CHAPTER 7 SUMMARY AND CONCLUSIONS AND FUTURE WORK

Towing-tank experiments are performed for a surface combatant advancing in calm water as it undergoes static and dynamic planar motion mechanism (PMM) maneuvers. The geometry is DTMB model 5512, which is a 1/46.6 scale geosym of DTMB model 5415 (DDG-51), with L = 3.048 m. The experiments are performed in a 3.048 × 3.048 × 100 m towing tank. The measurement system is a custom-designed towing-tank maneuvering test flow-map measurement system, which features a PMM for captive model testing with an integrated stereoscopic particle image velocimetry (SPIV), a Krypton contactless motion tracker, and a 6-component load cell. The data includes static drift and dynamic maneuvering forces and moments, motions, and phase-averaged local flow-fields for dynamic maneuvers. Quality of the data is assessed by evaluating the statistical convergence and by estimating the measurement uncertainty. The forces/moment measurements and UA are conducted in collaboration with Force Technology (FORCE)/Danish Maritime Institute (DMI), Istituto Nazionale per Studi ed Esperienze di Architettura Navale (INSEAN), and the 24th-25th ITTC Maneuvering Committee. The collaboration includes overlapping tests using the same model geometry with different scales, for validation of procedures and identification of facility biases and scale effects.

Statistical convergence of data is evaluated by monitoring the convergence of confidence interval of mean value while increasing the number of data, N. Data are first tested for randomness, stationarity, and normality. For the tests, deterministic components of the data are removed from the data time histories, which are the time-mean values for static drift data and the harmonic oscillations with the PMM frequency as the fundamental harmonic for the dynamic tests. Test for randomness is by inspecting the frequency spectrum of the data via Fast Fourier Transform (FFT). Forces and moment data are random fluctuations, but narrow-banded with peak frequencies near at 3, 4, 5, 7, and 10 Hz, for both static drift and dynamic tests. The peak frequencies are from the natural frequencies and the mechanical vibrations of the loadcell and the PMM and the deriving carriages, or in combination. Motions (heave and pitch) data are superposition of random fluctuations on a transient oscillation. The transient oscillation is of typical frequency f_{tr} $\approx$ 0.255 Hz due to start-up transient, which decays with time. Test for stationarity is by using two non-parametric (i.e., distribution-free) statistical procedures, 'Run test' and 'Trend test'. Forces and moment and motions data for the most of cases of static drift and dynamic tests are stationary from the tests at a 5% level of significance (i.e., with a 95% probability). Normality of data is examined by using the Chi-square (X^2) goodness-of-fit test. Test results indicate that all data variables are not normal as those fail the test with typical X^2 values, 61, 72, 120, 122, 146 for F_x, F_y, M_z, z, θ, respectively, at a 5% significance level (the acceptance region is $X^2 \leq 51$ for a degree of freedom $n = 36$). Monitoring the statistical convergence of data is by defining a statistical convergence error, $E_{sc} = c \cdot s / N^{1/2}$, where c is a constant, s is the standard deviation of data, and N is the number of data. For a 95% confidence level, the constant $c = 2.0$ by using the Student-t statistic when data is normal, whereas $c = 4.5$ by using the Tchebycheff inequality when data is not normal with an unknown distribution. For static drift data, $E_{sc} \leq 3\%$ for all the forces and moment and motions data with $N = 2{,}000$, a typical data number, and with $c = 4.5$ by using the Tchebycheff inequality as those data variables are not normal from the normality test. Nonetheless, for forces and moment, the apparent shapes of the probability density function (pdf) are close to a normal pdf, suggesting that those variables data may be close to normal in a practical sense. If normality is assumed for those data, then $E_{sc} \leq 1\%$ with $c = 2.0$ from the Student-t statistic. Evaluations of statistical convergence for dynamic tests data are still on going. On the other hand, for the SPIV flow field data, phase-averaged velocity data are normal (as well in a practical sense). Then, the phase-averaged normal Reynolds stresses (corresponding to the variance of velocity in terms of statistics) follow the χ^2-distribution. Accordingly, the statistical convergence error E is defined for phase-average velocity by using the Student-t statistic and E_U for Reynolds stress by using the χ^2-statistic, respectively, similarly as E_{sc} for forces and moment and motions data. Even with a relatively smaller number of data for phase-averaging, $N \sim 200$, the statistical convergence error values are fairly small, usually $E \leq 1\%$ of U_C for velocity data and $E_U \leq 10\%$ of the range value of turbulent kinetic energy, $[k]$, for Reynolds stress data.

UA for forces and moment and motions data follows the ASME (1998) and AIAA (1999) Standard and guidelines; errors/uncertainties definitions, systematic/random categorization, and large sample size/normal distribution 95% level of confidence assumptions. The procedures are based on estimates of systematic bias and random precision limits, and their root-sum-square combination to ascertain total uncertainty, U_r. For static drift test, U_r is typically about 2 ~ 4% for forces and moment and about 1 ~ 2% for heave and 20 ~ 30% for pitch motions, respectively. For both forces/moment and motions data, bias limit is predominant over the precision limit, contributing more than 90% to U_r for the most of cases. For dynamic tests, U_r is about 1 ~ 10% for forces and moment, usually larger for X force, and about 2 ~ 6% for heave and 10 ~ 40% for pitch motions. Precision limit is dominant for X force and heave motion, while bias limit is dominant for Y and N and pitch motion, respectively contributing more than 70% to U_r in most of cases. For forces and moment data, compared with two different facilities (FORCE and INSEAN) using different scales (model length L = 4 m and 5.7 m, respectively), the overall U_r values are almost independent of L for static drift test, whereas decreasing with L for dynamic tests. The U_r values as well show a trend with Fr, usually decreasing with Fr. In addition to the aforementioned UA procedures, two conceptual biases, data asymmetry bias B_{asym} and facility bias B_{FB}, are defined and evaluated. B_{asym} is to account for data asymmetry that exceeds U_r estimations. B_{asym} is typically large for X force and heave and pitch motions, in general about 7%, 20%, 40%, respectively. B_{asym} for X is negligible for FORCE data and about 8% for INSEAN data. However, B_{asym} for Y and N are typically small or negligible for all the facilities data. B_{FB} is to account for the use of different test facilities and different measurement equipments between the facilities. For static drift, IIHR and INSEAN data are certified within a certificate interval U_D about 3 ~ 11%, whereas INSEAN data include B_{FB} about 3 ~ 4%. For dynamic test data, most of IIHR data are certified but with relatively large U_D about 3 ~ 30%, whereas FORCE and INSEAN data for several cases are uncertified with B_{FB} about 2 ~ 7%.

On the other hand, the UA for phase-average SPIV flow field data follows the ASME PTC 19.1-2005 Standard (ASME 2005) that is a revision of the ASME (1998) Standard. The procedures are estimations of the systematic and random standard uncertainties at the standard deviation level, and their root-mean-square combination to ascertain the combined standard uncertainty and subsequently the expanded uncertainty $U_{R,95}$. The systematic standard uncertainty is estimated by calibrating the SPIV to the 'open-water' test results. The open-water test is to measure the free-stream flow field without the model installed, while the SPIV is towed straight (for uniform flow test) or in pure yaw motion (for open water pure yaw test). The random standard uncertainty is estimated end-to-end by repeating the test (the actual test with model installed). From the UA, the absolute uncertainty ($U_{R,95}$) of the SPIV measurement is about 2 ~ 3% of U_C for U (out of plane component), and about 1 ~ 2% of U_C for V and W (in-plane components), respectively. Whereas the relative uncertainty ($U_{R,95}/R$) is about 3 ~ 4%, 12 ~ 29%, and 26 ~ 32% for U, V, and W, respectively. For Reynolds stresses, the square root of absolute uncertainties, $U_{R95}{}^{1/2}$, are about 2 ~ 3% of U_C for the normal (uu, vv, ww) stresses and about 1 ~ 2% of U_C for the shear (uv, uw, vw) stresses, respectively. The relative uncertainties are about 25 ~ 50% inside the boundary layer region, whereas typically large > 100% at the outer region due to the small magnitude of the R. The present UA results are generally similar with Gui et al. (2001a) for steady test and relatively larger than Longo et al. (2007) for unsteady tests.

Forces and moment data trends with the drift angle β for static drift test are as per predicted by the Abkowitz (1966) mathematic model; quadratic for X and cubic for Y and

N. Time histories of forces and moment data for dynamic pure sway and pure yaw tests are typically the 2nd-order dominant (about 70% of amplitude) oscillations for *X* with superposed on mean values, whereas the 1st-order dominant (90 ~ 99% of amplitude) oscillations for *Y* and *N* with phase shifted with respect to the forced motions. For yaw and drift tests, all of the *X*, *Y* and *N* time histories are the 1st-order dominant oscillations with superposed on non-zero mean values. Hydrodynamic derivatives are evaluated from the forces and moment data by using two different methods; '*Multiple-Run* (MR)' method and '*Single-Run* (SR)' method. The MR method is by curve fitting the forces and moment data obtained from a series of tests over a range of PMM parameter of interest. In contrast, the SR method is using the data from a single realization of dynamic test. Linear derivative values by using the MR and the SR methods are similar each other, with a ratio value, SR/MR = 0.5 ~ 1.5 in general. The ratio value approaches closer to a unity as the PMM motion becomes larger. In contrast, non-linear hydrodynamic derivatives values using the SR method are considerably different from those using the MR method, with the ratio SR/MR = $10^{-1} \sim 10^{2}$. The ratio value is particularly larger/smaller when the PMM motion is small. Validities of the hydrodynamic derivatives are examined by evaluating the error, E_R (%), in reconstructing the forces and moment time history by substituting the derivative values back into the Abkowitz (1964) mathematic model. For MR method, the error value is in general E_R (%) < 20 over the whole range of the tested PMM parameters. However, for SR method, the error value is typically huge, E_R (%) < 600, when the PMM motion is small and relatively large, E_R (%) < 50, as the PMM motion becomes larger. Consequently, the MR method is more rigorous than the SR method, and the SR method is only suggested when the PMM motion is large enough. From the speed variation test, the hydrodynamic derivative values exhibit trends with *Fr*. Typically the linear derivatives are nearly independent of *Fr*, whereas the non-linear derivatives exhibit rather strong dependency on *Fr*. Hydrodynamic derivative values as well exhibit a trend with the model size (scale). When compared with the two different facilities

(FORCE and INSEAN) data, generally the sway derivatives are nearly independent of model size whereas the yaw derivatives (particularly yaw acceleration derivatives) exhibit considerable dependency on the model size. However, for the non-linear derivatives, general conclusions are precluded as the data exhibit large scatters in the comparisons.

Motions data trends with drift angle β for static drift test and the trends of the time histories for dynamic tests resemble those of the forces and moment data; the overall trends of heave and pitch motions are similar to X (quadratic with β and the 2nd-order dominant oscillations) and those of roll motion is similar to Y and N (cubic with β and the 1st-order dominant oscillations). Between the motions, heave and roll motions are nearly independent, whereas pitch and roll motions are rather strongly coupled each other. Motions data as well exhibit correlations with forces and moment. Four different mount conditions are compared to see the effect of motions on the forces and moment; FX_0 (fixed at evenkeel), $FX_{\sigma\tau}$ (fixed sunk and trim), $FR_{z\theta}$ (free to heave and pitch), and $FR_{z\theta\phi}$ (free to heave, pitch, and roll). Between FX_0 and $FX_{\sigma\tau}$, forces and moment usually increase up to about 10% ($\xi_{\sigma\tau} = 1 \sim 1.1$) due to the effect of sinkage and trim. Between FX_0 and the $FR_{z\theta}$, the increase in forces and moment is typically 10% ~ 30% ($\xi_{z\theta} = 1.1 \sim 1.3$) due to the effect of heave and pitch motions. Between $FR_{z\theta}$ and $FR_{z\theta\phi}$, forces and moment are similar each other ($\zeta_\phi \approx 1$) indicating the effect of roll motion on the forces and moment is small or negligible. Despite the differences in forces and moment, the linear hydrodynamic derivatives from the FX_0 and $FX_{\sigma\tau}$ conditions are usually similar with those of the $FR_{z\theta}$ condition ($\zeta_{0,\sigma\tau} = 0.9 \sim 1.1$), whereas the non-linear derivatives for the former conditions are smaller than for the later condition ($\zeta_{0,\sigma\tau} = 0.2 \sim 1.0$). Between the $FR_{z\theta}$ and $FR_{z\theta\phi}$ conditions, in general linear derivatives are similar ($\zeta_\phi = 0.9 \sim 1.1$) between the mount conditions, whereas the non-linear derivatives values show rather large differences ($\zeta_\phi = -0.4 \sim 3.6$). Consequently, the effects of the motions on hydrodynamic derivatives are small for linear derivatives, however may large for non-linear derivatives.

Phase-averaged flow field measurement results indicate maneuvering-induced vortices and their interactions with the turbulent boundary layers. The data comprises axial velocity contours, cross-flow velocity vectors and streamlines, turbulent kinetic energy and Reynolds stresses contours, and axial vorticity contours, respectively for pure sway and pure yaw tests. The vortical flow structure includes sonar dome vortex, bilge keel vortices, fore and aft body keel vortices, and free surface vortices, which can be more clearly identified from the complementary CFD simulation results. The average axial velocity within the boundary layers and inside vortices is about 0.8 U_C, nearly constant along the model length. Local minimum value is 0.65 ~ 0.4 U_C, larger at the bow and decreases monotonically along the model length. Turbulent kinetic energy $k^{1/2}$ is about 5% of U_C for pure sway and about 7% of U_C for pure yaw, respectively, in average. The local maximum $k^{1/2}$ value is about 11% of U_C for both tests. Reynolds stress is anisotropic, where *uu* and *uv* are the largest normal and shear stresses, respectively. Sonar dome vortex is the strongest one, and bilge keel and aft body keel vortices are the second and third ones. The maximum axial vorticity value of the sonar dome vortex is similar for both pure sway and pure yaw tests, whereas the bilge keel and the aft body keel vortices are about 2 ~ 3 times stronger for pure sway.

Limitations of the present work include: 1) the model is un-appended except for portside and starboard bilge keels, and not equipped with shafts, struts, propellers, or rudders. Accordingly the hydrodynamic derivatives values evaluated from the forces and moment data and the vortical flow field data (particularly at the stern where the rudders and propellers are working) may differ from those from a fully appended condition, 2) the model is constrained in heave, pitch, and roll motions for the SPIV measurements, thus the flow field data may differ from the free motions condition, 3) the number of longitudinal locations for SPIV measurements is limited (six *x*-locations) and the flow field data in the direction are sparse and not sufficient to be connected to show the fully three dimensional flow structures. The near future works planed, in conjunction with and to resolve those limitations, include a PMM test in headwind and/or wave for a fully appended (except for propellers) model (ONR Tumblehome), a fully three-dimensional PIV (e.g., a tomographic PIV) flow field measurement for the DTMB 5512 model in a static drift maneuver with a large drift angle $\beta = 20°$, and a fully 3-D (or Stereoscopic) PIV flow field measurement for a free running model.