Image Cover Sheet

CLASSIFICATION	SYSTEM NUMBER 501058
UNCLASSIFIED	

TITLE

REDUCTION OF WHIPPING STRESSES IN WARSHIPS: AN EXPLORATORY MODEL TEST

System Number:

Patron Number:

Requester:

Notes:

DSIS Use only:

Deliver to:

REDUCTION OF WHIPPING STRESSES IN WARSHIPS: AN EXPLORATORY MODEL TEST

Samon Ando
Defence Research Establishment Atlantic, P.O. Box 1012, Dartmouth, NS, B2Y 3Z7, Canada

Greg Hermanski
Formerly of Institute for Marine Dynamics, P.O. Box 12093, Postal Station A, St. John's, NF, A1T 3T5, Canada. *Present Address*: Advanced Marine Enterprises, 1725 Jefferson Davis Highway, Suite 1300, Arlington, VA 22202, U.S.A.

ABSTRACT

An exploratory towing-tank test with a segmented structural model of the Halifax-class frigate was conducted to investigate the concept of reducing the slam-induced hydroelastic shocks by an elastomer bonded to the exterior of the ship's bottom forward. We affixed a 6.35-mm thick sheet of elastomer (closed cellular rubber) to the forward 1/4 ship length of hull bottom from the keel up to 33 percent of draft. We found a 15-percent reduction, in terms of zero-crossing peak-to-trough values, in the magnitude of the most severe slam-induced vertical bending moment amidships at model speed corresponding to 20 knots full scale in sea state 7. Reductions were also realized for bow acceleration, shear forces, and pitch angles. The results showed that the severer the sea state, the greater the cushioning effect. Further model tests are needed to categorically establish the relative influence of three types of impact on whipping stresses for Halifax-class frigates: bow-bottom slamming, bow-flare impact, and green seas on the fore deck.

1. INTRODUCTION

In rough seas, ships are forced to limit their speeds and/or change their courses to avoid excessive pitch and heave motions, for large motions invariably lead to slamming and/or the shipping of green seas on the foredeck. The slam-induced hydroelastic shocks and the ensuing whipping response can cause damage to the hull structure either through exceeding the ultimate stress limits when superimposed on the slow-varying wave-induced stresses or through accelerating fatigue cycles. Shipping green water plays havoc with equipment and weaponry exposed on deck. Although warships spend a smaller percentage of time at sea cruising at their full speed than do merchant ships, when the need does arise for them to go at full power, they are expected to make the best possible speed regardless of the prevailing sea conditions. Thus, one of the on-going research projects at Defence Research Establishment Atlantic (DREA) seeks to develop practical, low-cost, and simple-design methods for mitigating slam-generated hydroelastic shocks to help extend the safe and effective operational envelope of Canadian naval vessels. The concept of using elastomer as a means of cushioning ships' bottom slam was developed by DREA (Ando 1989) and has been tried on a SWATH ship model (Datta & Ando 1992). In this study, we applied the concept to a conventional frigate and conducted an exploratory model test to determine if and to what extent the effect of slam-generated hydroelastic shocks on a monohull ship could be mitigated with elastomer bonded to the exterior of the bow bottom. Exploratory experiments such as this are necessary because the complex nature of interaction between rough seas and ship precludes development of a reliable mathematical model in the foreseeable future. For a navy, the concept offers an added benefit to warships' overall effectiveness, for in addition to possible reduction of slamming impact, elastomer attached to the exterior of hull bottom can act as an impedance discontinuity and will help reduce radiation of hull-borne noise.

The 6-m structural model of the Halifax-class frigates used in this study is divided into six segments and fitted with a continuous flexure backbone. The model was run at speeds corresponding to 15 knots and 20 knots in full scale in irregular head waves of sea states 5, 6, and 7. Two sets of identical runs were repeated for each combination of forward speed and sea state: one with the elastomer (a 6.35-mm thick sheet of closed-cell rubber) bonded to the forward 1/4 ship length of the hull bottom from the keel up to 33 percent of draft, and the other without the elastomer. The two sets of measurements were then analyzed and compared to determine the differences.

We found a 15-percent reduction, in terms of zero-crossing peak-to-trough values, in the magnitude of the most severe slam-induced vertical bending moment amidships at model speed corresponding to 20 knots full scale in sea state 7. Reductions were also realized for bow acceleration, shear forces, and pitch angles. The results showed that the severer the sea state, the greater the cushioning effect. Time series data and recorded videos of the hull-wave interaction suggested that, for the Halifax-class hull, the bow-flare impact may contribute significantly to transient loads on hull structure, most notably to the two-node vibratory bending moment amidships, even though the Halifax-class hull's bow flare is relatively modest. Further model tests are needed to categorically establish the relative influence of three types of hydroelastic shocks for the Halifax-class ships: bow-bottom slamming, bow-flare impact, and green seas on the foredeck.

2. MODEL EXPERIMENT

Figure 1 shows the model (NRC/IMD model M460) of the Halifax-class frigate. The 4735.4-tonne frigate measures 134.7 m LOA, 124.5 m LBP, 14.8 m beam, and 4.63 m draft. The model was built to 1/20 scale out of fiberglass, and segmented at stations 2.5, 5, 7.5, 10, and 13.7. (The aftmost segment is larger than the rest in order to accommodate propulsion equipment.) The backbone comprises four continuous stiffeners of carbon fiber composite material. It is centered transversely in the model and the vertical height of its centerline coincides with the model's vertical neutral axis. Primary attention was given to modeling the vertical bending stiffness, with only secondary importance given to vertical shear stiffness and lateral bending and shear stiffnesses. (No effort was made to simulate the torsional behavior correctly.)

The self-propelled model was fitted with twin-screws, shafts and shaft supports, a single rudder, bilge keels, and centerline sonar dome. Using plexiglass, simplified superstructure and deck, including a forward deck breakwater, were built so that the presence of green water on the deck could be dynamically modeled. Bilge keels, deck, and superstructure were cut at each segment joint. The desired and actual values of pitch radii of gyration are 0.25 LBP and 0.302 LBP, respectively. The model's natural period of pitch was measured to be 1.10 s.

The elastomer used in this test was a 6.45 mm (1/4 inch) thick (12.7 cm thick in full scale) sheet of closed-cell Neoprene (Rubatex™ stock number G-231-N). Specifications of its physical properties include: compression deflection (or the weight required to compress a 2.86-cm diameter disc by 25 percent), 0.14 to 0.35 $\mathrm{kg/cm^2}$; average density, 160 to 320 $\mathrm{kg/cm^3}$; and the maximum water absorption by weight, 5 percent. We chose G-231-N because it offers the largest deflection-force ratio of all the Rubatex™ stock. As shown in Fig. 1(c), we covered the exterior of the bottom of the forwardmost two segments, or 1/4 model length, from the keel up to the 1.5-m (full scale) waterline except for the sonar dome with sheets of elastomer. Total weight of the elastomer was 0.8 kg (model scale), or 0.13 percent of the designed displacement.

Carriage speed, wave elevation, pitch angle, heave acceleration, and relative bow motion (RBM), were sampled at 20 Hz (filter frequency 10 Hz), and segment accelerations, bending moments, and shears at 200 Hz (filter frequency 100 Hz). The backbone was instrumented at each of the five segment joints with strain gauge bridges to measure vertical bending, vertical shear, horizontal bending, horizontal shear, and torsion. A fault in the vertical bending moment gauges located at the joint of segments 2 and 3 required installation of new gauges, which were placed 25 mm forward of the joint. RBM was measured by a resistance gauge attached to the hull at station 2. Wave elevation was measured with a sonic probe mounted at the forward end of the carriage approximately 6.43 m ahead of the model midships.

The test was conducted in the Institute for Marine Dynamic (IMD)'s towing tank in St. John's, Nfld. The tank is 200 m long, 12 m wide with a water depth of 7 m. The double-flat wave maker can generate regular waves up to 1 m in height and irregular waves of about 0.6 m significant wave height. The Bretschneider spectrum,

$$S(f) = (A/f^5)\exp\left(-B/f^4\right),$$

was used to simulate all irregular waves, where S is the spectral density ($\mathrm{m^2/Hz}$); f the wave frequency (Hz); $A = (5/16)H_s^2 f_p^4$; $B = (5/4)f_p^4$; H_s the significant wave height (m); and f_p the modal frequency (Hz). The full-scale values of (H_S, f_p) used for this test were (3.26 m, 0.103 Hz), (5.0 m, 0.0806 Hz), and (7.5 m, 0.0667 Hz) for sea states 5, 6, and 7, respectively. The tank's wave maker can exactly repeat a particular time history of wave elevation for a given sea state. The model was run at $Fn = 0.221$ and 0.294 (Froude number $Fn = U/\sqrt{gL}$, U is the model speed, g the acceleration of gravity, and L the model length between perpendiculars), or 15 and 20 knots in full scale. Runs required at least 30 minutes full scale in a stationary sea state to ensure occurrence of sufficiently severe slamming for the given sea state and model speed, as well as to obtain reliable statistics. To achieve this, a time-domain realization of the required duration of a particular wave spectrum was broken up into a number of shorter segments: 11 segments for $Fn = 0.294$ and eight segments for $Fn = 0.220$. For a given sea state, the same pre-computed time-series drive signals were fed to the wave maker for the two sets of runs: one with elastomer attached to the bow bottom, and the other without elastomer. Thus, the model was subjected to identical wave elevations in the time domain in both sets, the only difference in the run conditions being the elastomer attached to the bow bottom in the first set of runs. After the test, data from all the run segments were spliced together in proper sequence to achieve a long run record for analysis. In this paper, only the results from sea state 7 are shown, because both magnitudes and frequencies of incident of slammings were much lower at lower sea states.

3. RESULTS AND DISCUSSION

Time histories shown in Fig. 2 are a sample of baseline data—that is, measurements obtained without elastomer—in sea state 7. These particular plots were obtained from run segment 4 of the 11 segments for $Fn = 0.294$. The time history of vertical bending moment (VBM) for this run segment highlights the frequently-observed phenomenon in this test: slams tend to occur in pairs. We believe that this has to do with the occurrence of wave groups in the simulated sea state. In this particular run, two large peaks were both preceded immediately by other ones. The two pairs of prominent peaks in the time history of midship VBM between $53.165\ \text{s} \leq t \leq 53.700\ \text{s}$ and $41.970\ \text{s} \leq t \leq 42.550\ \text{s}$ were respectively the largest and the second largest peak-to-trough midship VBM's for this speed and sea state. Recorded video shows that in both of these instances, the bow first lifts up completely free of water after meeting the first crest of a swell, and, on its descent, it dives into the face of the second crest and continues the descent until it is completely submerged and the foredeck awash with green water. As the wave crest travels aft, the bow lifts up, and as it does so, the foredeck scoops up some considerable amount of green water, which runs off prominently as the model pitches further upwards.

Also shown in Fig. 2 are expanded plots of a five-second period in which the largest midship VBM occurred, along with time histories of pitch, the vertical shear force (VSF) at station 5, relative bow motion (RBM), the relative bow velocity (RBV), and the bow vertical acceleration at station 2. RBV was obtained by numerically differentiating RBM. The sign definition for the variables in Fig. 2 are as follows: a vertical bending moment is positive in hogging; a vertical shear force is positive when it tends to shear off the aft part of the hull at a given station upwards and the forward part downwards; a pitch angle is positive when the bow is up; and a vertical acceleration is positive downwards. We can see that the first peak of the hydroelastic shock in the elastic backbone is registered just before the bow reaches the maximum of its pitch downward motion. Because the rise times of these impulsive forces are short compared with the natural pitch period of M460, pitch response in Fig. 2 resembles a typical low-pass filter. Small reversals of VBM in the plots indicate the whipping response of the hull girder. (The two-node vibration for M460 has a period of about 0.15 s, or in terms of frequency, 6.5 Hz.) Relatively small though they are, such cyclic loads do some fatigue damage, which may or may not be significant compared to the damage done by the slow-varying encounter-frequency cycle on which they are superimposed. Figure 2 shows that slow-varying midship VBM and pitch motions are almost in phase as they should be, and that VBM amidships and VSF at station 5 are also almost completely in synch.

In the time history of the bow vertical acceleration at station 2 in Fig. 2, upward impulsive forces are apparently applied at times t_a and t_b. At these instants, RBM is positive, meaning that the water surface is above the designed load waterline, even allowing for some amount of zero drift in the record. The pitch time history shows that t_a and t_b are just before maximum downward pitch, and RBV is 2 m/s and 3 m/s approximately, or 8.9 m/s and 13.4 m/s in full scale, at these instants.

Figure 3 is presented to exemplify the effect of the elastomer attached to the bow bottom on those responses shown in Fig. 2. The solid line shows the baseline responses without the elastomer from run segment 4 at Fn = 0.294 in sea state 7, and the short-dash line the responses from the corresponding run segment with the elastomer attached. With the elastomer attached, the zero-crossing peak-to-trough and trough-to-peak values of midship VBM in Fig. 3 are attenuated by the following amounts: AB 9.0 percent; BC 8.2 percent; CD 14.7 percent; and DE 13.0 percent.

Figure 3 shows clearly that the elastomer is mitigating slam-induced hydroelastic shocks. Referring to the RBM time history in Fig. 2, we see that the bow is already immersed at least up to the designed waterline when the large impulsive force is registered at the sensors. An ancillary effect of the elastomer evident in Fig. 3 is that, immediately after the impact, the periods of primary cycles are lengthened somewhat, whether it be pitch, VBM amidships, or the vertical acceleration at station 2. As well, Fig. 3 indicates that the model responses to large random waves may be nonlinear, but they are nevertheless repeatable, so long as the tank's wave maker can exactly reproduce a particular wave train.

From the videos, we found that during the two impacts occurring at about t_a and t_b in Fig. 2, the wave surface takes about 0.25 s and 0.37 s, respectively, to reach the weather deck (which is 0.64 m above the baseline) after it has touched the forefoot as the emerged bow descends. The average relative velocities between the bow and wave surface based on these time measurements are 2.65 m/s and 1.83 m/s, respectively, or in full scale 11.5 m/s and 8.2 m/s. The threshold velocity for bottom slamming proposed by Ochi (1967) is 12 ft/s (3.66 m/s) for a 520-ft (158.5-m) ship, which corresponds to 3.23 m/s when Froude-scaled to the Halifax-class ship. These average speeds far exceed the Ochi threshold velocity. Yet, because of the fine form (deadrise angles of the Halifax-class hull at stations 1, 2, 3, 4, and 5 are approximately 78, 60, 50, 38, and 33 deg, respectively), re-entry of the forefoot into the water is very smooth, and spray, a telltale sign of bottom slamming, is almost totally indiscernible in the videos until the up-swelling wave surface reaches the deck edge and is parted at the bow flare.

Figure 4 summarizes the main outcome from the tests at Fn = 0.220 and 0.294 in sea state 7. (Results from sea states 5 and 6 are much less severe and will not offer much insight.) The values in Fig. 4 are the magnitudes of the primary cycles in zero upcrossing segments (that is, peak-to-trough values, or the difference between the maximum positive value and the maximum negative value per zero-upcrossing segment). The bar charts show the averages of the largest n zero-crossing peak-to-trough values ($1 \leq n \leq 10$) of VBM amidships, VSF at station 5, bow vertical accelerations at station 2, and pitch angles measured from the runs with and without elastomer attached to the bow bottom. The dots (connected by lines) show the percent changes realized with the elastomer. As noted in Fig. 3, the largest midship VBM (n = 1) at Fn = 0.294 is 15 percent lower with elastomer attached, and, for the averages of the largest ten values, the reduction amounts to about 13 percent and above. The largest vertical shear force at station 5 (1/4 L abaft the FP) was reduced by about eight percent and the average of the largest ten values by 13 percent with the elastomer. The elastomer caused reduction in pitch angles as well, the reduction amounting to about six percent in terms of the average of the largest ten values. By comparing the results for Fn = 0.220 and 0.294 in the same sea state in Fig. 4, we can see the effects of reducing ship speed on the responses: both magnitudes and amounts of reduction of the measurements are smaller for the slower speed. Note that the reductions of the zero-crossing peak-to-trough values summarized in Fig. 4 were realized in spite of the fact that the elastic property of the elastomer we used might not be optimal; it is possible that a softer elastomer might have produced larger reductions, since the basic mechanism by which a cushioning material mitigates a shock is through being deformed in response to the forces induced (thus the cushioning material should deform significantly to be effective).

4. CONCLUSION

This test provides compelling evidence that elastomer can mitigate the effect of the slam-induced hydroelastic shocks on a ship hull. For a model of the Halifax-class frigate of the Canadian Navy, we found a 15-percent reduction in the magnitude of the largest midship vertical bending moment, in term of zero-crossing peak-to-trough values, at a model speed corresponding to 20 knots full scale in sea state 7. The severer the impact, the more effective the cushioning appeared to be, despite the fact that we had chosen an elastomer for this test primarily because of its ready availability, not for optimal elasticity. The evidence suggested that the bow-flare impact might also be a significant contributing factor in the impulsive loads experienced by the model.

ACKNOWLEDGEMENTS

This study was conducted with cooperation of the US navy, and we would like to thank our US colleague, Allen Engle of Naval Sea Systems Command (NAVSEA), US Navy, for allowing us to use data from a NAVSEA-funded model test at IMD as baseline data in our study. The first author would like to acknowledge the timely help he received from Mike Sullivan of IMD in connection with data analysis after the second author's departure from IMD.

REFERENCES

Ando, S., 1989. Cushioning of Slamming Impact by Elastomeric Layers, *Journal of Ship Research,* vol. 33, No. 3, pp. 169-175.

Datta, I. and S. Ando, 1992. Use of Elastomeric Layers for the Reduction of Slamming Impact on SWATH Vessel Wetdeck, 2nd Canadian Marine Dynamics Conference, Vancouver, B.C., August 1993.

Ochi, M.K., 1967., Ship Slamming—Hydrodynamic Impact Between Waves and Ship Bottom Forward, in Fluid-Solid Interaction, J.E. Greenspon (Ed.), pp. 223-240.

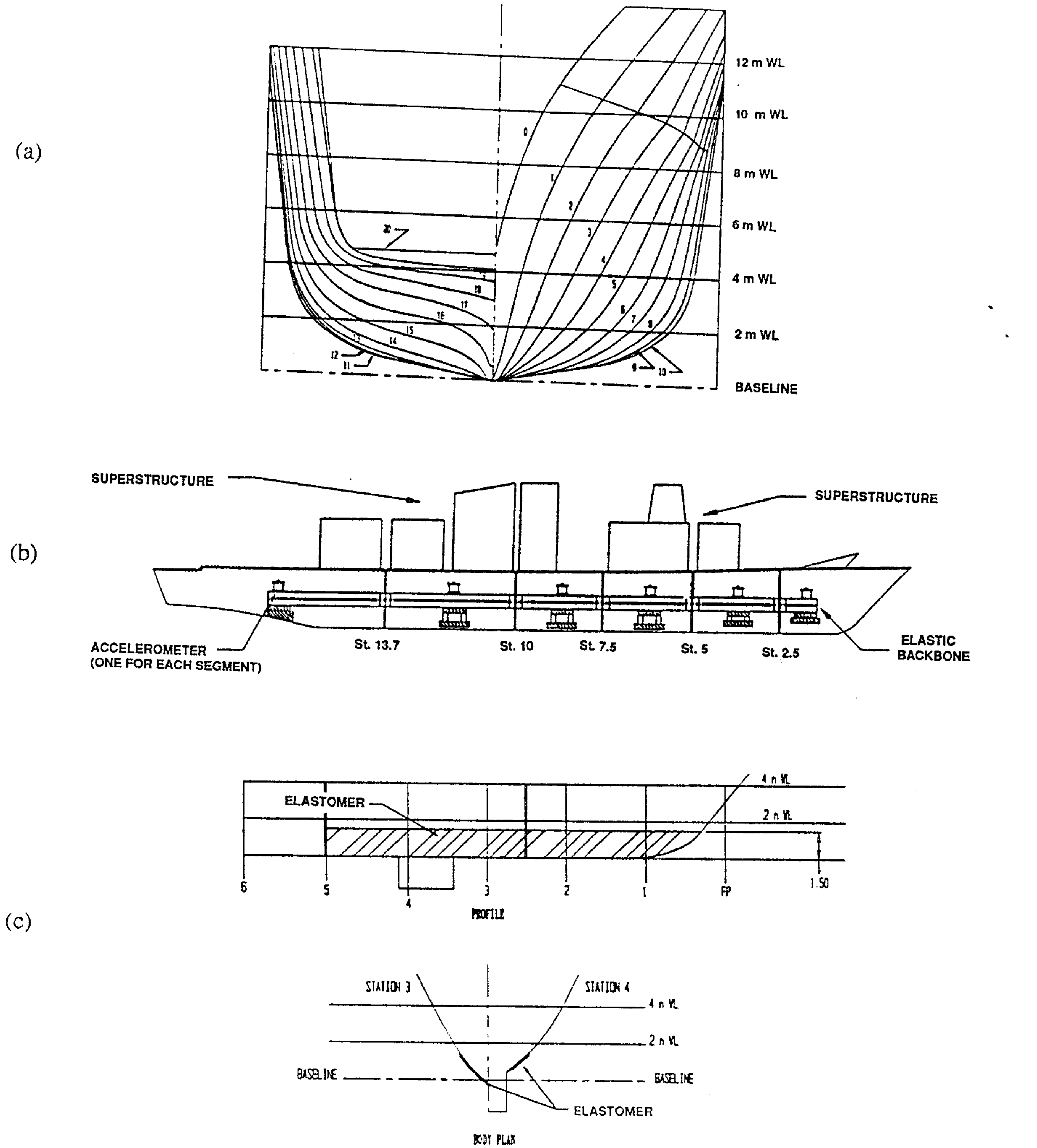

FIG. 1. Model 460. (a) body plan; (b) segment layout; and (c) position of elastomer sheets.

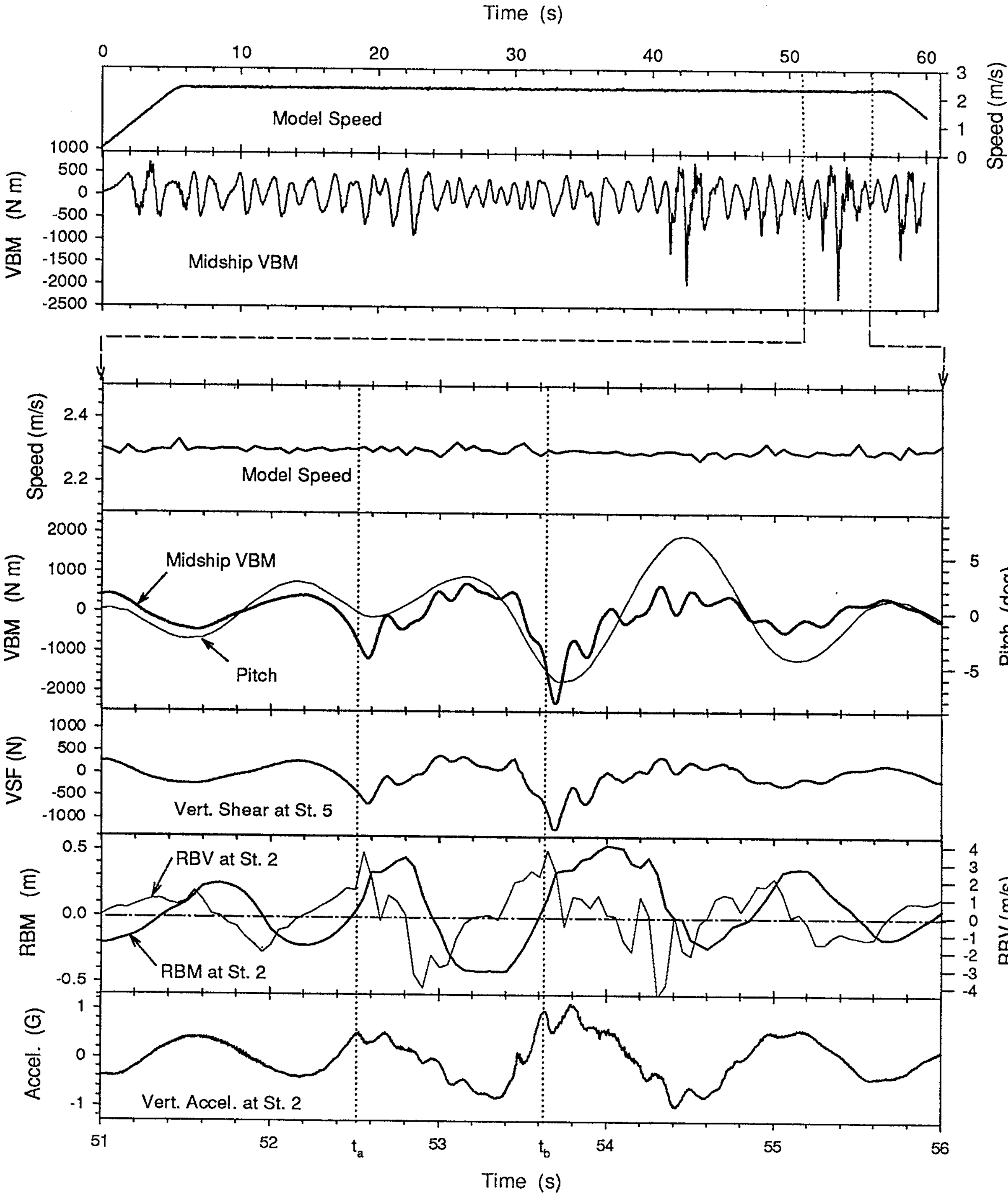

FIG. 2. Time histories of model speed, vertical bending moment (VBM) amidships, pitch angle, vertical shear force (VSF) at station 5, relative bow motion (RBM), relative bow velocity (RBV), and bow vertical acceleration at station 2 obtained from run segment 4 of 11 for sea state 7 at Fn = 0.294 without elastomer. (Units are in model scale.)

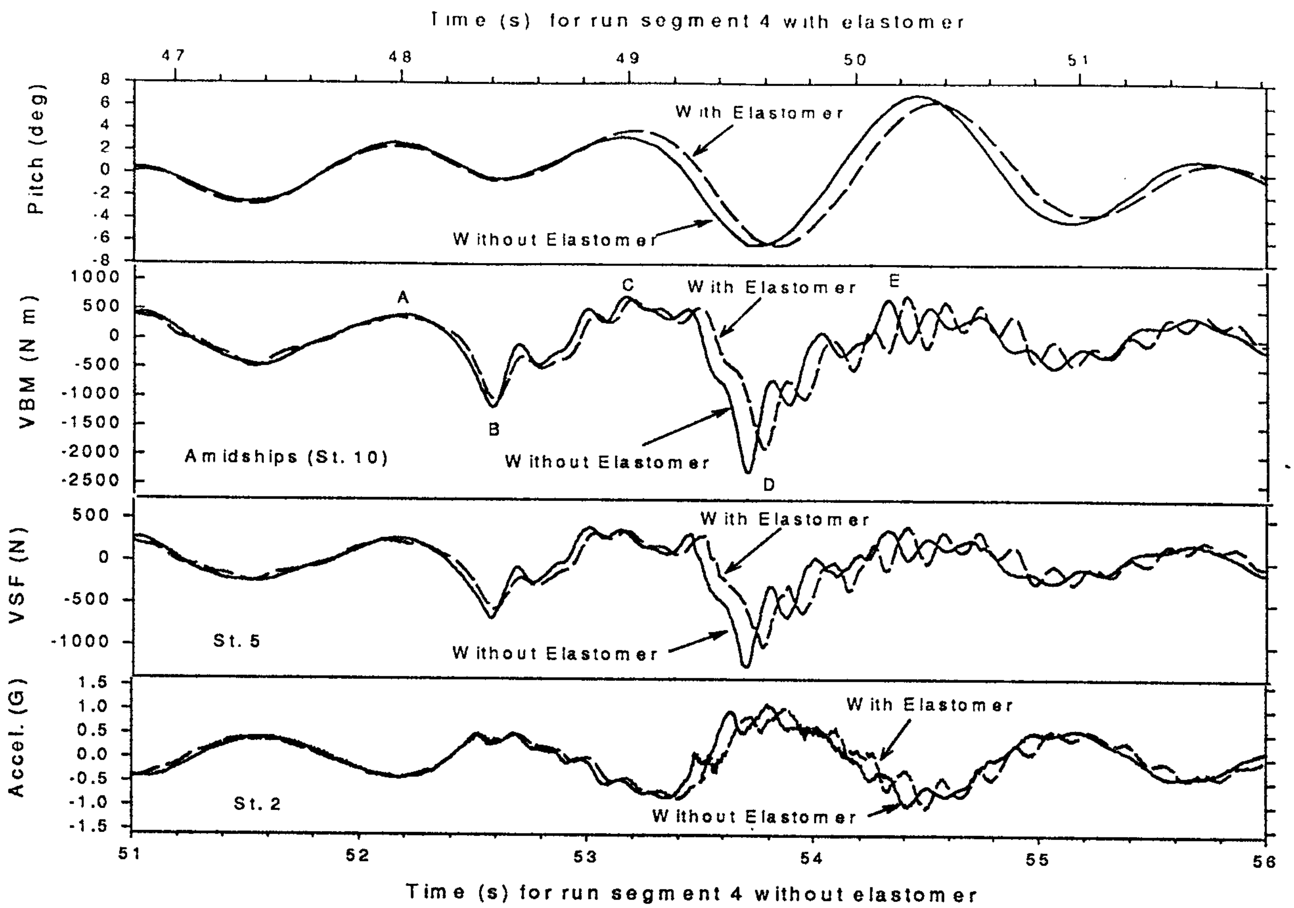

FIG. 3. Comparison of time histories of pitch angle, VBM amidships, VSF at station 5, and vertical acceleration at station 2 recorded in run segment 4 of 11 at $Fn = 0.294$ in sea state 7 without elastomer and in the same run segment with elastomer affixed to bow bottom (units in model scale).

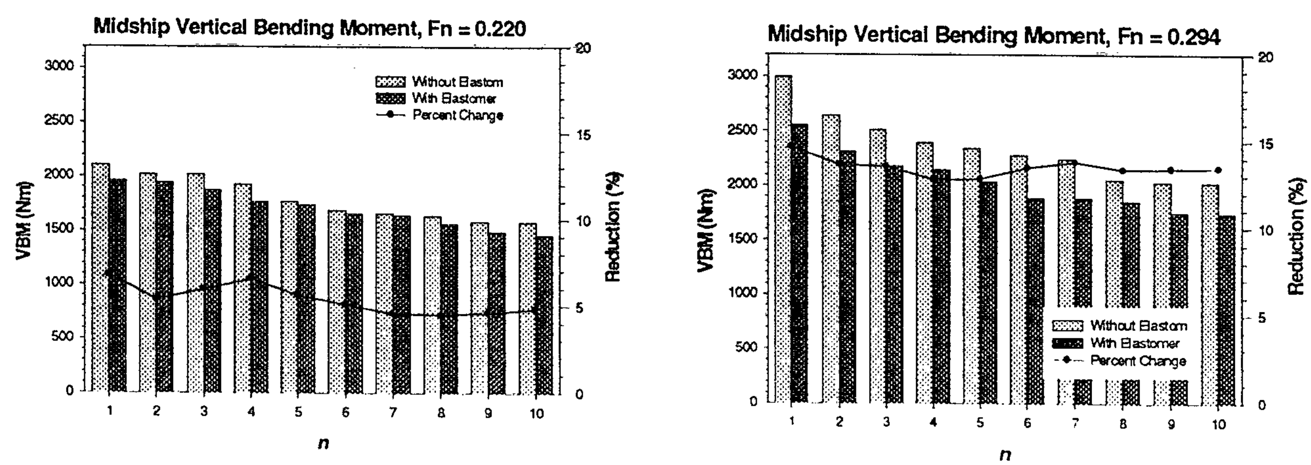

FIG. 4. Averages of n largest zero-crossing peak-to-trough values of responses (model scale) in irregular head waves (sea state 7) with and without elastomer attached to bow bottom. Fn = 0.220 and 0.294 correspond to 15 knots and 20 knots full scale, respectively.

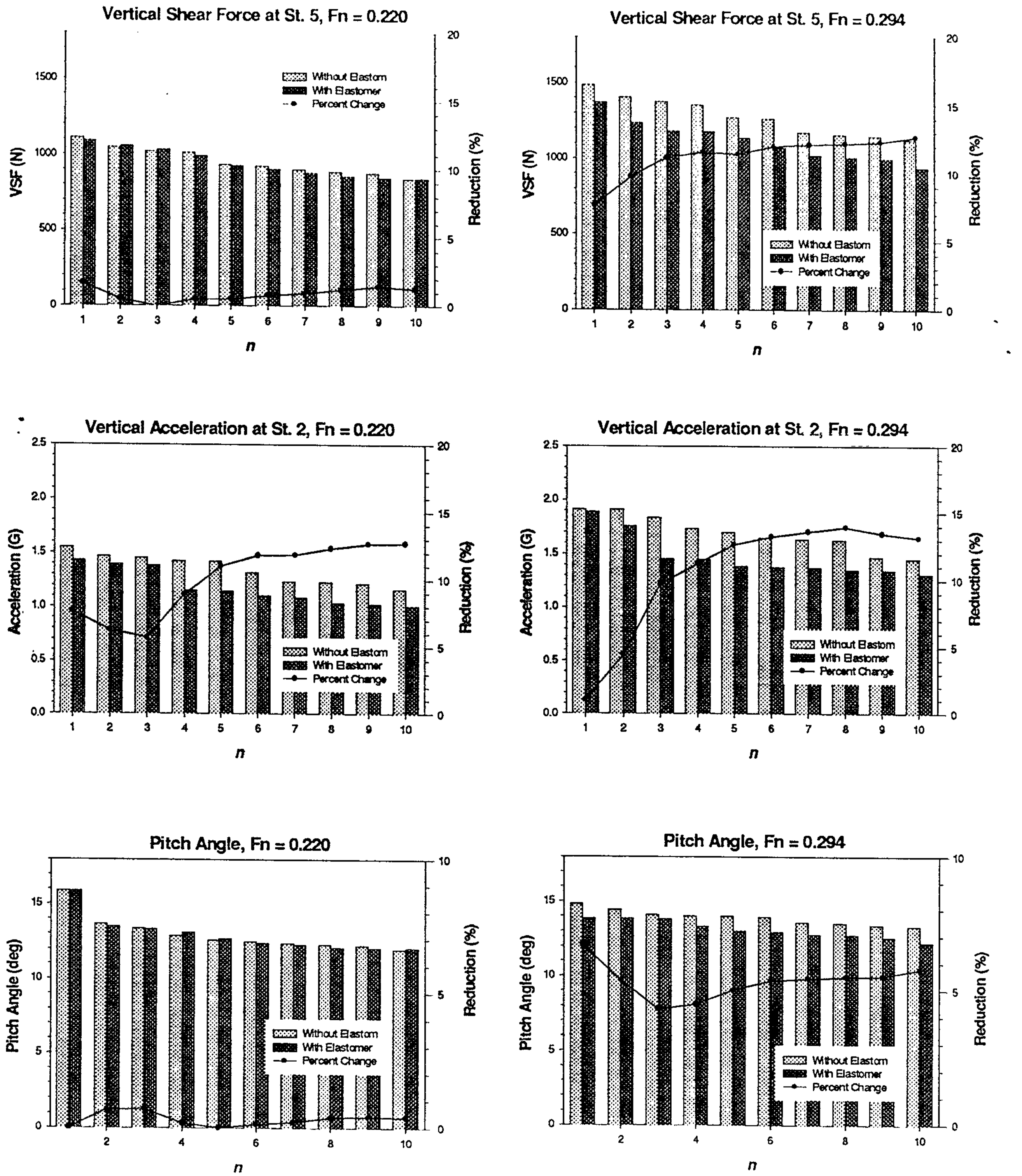

FIG. 4. Continued.

#501058