THE SOCIETY OF NAVAL ARCHITECTS AND MARINE ENGINEERS
One World Trade Center, Suite 1369, New York, N.Y. 10048
Paper to be presented at the Ship Vibration Symposium
Arlington, Va., October 16–17, 1978

The Considerations of Vibrations and Noise at the Preliminary and Contract Levels of Ship Design

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ABSTRACT

The nature and the extent of the engineering effort devoted to vibration and noise up to and including the contract design of ships are dependent on several factors. The key factors are related to the owner's philosophy on design and on the availability of suitable analyses procedures. Much reliance is placed on past design practices and experience. It is fairly usual to estimate and compare natural frequencies of hull and shafting vibration with propeller blade frequencies. The direct effort devoted to noise is minimal.

Results of the research and development programs over the recent years are now emerging as rules, regulations, guidelines and analyses procedures which should be heeded and applied in the course of design. The analyses procedures do require additional experimental and full-scale verification. There is need to update and or develop new empirical formulas to estimate hull natural frequencies of modern ships. It is advisable for SNAME to consolidate and publish all relevant reference material for vibration and noise in form of a loose-leaf "text book".

INTRODUCTION

General

In general, ship design is performed in three phases, namely; concept, preliminary/contract and detail.

This paper offers a designer's viewpoint of the considerations given to vibration and noise in the preliminary and contract stages of a ship design, with emphasis on merchant ships. Before going any further, it is desirable to explain why the paper did not include detail design.

At the completion of the contract design and the specifications, the owners enter into a contract with a shipyard for construction and delivery of the ship. Concurrently, the technical and legal responsibility of the design, at least in a broad general sense transfers from the owner to the builder. Consequently the demarcation between the contract and detail design phase is significant.

Further, one of the aims of the Vibration Symposium-1978 is to present the views of all the different parties involved and interested in ship design, construction and operation. Now, since normally in the United States the owner retains an independent naval architecture firm to prepare preliminary/contract design and specifications, it is proper for the authors as members of such a firm to limit the paper to contract design. Of course, there are unique cases, particularly with respect to LNG carriers and tankers where the complete design is prepared by the shipbuilder.

The main purpose of the paper is to state the nature of the design effort devoted to vibration and noise, the restraints to this effort and what additional effort could be beneficial. The views offered here have been discussed informally with several other designers.

To some degree this paper is an integration or synthesis of several papers on the Symposium program. It discusses the eventual combined application of the many specialized aspects of vibration and noise analysis. The paper is not a result of any specific new work and the details of procedures and methods mentioned or discussed are expected to be found elsewhere.

It is hoped that the paper will impart an understanding amongst the owners, designers and builders to appreciate the problems that each party faces in dealing with vibration and noise.

Design Phases

There is no clear-cut definition of the extent or the depth to which a design is carried in the concept, preliminary and contract design phases. It is very much dependent on the ship type, the schedule, the owner's preference and the relationship between the owner, the designer and the shipbuilder. This relationship is dependent upon whether the owner is his own designer or retains an independent naval architect and also whether the builder is actively involved in the design.

For new ship types and special purpose vessels the tendency is to perform additional work in each design phase to insure technical and economic success.

A concept design determines the approximate principal dimensions, payload and performance. The confidence level is such as to insure that the design will satisfy its technical and cost goals and constraints. The drawings are usually limited to a set of rough lines and general arrangement which delineates the compartmentation and major machinery.

A preliminary design begins with performance of extensive trade-off studies related to all the major systems and subsystems. The trade-off studies result in a single set of principal characteristics, lines, general arrangement, structures and machinery. Of course it includes hydrostatic, powering, scantling, weights and stability calculations. Frequently the preliminary design is subjected to resistance and propulsion tests. Seakeeping tests are performed sometimes if the development of a new hull form is involved.

The contract design phase in general is the final cycle in the design spiral. It involves the preparation of contract and guidance drawings and the specifications. The end product is expected to permit shipyards to prepare firm fixed price quotations and schedule for the construction and delivery of the ship.

Types of Vibration

Vibration of an object is said to occur when it is set into an oscillatory motion. As the object vibrates it disturbs the air particles near it which in turn causes changes in the normal atmospheric pressure which are transmitted with the speed of sound. When the rate of vibration or pressure variation is in the audible range (20 to 20,000 Hz), the human ear will translate that vibration to sound. Consequently, in case of ships, giving consideration to vibration is important from both the physical movement and noise standpoints.

There are various types of vibration due to different sources that occur in different parts of the vessel. These may be grouped as follows:

Springing	-	Steady state 2-noded vertical vibratory response of the main hull girder induced by short waves.
Slamming	-	Transient response of the main hull girder forced by impact with oncoming waves.
Propeller Induced	-	Vibration of the main hull girder, local structure, shafting and/or machinery due to alternating forces generated by the propeller.
Machinery	-	Vibratory response of a piece of machinery and/or the hull girder or local structure due to alternating forces produced in a machinery component.

These various types are all considered and discussed in this presentation.

Types of Noise

There are various types of noise due to different sources which may be grouped as follows:

Propeller Induced	-	Structural and airborne noise in the aft part of a vessel due to alternating forces generated by the propeller.
Machinery	-	Structural and airborne noise generated by vibration of machines and the machine's foundation.
Fluid Flow	-	Structural and airborne noise caused by flow of air in the HVAC ducting system and by flow of air, steam and water in the piping systems.
Electrical Component	-	Airborne noise or a 60 cycle hum from transformers and similar components.

RULES, REGULATIONS AND GUIDELINES

General

It is only in recent years that classification society rules and governmental regulations have begun to address the subject of vibration and noise to any substantial degree. Concurrently guidelines have begun to be formulated and made available to the ship designers and builders. The progress in this direction has followed the growing development of vibration and noise technology through R & D. The greater awareness of the impact of vibration and noise on human factors and economics of ship operation has of course been a prime influence on the parties concerned.

The significant requirements of the available rules, regulations and guidelines are presented herein. To what extent those can be satisfied in the contract design stage depends on the depth of the design.

American Bureau of Shipping (1)

The hull section of the American Bureau of Shipping (ABS) Rules does not mention "noise" and "vibration", however, the requirements of these rules have been established based on analyses and experiences which may have involved vibration and noise. The point to be made is, however, that the designer need not be concerned with these aspects in a direct sense.

The machinery section of the ABS Rules addresses "vibration" under the subsection for internal-combustion engines with respect to torsional vibration. Therein, requirements are set for allowable stress values and a determination of barred operating ranges for crankshafts and propeller shafts.

Det Norske Veritas (2)

The hull sections of the Det Norske Veritas (DNV) Rules address vibration and noise in a number of places. Consideration of local vibration from propeller and auxiliary machinery is addressed in the section, "Design Principles".

The sub-section on "Plating and Stiffeners" has a tentative rule for local vibration in the afterbody and machinery spaces which states that: "Plate fields and panels are to have a natural frequency of vibration in the fundamental mode which is higher than the expected local exciting frequency from engine and propeller blades." The sub-section "Sternframes and Stems" gives propeller-hull, rudder clearances for both single and twin-screw ships with moderately cavitating propellers to give acceptable pressure pulses on the various components involved.

The section on "Steam and Gas Turbine, Diesel Engines, Reduction Gears, Shafting and Propeller" requires torsional vibration calculation to be submitted for approval for all propulsion installations and for auxiliary diesel engine machinery of more than 200 KW. It is also indicated that the axial and whirling shafting vibration calculations may be required. The section on "Components, Installation and Workmanship" gives limits of vibration on bulkheads, beams, deck, bridge, machinery and masts, and it is noted that noise may be a consideration but no limits are given.

Lloyd's Register of Shipping (3)

No hull structure vibration or noise requirements are specified in the Lloyd's Register of Shipping (LRS) Rules. The section on "Main and Auxiliary Engines and Associated Machinery Components" requires that torsional vibration calculations be performed for oil engines, auxiliary oil engines over 110 KW and turbines and electric propelling motors along with shafting and propeller. It is further mentioned that: "Unless the responsibility for preparing and submitting this information is specifically advised, it is the responsibility of the Shipbuilder as main contractor to ensure, in cooperation with the Enginebuilder, that this information is prepared and submitted."

Bureau Veritas (4)

No hull structure vibration or noise requirements are specified in the Bureau Veritas Rules. They have however, published various detailed recommendations (5) pertaining to the reduction of vibration by analysis and give some formulas and limits therein.

The section on "Propelling and Auxiliary Machinery" has lateral and torsional vibration requirements for steam turbine, and torsional vibration requirements for propelling electric motors, internal combustion engines, and shafting.

In addition, it should be noted that Bureau Veritas has been actively involved in the design of various vessels from the standpoint of vibration and have developed a computer system for such analyses (6). These studies were not a necessary part of classification.

Nippon Kaiji Kyokai (7)

Nippon Kaiji Kyokai does not have any specific requirements for noise and vibration. With respect to vibration, it is mentioned in the section on "Prime Movers, Power Transmission System and Propulsion Shaft System" and "Boilers and Pressure Vessels" that "Since the formulas for the strength of...... are based upon the consideration that there is no dangerous vibration in the installation within the range of operating speeds, the manufacturers of the machinery are required to pay special attention to this point and take responsibility in the application of these formulas."

International Standards Organization

The American Standards Institute is the U.S. representative of the International Standards Organization (ISO). The ISO has published proposed recommendations for acceptable levels of vibration for humans (8). ISO does not impose requirements however, and its standards are mandated only be agencies who wish to invoke them. The Occupational Safety Hazard Agency is such an agency.

Society of Naval Architects and Marine Engineers

The Society has published several technical and research publications which include a code for gathering, interpreting and presenting data (9, 10); various data sheets pertaining to actual ships (11); and a code on acceptable vibration of marine steam, gas turbine and auxiliary machinery plants (12).

Further, another code is being developed concerning the establishment of guidelines for evaluating a ship hull with respect to its vibration and noise environment.

ANALYSES PROCEDURES

General

Till the advent of high speed computers, vibration analyses were limited to the estimation of natural frequencies using empirical formulas or full integral methods based on classical beam theory. The latter were often considered too time consuming and were not performed. Neither of these approaches gave reliable estimates of higher modes of vibration.

Computers have provided the stimulus for the development of theory and calculation procedures to obtain greater insight into vibration.

This has come at the crucial time when ships have been getting larger and faster with great variations in the structural configurations. These trends have resulted in structural and hydrodynamic characteristics of the ships that are beyond the range of past experience, sometimes in a subtle way. This in turn has resulted in unexpected changes in their response to both static and dynamic loads (waves, slamming, propeller, machinery). As a result, all this has brought about new problems, or more correctly, problems that were not so important in the past have now become more important. The implications to the designer are that he must have a much greater fundamental understanding of the phenomena that determine both the dynamic loadings and the structural response of the ship.

In view of the foregoing it is desirable to summarize here the latest vibration analysis procedures available to the designers.

Structure

Aside from empirical methods (such as the formulas of Schlick, Todd, Marwood and Burrill for estimation of hull natural frequencies) (13) today's methods for vibratory structural analysis of ships' hulls are computerized structural analysis algorithms. There are programs available that were developed specifically for the analysis of ship vibrations, as well as general purpose programs which can be adapted to analyze these vibrations. The ship oriented programs that have been available for some time are GBRCI, GBRC2, GBRP (14, 15, 16, 17, 18) and SHVRS (19, 20, 21) which model the ship as a beam. These programs allow damping and buoyancy to be modelled. The GBR set of programs allow any number of subsystems to be attached to the hull and can analyze vertical and coupled horizontal-torsional vibration. The SHVRS program is for vertical vibration and allows the modelling of the superstructure and propulsion system with fore-and-aft and vertical degrees of freedom. The programs can accept propeller excitations as point loads. The better known general structural analysis programs are NASTRAN (22), DYNAL (23), STARDYNE (24) and ANSYS (25). These programs are similar in that they allow detail simulation of the structure by 3-dimensional modelling of finite elements of the membrane, plate and beam types. References (26) and (27) are published examples of finite element analyses.

The degree of structural modelling detail required to indicate critical response must be considered carefully since, if the model is oversimplified, an actual vibration problem may escape identification, while overly complex models will result in more costly analyses of limited additional value.

Sub-resonators such as double bottoms, bulkheads, propulsion systems, superstructure, etc. require modelling not only from the standpoint of determining their own response, but also because of the important interactive effects between them and the hull that can significantly affect system and subsystem responses (19, 20).

In addition to modelling details and sub-resonating systems, the problems associated with obtaining accurate solutions are determination of damping, rigidities between subsystems, and boundary conditions.

Loads

The types of loads that must be considered in ship vibration can generally be grouped into the following categories:

- o Propeller induced
- o Machinery induced
- o Wave induced transient (slamming)
- o Wave induced cyclic (springing)

Propeller induced vibratory forces are of two types:

- o Bearing Forces - Forces transmitted directly to the ship through the propeller and shaft.
- o Surface Forces - Forces transmitted to the surface of the stern by the unsteady pressure field of the propeller.

Numerical methods for computing bearing forces have been developed (28, 29, 30), and others are under development, as shown in Table 1. The experimental prediction of bearing forces has also been accomplished by various individuals and organizations (31, 32, 33, 34).

In general, model tests have been preferred over numerical computation methods, table 2, to obtain surface forces. The numerical methods have had the drawback of not being able to account for the contribution of blade cavitation in the surface forces,which can be significant.

The various methods have not been compared to each other and full scale measurements in the general literature, although this is the subject of a current Ship Structure Committee project, "Study for Propeller Induced Vibration in Hull Structural Elements."

Source Ref.	Method
Davidson Laboratory	Unsteady Lifting Surface
MIT (Kerwin)	Unsteady Lifting Surface
NSRDC (Chertock)	Unsteady Lifting Surface
NSMB (Verbrugh)	Unsteady Lifting Surface
MIT (Brown)	Unsteady Lifting Line
Univ. of Mich. (Vorus)	Unsteady Lifting Line
Univ. of Mich. (Vorus)	2-D Unsteady Strip
Burill	Quasi-Steady

Table 1

Computation Methods for Propeller Induced Bearing Forces (35)

Source Ref.	Method
Univ. of Michigan (Vorus) (37)	Green's Theorem Approach
Davidson Laboratory (38)	Diffraction Method
Huse (36)	Solid Boundary Factors

Table 2

Computation Methods for Propeller Induced Surface Forces (35)

Exciting forces are produced by virtually all rotating components of the propulsion system and other machines. The forces originating with the various components vary widely in both magnitude and frequency. However, they can be minimized if the balance and eccentricity tolerances on rotative parts are within acceptable limits.

With respect to wave excitation forces in the analysis of springing (13), investigators have employed the forces computed for rigid-body ship motions using 2-dimensional theory (39, 40, 41).

In this paper slamming refers in a broad sense to the transient dynamic wave loadings which result in whipping type vibration of the hull. The transient loading can be due to bottom slamming, bow flare impacts and green water over the bow. The magnitude, duration, and shape of the slam-pulse-excitation force has eluded accurate prediction in both the experimental and theoretical fields. Most experimental efforts have been aimed at predicting pressures to aid in the design of bottom plating, but little has been done to determine force-time histories. Records of experimental data on full-scale slams exist, and theories of the slamming phenomena have been developed (42, 43, 44).

Noise

Analytical techniques for predicting noise levels during the design stages of ships have not yet been proposed. Procedures for predicting noise levels in general do exist but more development and data are required before they become analysis tools (45). Consequently, the "analysis" of noise is embodied in good design practice.

ENGINEERING EFFORT DEVOTED TO VIBRATION AND NOISE

The nature and the extent of the engineering effort devoted to vibration and noise up to and including the contract design of a ship is dependent on the following principle factors:

- o Newness of the ship type and size
- o The capability of the existing theoretical and experimental methods
- o The level to which the design is advanced
- o The design budget
- o The design schedule

The least that is done by any designer is to state in the specifications that the ship shall be free of any unacceptable vibration and noise. In addition the designer follows good design practice and guidelines which may include the following:

- o Stern lines which allow good flow to the propeller and propeller clearance
- o Arrangement - segregation of machinery spaces from living spaces
- o Structural system that insures adequate primary and local stiffness and good continuity
- o Allowance of conservative weight margin for the foundations, particularly those for the main engine, gears and thrust bearing
- o Ventilation system with safe register velocity, baffler and large plenum chambers
- o Machinery resilient mounts
- o Shielding and insulation
- o Piping systems with safe flow velocities

With regard to actual analyses, it is fairly common practice to accomplish three items, namely:

- o Calculation of the natural frequencies of the vertical transverse and torsional vibrations using the available empirical formulas, if applicable.
- o Calculation of hull and shafting mode shapes and natural frequencies using analytical methods.
- o Comparison of the blade frequencies with hull and shafting natural frequencies.

More recently the designers may introduce numerical criteria with respect to vibration and noise in the specifications. For structure and machinery criteria may refer to frequency, velocity, acceleration and amplitude limits. Noise levels may be specified for various compartments.

In order to illustrate a comprehensive effort devoted to vibration and noise attention is focused on the recent classic, Sealand's SL-7 container ship. It is a good example in which the owners took advantage of the best available design tools and carried the contract design to a very advanced stage before submitting it to the shipyards (46). The owners had recognized that they were setting out to acquire a prototype and it would be wise to provide a suitable design budget. Even then the design schedule was kept tight - approximately six months. Listed here are major aspects of the design program as they directly or indirectly involved the consideration given to vibration.

- Resistance Tests
- Open Water and Self Propulsion tests with stock propellers
- Flow Tests
- Wake Survey
- Complete propeller designs (two) and self-propulsion and cavitation tests
- Sealoads and ship motion calculation
- Conventional and finite element structural analyses
- Vibration analysis beginning with simple modeling and increasing in complexity as additional input data was generated:

a. Three independent calculations of propeller exciting forces and moments
b. Calculations of the torsional, longitudinal and lateral vibration characteristics of the shafting system
c. Calculations of hull and deck house vibratory response using finite-element analyses
d. Consideration to install hull vibration dampers and "resonance changers" for the shafting

In general the owner of the SL-7 claims to have adopted the philosophy - "Why make the shipyard responsible for factors over which they had little control?"

The foregoing was a brief statement of the range of consideration given to vibration and noise. Now it is desirable to discuss the reasons. When a designer has successful similar designs with operation experience to refer to, the natural tendency is, and to a great degree justifiably so, to omit any extensive analyses. He follows good design practice and selects a propeller rpm which will avoid resonance with the hull and shafting in the normal operating condition.

In certain cases it is almost futile to perform any analysis since the answers are unlikely to help the designers to modify the design. A good example of this is a semi-submersible drill platform. Here the living quarters, offices, work area and the machinery (generally diesel) spaces are close together in the upper hull. It is nearly impossible to structurally isolate the compartments because the continuity of the upper hull is imperative to the structural integrity of the platform. In such a case the designer must rely on heavy machinery foundations and machinery shielding in addition to insulation to minimize vibration and noise.

One of the hesitations in increasing the design work with respect to vibration is the questionable accuracy of the analytical prediction, and consequently the difficulty in justifying its cost, both financial and timewise. This situation is particularly prevalent in the early stages of the design when the inputs for the analysis may be available in a rough form only and in some instances not available at all. The input in question may be related to machinery, structure or hydrodynamics.

Machinery manufacturers do, and have to, provide information required to perform the vibration analysis but the usual problem is related to the timely availability of the relevant information to the designer. In general detailed specific information is not available until the unit is selected and the purchase is fairly certain. Information includes weights, centers and inertias of fixed and moving parts, together with certified drawings. In many instances when design modification developments are involved, this information is not available until the detail design is well underway. In case of diesel machinery it is common practice for the manufacturere to supply the torsional vibration analysis.

In this review of what the designer does and does not do, it is necessary to inject a word about the owner's attitude; after all the owner has the final say on how much time and money will be spent up to the contract design. In general, the design budget (time and money) is proportional to the size of the owner's operations and his own knowledge of ships. It is not uncommon for owners to rely on limited contract design and expect the shipbuilder to complete the design. The basic reasoning behind it is that it should reduce design cost and time. It should be pointed out that some builders prefer to bid on limited contract design for their own reasons.

Few have to be convinced that excessive vibration and noise on board ship can be damaging in different ways. And further, the solutions can be costly when the problems are tractable. The damage and the solution of one bad problem can cost more than a good size analysis and a test program in course of design. In view of this it behooves the owner and the naval architect to spend the necessary time and effort to insure reference to available design data and employment of analytical and experimental design techniques. Also, the owner should demand tight but practical specifications.

In general there appears to be a lack of application of the available computer programs for vibration analyses of the hull and major subsystems, such as the inner bottom and deckhouse. The programs can be used profitably in the preliminary and contract design phases to perform trade-offs and detect response trends due to the variation of specific design features. Examples of design variation in connection with vibration that can be studied are:

- Shape and fore and aft location of deckhouses and the stiffness of their connections to the hull
- Location of principle bulkheads
- Location and stiffness of the main machinery foundations
- Double bottom structure in way of machinery spaces
- Cargo and ballast distribution
- Propeller location/stern overhang
- Number of propeller blades and propeller rpm
- Propeller shaft size and support locations
- Strength and stiffness of hull ends

It is believed that such analyses programs will foster greater interaction between the hull, structure, machinery and propulsion system designers; this in turn should result in a well balanced and integrated design.

As in the case of the SL-7 design, the prudent attitude would be to start with simple models and then update the calculations with increasingly complex models as the necessary inputs are generated.

CONCLUSIONS AND RECOMMENDATIONS

1. The nature and the extent of the engineering effort devoted to vibration and noise up to and including the contract design of a ship is dependent on the following principle factors:

- Newness of the ship type and size
- The capability of the existing theoretical and experimental methods
- The level to which the design is advanced
- The design budget
- The design schedule

2. The most common consideration of vibration up to contract design level is limited to the comparison of the natural frequencies of vertical and horizontal hull vibration and shafting with propeller blade frequencies.

3. It is recommended that structural analyses programs be used in preliminary and contract designs to perform trade-off studies and detect response trends with variation of specific design features, i.e., locations of deckhouses, bulkheads and main machinery, stiffness of connections between major structural subsystems, etc.

4. It seems that there are two main deterrents to the application of hull vibration analysis procedures. One is the uncertainty of estimating the effective different types of damping and stiffness, particularly that of connections between major subsystems. The other is insufficient or the lack of full-scale and experimental verifications of the procedures. (The problem of estimating the excitation is not overlooked but it is believed that considerable useful relative analysis can be performed using estimated loads.)

5. The existing empirical formulas for the estimation of the hull natural frequencies are outdated for many of the new ship types and sizes, such as the RO/RO, container ships and LNG carriers. It is recommended that a full scale measurement program be undertaken to develop new empirical formulas or revise the existing ones for a variety of ships.

6. Criteria, guidelines, analysis procedures and experimental methods related to ship vibration are spread over many sources. It is recommended that it be considered to make this available in a collective form. It could be in the form of a "text book" that covers hull and structural subsystems, propulsion systems and machinery. However, the "text book" should be in a loose-leaf form to which new information can be added and outdated information removed.

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