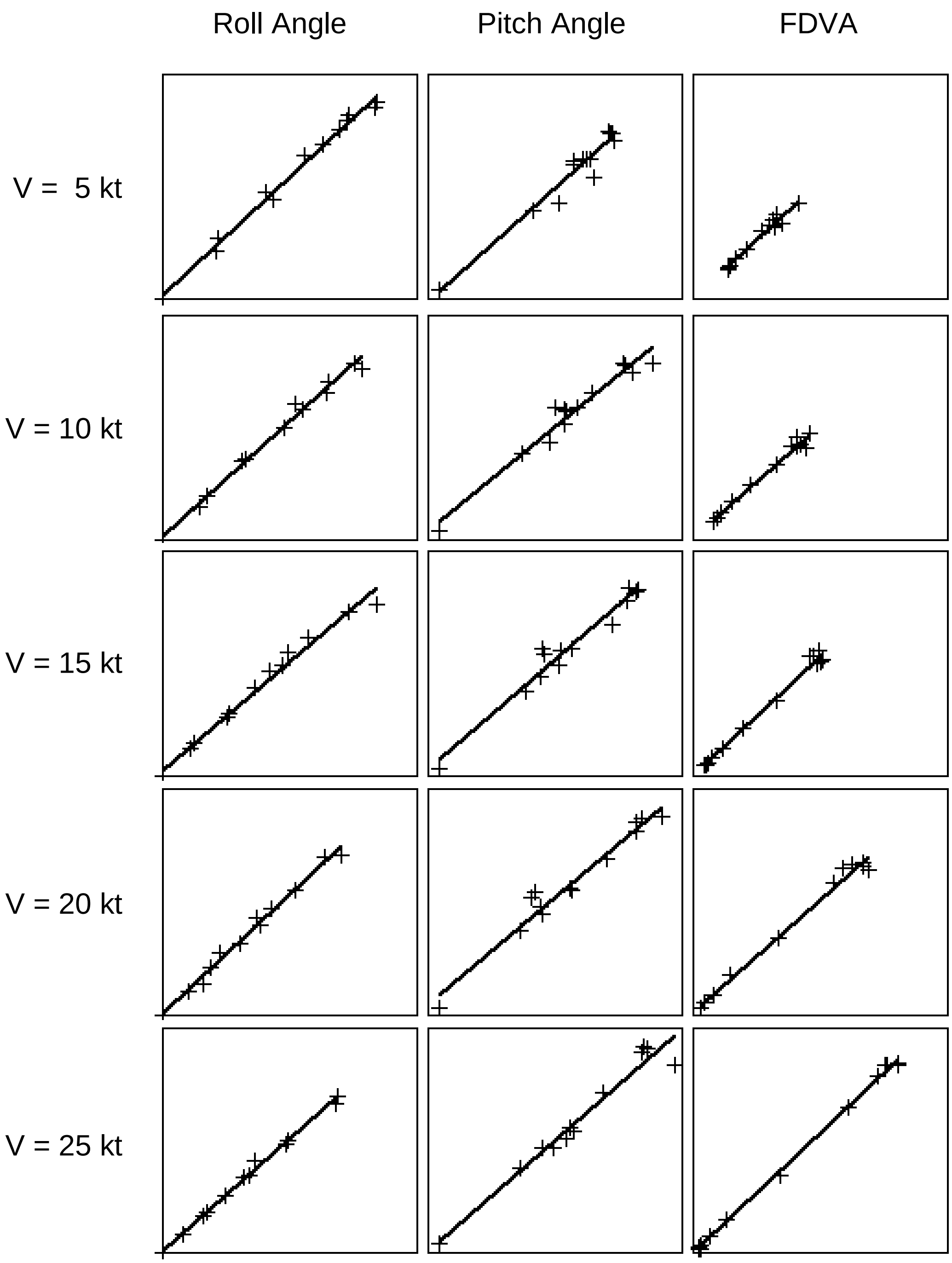

FIGURE 3 Roll Angle, Pitch Angle and FDVA data with linear regressions for ship headings of 0 to 180 degrees.

Figure 4 compares *SHIPMO* frequency-domain F_{LAT}* calculations with *DYNAFACE* time-domain $F_{R(MP)}$ calculations, for the "on-deck case", in a significant wave height, H_{SIG}, of 4 metres. The left-hand-side (LHS) shows contours of F_{LAT}* for various ship headings (radial spokes) and ship speeds from 5 through 25 knots, and the RHS shows $F_{R(MP)}$. The asterisk (*) is added to the F_{LAT} notation to indicate that the parameter F_{LAT}* includes a scale factor of 10^5, as follows.

$$F_{LAT}^* = 10^5 F_{LAT}$$

[F_{LAT} units **g**, F_{LAT}* units **g** x 10^{-5}]

This scale factor provides an overall good match of amplitudes for polar and regression curve plots, and is held constant for all conditions examined in this paper. This factor has no effect on the correlation coefficients examined later. While the *DYNAFACE* and *SHIPMO* forces are not identical, some consistent trends are evident.

- Maximum F_{LAT}* and $F_{R(MP)}$ values are at a ship heading of 15 degrees aft of beam seas for all speeds except 15 knots, where the maxima are 30 degrees aft the beam.

- Ship headings between beam seas and 60 degrees aft of the beam appear to have consistently the highest correlation (calculated correlation coefficients are presented subsequently); this range of ship headings is important, as it includes all calculated $F_{R(MP)}$ maximum values.

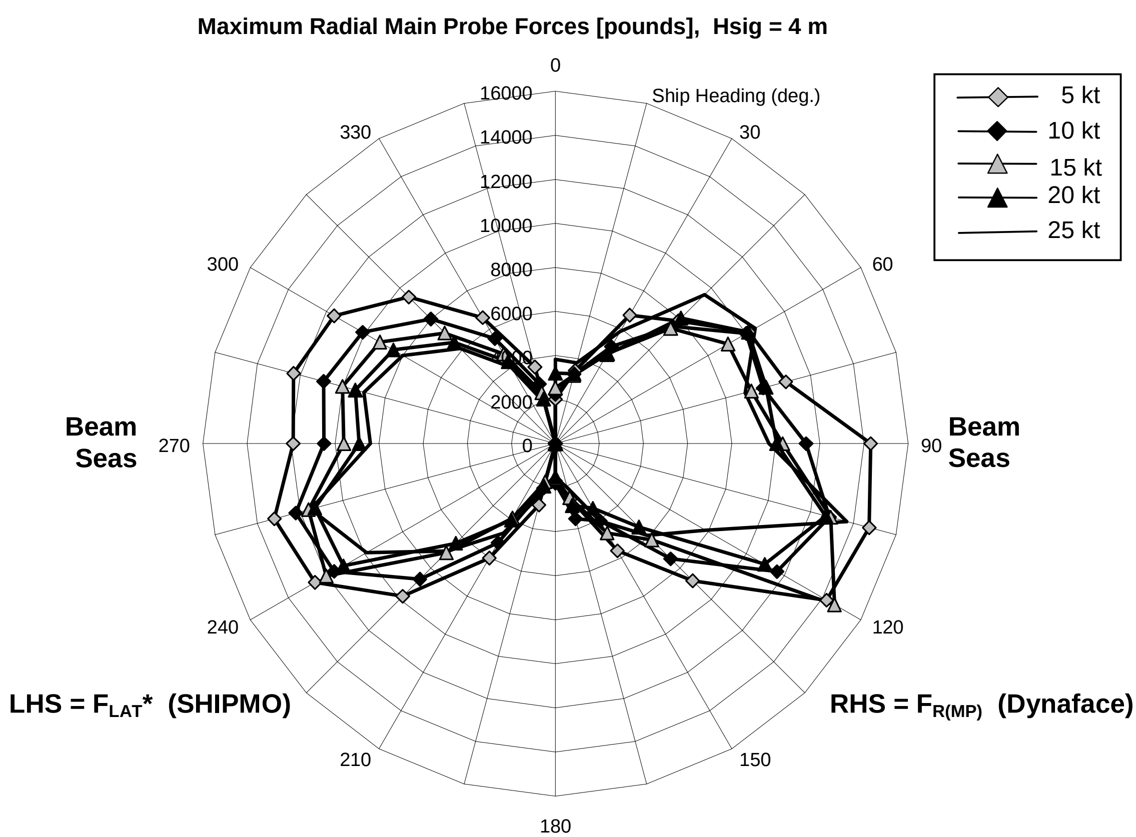

FIGURE 4 SHIPMO F_{LAT}* (LHS) and Dynaface $F_{R(MP)}$ (RHS), H_{SIG} = 4 m

Figure 5 compares F_{LAT}* (LHS) and $F_{R(MP)}$ (RHS) for 4, 5, and 6 metre significant wave heights, and ship speeds of 5 and 20 knots. The correlation in 4 metre waves appears to be preserved in the 5 and 6 metre waves.

Table 4 shows correlation coefficients (Pearson 'r' values) and "variance explained" (r^2) calculated for the 0 to 180 degrees ship headings for all ship speeds and wave heights.

Table 5 shows the same calculations for ship headings from 90 to 150 degrees (i.e. beam seas to 60 degrees aft of the beam), where all maximum values occur for both $F_{R(MP)}$ and F_{LAT}*.

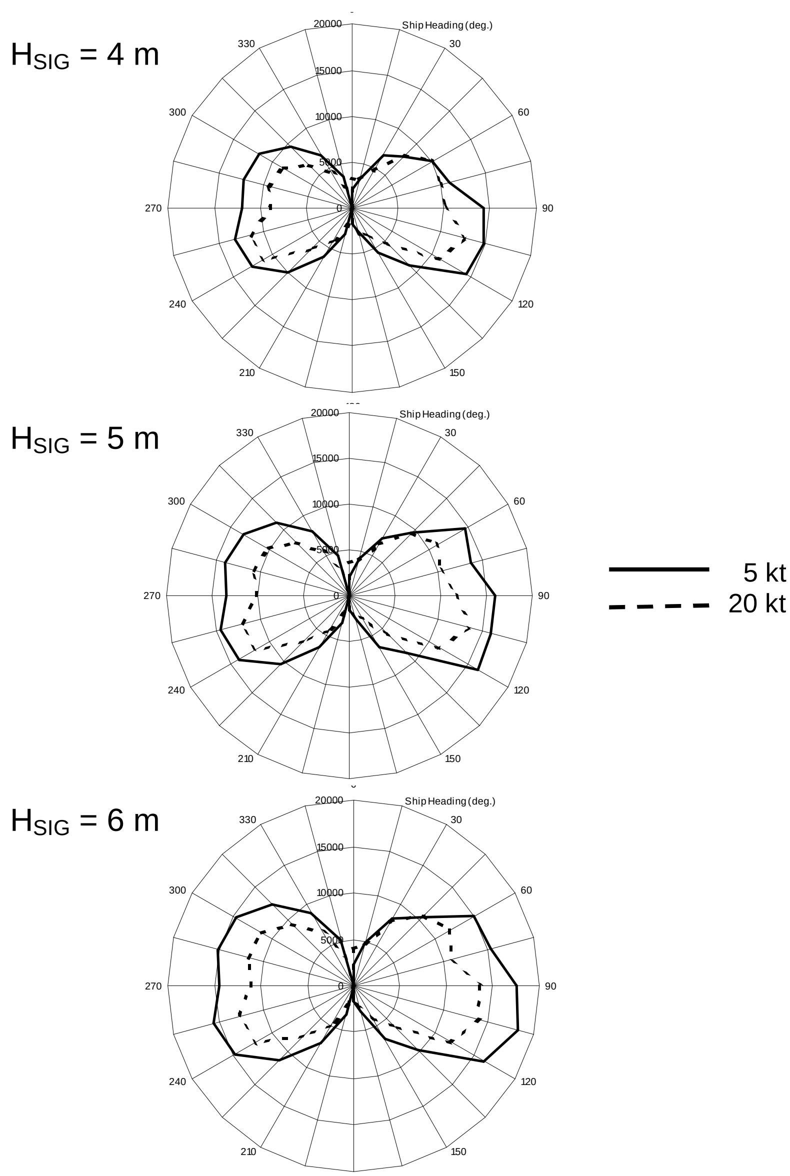

FIGURE 5 SHIPMO F_{LAT}* (LHS) and Dynaface $F_{R(MP)}$ (RHS), H_{SIG} = 4, 5 and 6 meters.

TABLE 4 Correlation between Dynaface $F_{R(MP)}$ and SHIPMO F_{LAT}*, for 0 to 180 degrees.

Hsig (m)	Correlation (r)					Variance Explained (r^2)				
	5 kt	10	15	20	25	5 kt	10	15	20	25
4	0.95	0.97	0.97	0.96	0.89	0.91	0.94	0.94	0.92	0.78
5	0.96	0.96	0.96	0.95	0.87	0.93	0.92	0.92	0.90	0.76
6	0.96	0.94	0.95	0.95	0.87	0.93	0.88	0.91	0.89	0.76

TABLE 5 Correlation between Dynaface $F_{R(MP)}$ and SHIPMO F_{LAT}*, for 90 to 150 degrees.

Hsig (m)	Correlation (r)					Variance Explained (r^2)				
	5 kt	10	15	20	25	5 kt	10	15	20	25
4	0.97	0.98	0.97	0.98	0.90	0.94	0.97	0.95	0.96	0.82
5	0.95	0.98	0.97	0.98	0.91	0.91	0.96	0.94	0.96	0.82
6	0.97	0.95	0.95	0.96	0.91	0.94	0.91	0.91	0.93	0.83

Figure 6 shows $F_{R(MP)}$ and F_{LAT}* data and linear regression curves for ship headings from 0 to 180 degrees. In each case, the vertical axis shows $F_{R(MP)}$ and horizontal axis shows F_{LAT}*. All axes have scales from 0 to 20,000, with units of pounds-force for $F_{R(MP)}$, and **g** x10^{-5} for F_{LAT}*.

For unidirectional waves, there is high correlation between $F_{R(MP)}$ and F_{LAT}*. For ship speeds of 5 through 20 knots, significant wave heights of 4, 5, and 6 metres, and ship headings from 0 through 180 degrees, the correlation coefficients vary from 0.94 to 0.98; and from 0.89 to 0.91 for the 25 knot ship speed.

No useful correlations were found for main probe maximum vertical force, nor for tail probe radial and vertical forces.

COMPARISON OF UNI- AND MULTIDIRECTIONAL WAVES

In this section, a parametric study is described that has been performed using *SHIPMO* to calculate HALIFAX Class frigate motions and generalized lateral force, F_{LAT}, at the flight deck in multidirectional waves, as the first step in evaluating the likelihood of observing higher probe loads than for unidirectional waves.

The *SHIPMO*/*DYNAFACE* unidirectional correlation analysis described in the previous section suggests that if higher F_{LAT} values are calculated for multidirectional waves, then it is likely that $F_{R(MP)}$ is also higher. Higher motions *per se* in multidirectional waves may indicate higher vertical loads, but this is not certain.

To investigate the effect of multidirectional seas, a parametric study was performed for ship speeds from 5 to 25 knots, in 5 knot increments, and for ship headings from 0 to 360 degrees, in 15 degree increments. Three wave types were considered:

1. unidirectional, H_{SIG} = 5.0 m, T_P = 12.4 sec (median for unidirectional study);
2. multidirectional, with thirteen cases having wind-generated waves (H_{SIG} = 4.0 m, T_P = 9.5 s) from 0 degrees and swell (H_{SIG} = 3.0 m, T_P = 12.5 s) from 0 through 180 degrees in 15 degree increments; and
3. multidirectional, with a single case having wind-generated waves (H_{SIG} = 4.0 m, T_P = 10.8 s) from 0 degrees and swell (H_{SIG} = 3.0 m, T_P = 14.0 s) from 030 degrees.

In all cases, multidirectional F_{LAT} values were lower than the unidirectional case. Thus, the worst-case design scenario for main probe radial force is unidirectional waves.

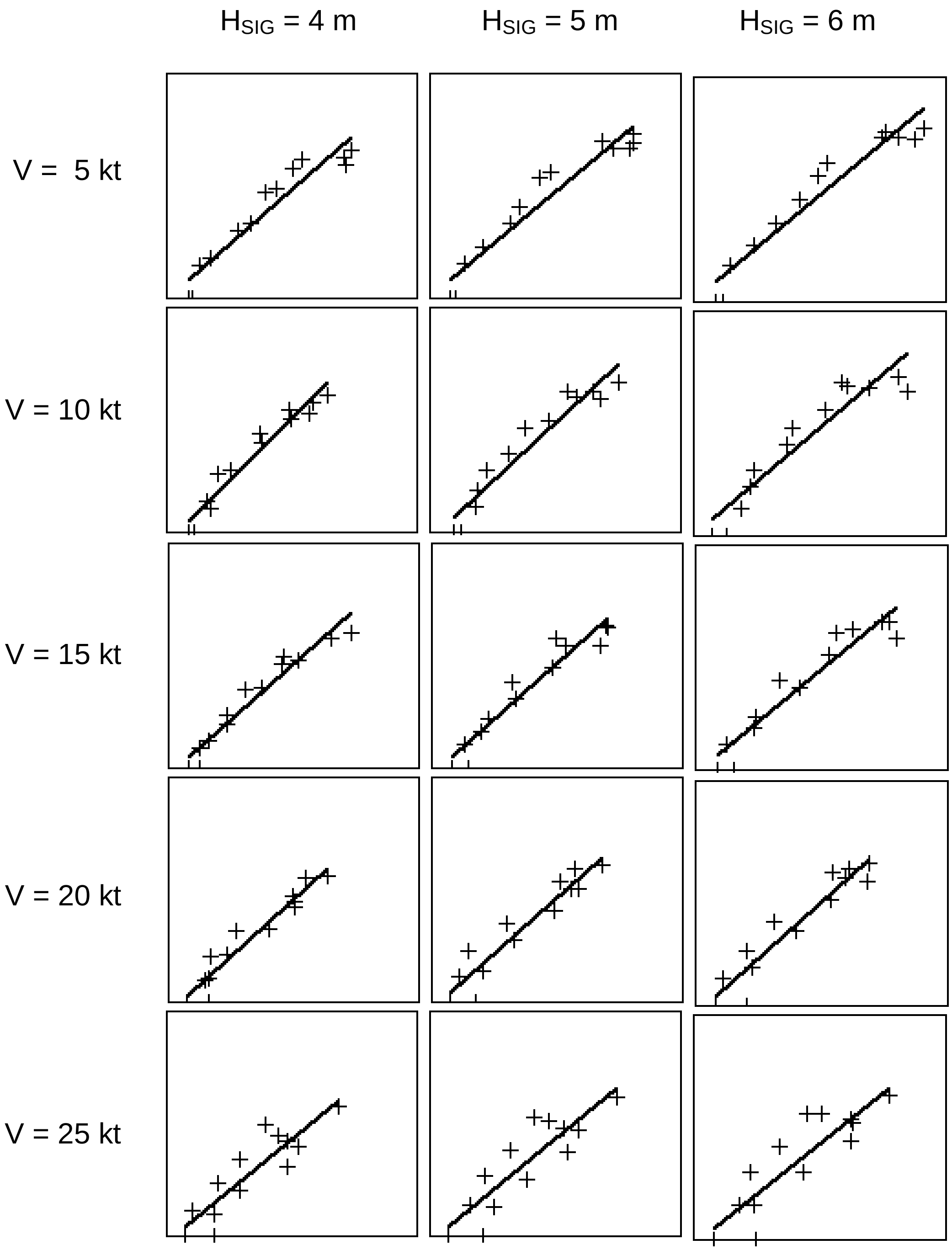

FIGURE 6 Dynaface $F_{R(MP)}$ vs. SHIPMO F_{LAT}* data and linear regressions for ship headings from 0 to 180 degrees.

Multidirectional Flight Deck Vertical Acceleration, FDVA, is closely dependent on the wave frequencies used to describe the seaway. Excluding relative winds outside of the Sea King operational envelope, there are many reasonable combinations of ship speed and heading that produce higher FDVA values than for unidirectional waves. For ‘most probable’ multidirectional waves, FDVA’s for ship speeds above 10 knots are from 105 to 110 percent of the unidirectional values. For other, highly probable wave frequencies, the multidirectional FDVA’s are lower than the unidirectional case. Thus, it is not obvious which design scenario is appropriate for vertical probe loads.

CONCLUSIONS

1. The high correlation between *DYNAFACE* main probe radial force, $F_{R(MP)}$, and *SHIPMO* generalized lateral force estimator, F_{LAT}*, for unidirectional waves suggests that useful and direct inferences can be made on the effects of multidirectional waves on $F_{R(MP)}$ by using SHIPMO to examine the behaviour of the F_{LAT}* in these seas. In other words, if F_{LAT}* is higher in multidirectional waves, then it is almost certain that $F_{R(MP)}$ will also be higher.

2. Correlation between the vertical force estimator and probe vertical forces was not supported largely due to intermittent probe contact and highly nonlinear features of the dynamic system, particularly in the vertical direction.

3. The high correlation between *SHIPSIM* time-domain and *SHIPMO* frequency-domain ship motions for unidirectional waves suggests that useful but indirect inferences can be made on the effects of multidirectional waves on probe forces, by using *SHIPMO* to examine ship motions in multidirectional waves. In other words, if ship motions are higher in multidirectional waves, then probe forces may also be higher, but this is not certain. A nonlinear transient dynamic simulation using *DYNAFACE* is required to determine the detailed effects of multidirectional ship motions on the probe forces.

4. A preliminary investigation of the potential effects of multidirectional waves suggests that multidirectional waves do not result in flight deck motion conditions that are significantly more severe than corresponding unidirectional sea cases when considering the horizontal (radial) component of probe loading. In the case of vertical loading, some operating conditions were found where vertical probe loading may be higher than in corresponding unidirectional seas. Again the effects of deck motions on securing forces should ideally be confirmed using the *DYNAFACE* helicopter response simulation when time series ship motion data, corresponding to multidirectional seas, is available.

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