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Vibration from a Shipbuilder's Point of View

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ABSTRACT

Increased propeller loading on large ships makes the avoidance of hull vibration correspondingly more difficult. The problem of the shipbuilder is compounded by the owner's insistance on numerical performance criteria, and in some cases on specific guarantees. The dilemma of the shipbuilder is discussed within the loose framework of all the uncertainties attendant to reliable prediction of ship vibration performance for a specific class of ships.

INTRODUCTION

The shipbuilders concern with vibration is essentially limited to two small groups within the organization: upper management and engineering. To upper management a ship's problems with vibration mean time and money for investigation of those problems, for physical ship alteration and for litigation. To the responsible shipyard engineering force the avoidance of excessive vibration is a normally understood professional task the urgency of which is singularly underscored by the sensitivity of management to the consequences of the problem. This paper endeavors to present the authors' personal perception of the shipyard engineer's problems, loosely tied to the framework of their experience with the large LNG ships designed and built at our shipyard.

Lacking expertise in each and every area related to ship vibration excitation and response, it is important to emphasize the earlier qualification that this paper deals with the authors' perception of, rather than with a definite statement on, the state of the art. From recent experience it is reasonable to expect enough contradictory definitive statements to be made at this Symposium to satisfy the desires of the attendees.

A lesser limitation of this largely philosophical discussion is that it is geared to the shipyard acting as its own design agent, and therefore being forced to assume maximum responsibility. This situation has become rather typical of U.S. merchant ship construction since the advent of the Merchant Marine Act of 1970.

THE SHIP SPECIFICATION

The obligations accepted by the Shipyard are spelled out in the ship's specification, and the ship contract will define penalties, if any, incurred upon failure to meet these obligations. Drafts of the ship's specification for the ship design discussed herein were written in 1970, and the final specification for the ships now being delivered and built was completed in 1972. The MarAd Standard Specification for Merchant Ship Construction, December 1972 edition, contains the following statement on vibration:

> "Special attention shall be paid in the design and construction of the vessel to the minimizing of vibration. The Contractor shall make every effort to locate and correct unsatisfactory vibration conditions arising during tests and trials or subsequently during the guarantee period."

A second and final mention of ship vibration is made under Test and Trials:

> "A vibration survey shall be conducted . . . The purpose of this vibration survey is to collect design data for use by SNAME and the marine industry."

Without conducting an extensive search, it seems that ship construction specifications to about 1970, including the one originally drafted by us, treated the problem of ship vibration in the same general qualitative manner.

Changes in this attitude appear to have been the result of the concern of a consultant, acting for a prospective owner-operator, about the potential for vibration inherent in the beamy, shallow draft and high propeller loading characteristics of the new breed of LNG carriers then on the drawing boards of shipyards all over the world. Simultaneously several standards committees were drafting proposals of acceptable vibration limits. As a result, prospective bidders were faced with a proposed specification with clearly defined acceptance limits on permissible hull and machinery response.

Our shipyard did not win a construction contract from that particular owner, in part possibly because the authors recommendation to management was that the state of the art did not allow sufficiently unequivocal prediction of ship vibration performance to accept penalties and guarantees. That recommendation is now regrettable from a business standpoint in terms of trial test data that indicate the ship met the proposed criteria with ample margin; however the basis for the recommendation has not changed. The results of the analytical and test program undertaken for this project, and generally described in later sections, underscore this conclusion.

Parenthetically, that particular consultant admitted that if representing the shipyard instead of the owner he would advise against agreement with the shipyard guarantees.

The need and timeliness of numerical criteria are not strongly disputed, and they have, with some modification, been adopted for actual contracts as "design objectives" in lieu of rigid acceptance standards.

The collection of proposed vibration performance standards is growing rapidly, with ISO and various SNAME technical panels promulgating such data. But from the shipyard's point of view the warning remains in effect: The proposed standards are indicative of what may be physiologically and mechanically desirable, but the means for guaranteeing ship compliance remain elusive.

To the extent that there is not as yet a generally accepted ship construction specification related to vibration, the specific wording used with any one project has definite proprietary characteristics and will not be discussed in detail. In a general vein we recommend the adoption of design objectives, with detailed explanation of the methodology that the shipyard expects to follow to reach those stated objectives. Boylston and Leback in reference (1) suggest that it makes sense for the owner to take contractual responsibility for other similar performance objectives. If such a desirable agreement by the owner is ever to be forthcoming in the field of vibration, it is this outline of the proposed technical approach and collaboration in its execution that would make it workable.

DESIGN

In a shipyard the distinction between in-house preliminary design and contract design is generally blurred, since contract pricing negotiations usually demand completion of the second phase. The single most important ship characteristic affecting vibration at this stage of design is stern configuration.

The choice of stern lines will be affected by prior shipyard experience, diverse and often conflicting external advice, and construction preferences and facility limitations.

There is probably little argument that the most uniform wake is to be obtained in an open water stern of sufficient length to provide a small rise angle and adequate propeller clearance. However, such a configuration complicates the development of adequate support for the main propulsion system. Compromises required to keep cost down by controlling ship length, or simply to control length in order to fit a particular building basin, will detrimentally affect both wake and powering requirements. Where segmented construction is employed to overcome length restrictions, independent floating of an open water stern requires extensive and expensive special fixtures.

Conventional single screw stern design varies in the amount of cutaway deadwood and the fitting of a bulbous stern. Each involves construction problems related to shape and to adequacy of stern bearing support. Judgement on the latter must be based on the magnitude of steady and alternating force components and on fairly complex structural analysis.

For the particular project that is the baseline of this discussion, lines were developed and models tested for at least one version of each of three distinct stern types: Conventional, bulbous and open water. Steady and alternating forces and moments were calculated for candidate five and six-bladed propellers based on harmonic analysis of model wake.

It must be obvious that this methodical, slow and expensive approach is not generally possible in the time available to the shipyard or designer during the contract design phase.

Development of a single consensus choice is probably as effective as tests of a variety of forms, since not all factors are optimum for any one shape, and the final choice can be both difficult and confusing unless this early test program is carried beyond stock propeller use and into cavitation testing and hull girder response analysis.

Shaft response was calculated for 5 and 6 bladed propellers. The latter was chosen in part because of whirling resonance induced by the 5-bladed propeller. The choice was complicated by conflicting opinions on the consequences of whirling on shafting and bearings; some stating that no failures due to whirling have ever been observed, others attributing the loss of tailshafts to this phenomenon. Additional confusion was contributed by an owner's consultant who established an arbitrary cutoff on permissible thrust variation, a value since proven incorrect. Without spelling them out in detail, it is apparent that many persons experienced in vibration have some figure of merit or cutoff value attributable to one variable or another, often based on little more than one observation. No criticism is implied, since the limitation of such numbers is obvious and we naval architects enjoy using them so much.

It is noteworthy that among the many uncertainties regarding ship vibration response, difficulties in calculating shafting natural frequency were not expected. Calculations from three sources eventually gave noticeably different results, attributable not only to possible variation in support stiffness assumptions but also to the longitudinal location of the reaction resultant within bearings.

It will become clear that the test and analytical effort in support of this ship construction program was unusually comprehensive, yet the authors share the feeling that eventual operational success was perhaps due as much to rigid insistence on those catch-all phrases of earlier less performance oriented specifications asking for good structural support and continuity. The massive grillage with which the engineers supported the machinery and bearings did not delight the waterfront, and the continuing resistance to daily requests for additional penetrations in webs and bulkheads in the deckhouse taxed our ability for rational explanation.

PROPELLER DESIGN AND MODEL TESTING

In the course of this aspect of the program the shipyard engaged the services of three institutions and one independent consultant. Three propeller designs were prepared by our consultants and tested in cavitation tunnels.

Resistance, self-propulsion and wake measurements were carried out in two large towing tanks, with surprising differences in wake distribution attributed by the testing agencies representatives to shortcomings of the other's velocity measuring devices, which were the Prandtl and 5-hole Pitot tubes. Statistical correction factors for extrapolation of tank to ship resistance data proved extremely accurate, which is of interest in regard to shipyard guarantees on ship speed, with which we feel far more comfortable than with those on vibration.

One consultant alerted the shipyard to then new findings of the dramatic amplification of propeller induced hull pressures due to cavitation. It was stated that these factors were in the order of ten, and would clearly have a strong influence on vibration response. That claim was disputed for a time by other experts, but European model and full scale measurements eventually produced agreement and made the calculation, measurement and reduction of these forces an essential part of our investigation. The discovery of heretofore neglected effects and the obvious lack of knowledge of such effects do not increase the engineer's confidence in prediction of ship vibration performance.

Many ships then in existence had been fitted with fins over the propeller in order to reduce vibration response observed in service. This shipyard's family of LNG ships was the first for which it was decided to mount fins during construction. Model tests had shown that the wake was homogenized, which in addition to reducing the possibility of measurable cavitation also had a noticeable beneficial effect on propulsive efficiency and ship speed.

In order to estimate hull exciting pressures, models with and without fins were tested in two depressurized water tunnels. One was large enough to accept the model as a whole and by testing with various locations of a "free surface" board it was possible to model the wake with good accuracy. This facility could not provide measurements of phase angles between pressure peaks on various hull mounted transducers. The other tank could accommodate only a foreshortened dummy model but was able to record pressures and phase angles. The wake distribution in the latter was not particularly good and it was with some reservation that the phase angles measured on one model were applied to the integration of pressures for the other. In neither facility was it possible to measure phase angles between hull and propeller forces.

The tests did clearly point to reduction in hull pressures as a result of fitting the fins. Total exciting force was further reduced by greater relative phase shifts of the version with fins.

It is well known that for the three American shipyards now building LNG ships the gestation period has been a minimum of six years. Not only is that an uncomfortably long period to wait for confirmation of predicted performance, but it allows time for additional hypotheses to cloud whatever confidence exists in the results of earlier efforts. Two such developments that came to our attention were the possibility that higher order components of cavitation induced pressures are of greater magnitude than the fundamental (yet cannot be measured in model scale), and that wake distortion due to scale effects and to the presence of the propeller should be considered in the analysis, though the prediction of such distortion is uncertain.

PREDICTION OF RESPONSE

Shipyards in the United States do not have the facilities for the type of model testing described in the preceeding section, and are therefore fully dependent on third parties. Other than selecting propellers from a standard series for preliminary design purposes, it is doubtful that many shipyards have the software and experience for detailed propeller design, for prediction of unsteady forces and moments and for prediction of type and extent of cavitation. Therefore, in this area also the shipyard is often dependent on consultants.

The third and final aspect of the problem is the prediction of hull girder response to propeller induced loads. As of two years ago the authors, in interviewing most major shipyards on an unrelated subject, found that none perform an in-house hull vibration analysis, depending instead on organizations with well established reputations. Coincidentally it was determined that little effort is devoted to prediction of local structural response, a decision backed by generally favorable results with the scantlings selected for adequate strength, augmented by the opinion that modifying the occasional vibrating local structure was less time consuming and costly than a detailed and rigorous analysis of all local structure in the design phase.

For the ships discussed in this paper the shipyard used the services of two well known organizations for prediction of engine room frequency response, and used the services of one of these organizations and those of an independent consultant for calculation of response of hull and deckhouse.

The prescribed exciting force for the hull-deckhouse response was predominantly made up of the alternating thrust and vertical propeller induced hull pressure force. Aside from the uncertainty regarding determination of the latter, we were also faced with advice from two sources to discard the horizontal force, which was likely to elicit a structural response only if a shaft critical frequency were excited. In fact it was later independently established that response to the horizontal (axial) excitation produced deckhouse responses of the same order of magnitude as the vertical pressure forces.

In view of that finding it also became necessary to establish the phase relation between these two forces. The opinion of a distinguished researcher in this field was that the forces were likely to be 180 degrees out of phase. If that assumption is correct, then in our case the ship benefited greatly from the larger thrust variation inherent in the six-bladed propeller. On the other hand, if these forces were in-phase, there was a possibility of exceeding design objectives.

A third, more widely known uncertainty regarding ship vibration response is the proper estimate of damping. One of our consulting organizations, to whom we turned because of a background in analysis and measurement, started out by assuming a critical damping ratio of 0.10. They later repeated the calculation for a ratio of 0.035, while we were getting some advice to use a value of 0.010. Presumably the effect of the critical damping ratio is most significant at or near a resonant frequency, but it is generally acknowledged that for large ships the excitation of one or another higher order critical is unavoidable.

Modeling of the ship for frequency and response analysis by a lumped mass-distributed stiffness type of approach appears to us to be less time consuming but to require more experience-derived skill than a more detailed finite element model possible on one of various available programs. It is at least the present intent of the authors to attempt future structural modeling in-house. Many shipyards, and ours is no exception, have become adept at modeling for static analysis, and now use rather complex models on a more or less routine basis. Furthermore it seems appropriate to accumulate a uniform internal data base to guide future designs. In-house analysis simplifies the cumbersome but real problem of frequent structural changes during the design process, which the shipyard may resist transmitting to a consultant in order to control costs.

Both a finite element and a lumped mass system were used by our consultants. The finite element model was a 2-dimensional simplification with element stiffnesses intended to reproduce the behavior of a three dimensional model of the stern and house. The lumped mass-elastic axis method was also employed to check the effect of variation of various parameters, such as damping, force phase angle, deckhouse height and deckhouse support stiffness.

In terms of measured full scale data the lumped mass system slightly underestimated response while the finite element model slightly overestimated response. This conclusion has no generality whatsoever as a result of the particular intent of each analysis, and the many uncertain assumptions discussed earlier.

It is our belief that shipyards tend to postpone structural response calculations until they are reasonably certain of structural configuration and mass distribution. It would be appropriate to undertake a simple lumped mass-elastic axis analysis at an early stage, since hull inertia and shear area can easily be estimated. By a simple yet methodical variation of parameters the shipyard may then at least have some guidance on choices of structural continuity, house proportions, deck stiffness, and relative effect of vertical and horizontal exciting force. In keeping with everything else in vibration analysis, at least some of these conclusions will conflict.

PERFORMANCE EVALUATION

Compliance with vibration design objectives is ultimately established by measurement on trials. Many and wondrous electronic devices now exist that facilitate recording of many channels of data and immediate display of response in whatever mode is desired. Exact predetermination is not necessary to select the location of transducers as long as sufficient lead wire is reserved for movement to nearby locations. Hand held instruments can be used to explore for more representative placement.

When evaluating the data one becomes aware of the variety in the format of published guidelines and in accepted procedures. Although not yet based on experience in vibration measurement, it is tempting to admonish that guidelines more or less arbitrarily selected be treated with a modicum of common sense. By way of example, our industry should wish to avoid the fate of sketches of acceptable porosity in steel welds arbitrarily established by the Pressure Vessel Code, with which nuclear vessel constructors attempt to comply by meticulous optical comparison under a microscope.

CCNCLUSIONS

1. Although many ships have had difficulty complying with vibration guidelines now being promulgated, it does appear that by extensive analysis and test, prudent and disciplined design and a measure of good luck we can build large high powered ships with good vibration characteristics.

2. It does not necessarily follow from the above that a shipyard should feel safe in adopting specifications with ship acceptance limits and guarantee penalties based on vibration performance.

3. All the many uncertainties, real or imagined, described in this paper could be greatly reduced by thorough ship instrumentation programs involving measurement of wake, hull pressures, shaft and bearing forces and moments, structural response, and by observation of cavitation.

ACKNOWLEDGEMENT

The sincere gratitude long ago expressed to our consultants in private is repeated here in public. The paper emphasizes disagreements only to make a point on the developing nature of ship vibration knowledge as it appears to the shipyard engineer. As a footnote it should be mentioned that our consultants were unanimous in their surprise at being congratulated on a job well done. Theretofore they had heard from a shipyard only when things went wrong.

REFERENCES

1. J. W. Boylston, and W. G. Leback, "Toward Responsible Shipbuilding", Trans. SNAME, 1975