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CONTEMPORARY STATUS OF DEVELOPMENT OF THE PROBLEM OF SHIP VIBRATION

(Sovremennoe Sostoianie I Razvitie Voprosa O Vibratsii Sudov)

by

Professor N.N. Babaev

Translated by B.V. Nakonechny, Naval Architect

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TABLE OF CONTENTS

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by

Professor N.N. Babaev

ABSTRACT

The paper gives a summary of the development of methods pertaining to the problem of ship vibration in Russian shipbuilding practice from 1900 up to 1956. The review includes such work done outside of Soviet Union as has been utilized in Russian practice, particularly the work of F.M. Lewis and J.L. Taylor in accounting for the inertia effect of the surrounding water as well as the former's work on propeller exciting forces. There are included the calculation of normal modes and natural frequencies of hulls, forced vibration and the prediction of propeller exciting forces, methods of dealing with damping, local vibration, particularly vibration of decks, vibration instruments, and the use of vibration generators.

INTRODUCTION

Fifty-five years ago, in September 1900, A.N. Krylov, who was at that time director of the model basin, made, with the aid of an instrument constructed by him, a recording of the vibration of the hull of the cruiser GROMOBOI. This was the first experimental investigation of vibration in the history of Soviet shipbuilding.

Starting from 1901, A.N. Krylov, having developed the theory of this phenomenon, started lecturing on ship vibration, first at the Naval Academy and later at the Polytechnic Institute in Petersburg. Krylov's lectures on ship vibration were later included in one of the chapters in his well known work "On Some Differential Equations of Mathematical Physics Having Application to Engineering" and in 1936 a separate book, "Vibration of Ships" was published. Such is the brief history of the creation of this important work of A.N. Krylov.

It should be mentioned that although the problem of ship vibration was treated by Schlick as early as 1884, the problems requiring the development of practical methods of dealing with ship vibration did not attract the attention of naval architects.

A.N. Krylov, in his course of lectures, presented for the first time practical methods of calculating forced vibration under the action of given external forces. Moreover, Krylov in the aforementioned work presented the mathematical principles of the theory of mechanical

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*Based on a paper presented by the author at the Scientific Technical Conference on Seagoing Qualities and Structural Mechanics of a Ship, dedicated to the memory of academician A.N. Krylov.

vibration in general covering small vibrations of systems with one and several degrees of freedom, lateral and torsional oscillations of rotating shafts, and also both longitudinal and lateral vibrations of beams. There are also given in this work the basic principles of the design of instruments for recording vibration and methods of integrating some nonlinear differential equations which occur in engineering vibration theory.

As a rule general methods are illustrated by concrete examples. A simple enumeration of problems discussed in the book "Vibration of Ships" shows that the ideas contained in this book formed the basis for solving the majority of dynamical problems in the structural mechanics of a ship and gave impetus to new developments in this field.

In the last fifty-odd years since the first book was published there have been important changes in naval architecture which gave rise to new problems. Both the increase in displacement and speed of ships and the consequent increase in power absorbed by the propellers resulted in higher amplitudes and frequencies of propeller exciting forces. The wide application of welding and of new varieties of ship steel, and also the cluttering of the ship with complex electronic equipment and instrumentation led to new specifications for allowable limits of vibration both for the hull itself and for local structures.

FREE VIBRATION OF A SHIP'S HULL

Generally speaking, the usual methods of free vibration theory can be applied to the calculation of natural frequencies and normal modes of a ship's hull considered as a nonuniform beam with free ends.

Because of the work of E.V. Krasnoperov, B.L. Sushenkov, and P.F. Papkovich, who showed how to select the initial mode in applying the method of Rayleigh to calculating the natural frequencies of a ship, this method found wide application and was partly utilized by V.V. Davydov and N.V. Mattes[1] for the practical determination of the first two modes of a series of cargo ships. They compared calculated and experimental results which showed Rayleigh's method to have satisfactory accuracy.

Other works based on energy methods are fully discussed by P.F. Papkovich.[2] In 1916 B.L. Sushenkov proved the convergence of the so-called method of successive approximations and showed how to apply this method to higher modes. By the end of the thirties this method was firmly established in shipbuilding practice. The most convenient method of calculation was found to be the one developed by U.A. Shimansky. The effectiveness of this scheme is attested by the fact that it readily yields frequencies and modes up to the fifth and in some cases up to the sixth as established in 1954 by S.K. Dorofeiuk. Moreover, the process of finding modes and frequencies is facilitated still further by the use of computers.

In calculating the higher frequencies of a hull it is necessary to take into account the deformation due to shear of its transverse sections.

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[1]References are listed on page 10.

The problem of allowing for the shear effect in the energy method was solved in 1929 by P.F. Papkovich. In 1941 U.A. Shimansky proposed a somewhat different method of accounting for the shear effect and at the same time his solution gives more accurate values of the frequency of the first mode than the method of P.F. Papkovich.

P.F. Papkovich and U.A. Shimansky took account of shear deformation only in determining natural frequencies. A.A. Kurdiumov,[3] after showing in 1951 the possibility of applying the method of successive approximations to the direct integration of the differential equation of lateral oscillations of a beam which took account of shear, presented a new method of accounting for the effect of this factor not only on the frequency but also on the modes of vibration of a ship's hull. We mention in passing that electronic computers are used abroad in the investigation of beam vibration allowing for shear and rotary inertia as shown by the work of Howe[4] published in 1955.

In vibrating, a hull entrains a part of the mass of the surrounding water. Of existing methods of calculating the effect of entrained water in Soviet shipbuilding practice the widest use has been made of the data of Taylor who improved Lewis' values for correcting for the nonprismatic form of the hull and who recommended a value for entrained water in horizontal hull vibration. Since the data of Lewis and Taylor are restricted to two- and three-noded vibrations of the hull, S.K. Dorofeiuk has extended this work. In 1954 he obtained values of coefficients of entrained water up to and including the fifth mode for both vertical and horizontal vibration. He also carried out an investigation of the effect of depth of water on the magnitude of entrained water.

It should be mentioned that the effect of the depth of water on free vibrations of a ship's hull also attracted attention abroad. This problem is discussed in works of Havelock and also of Johnson and Marwood, published in 1951–1954.[5]

For tentative evaluation of the frequencies of higher modes of hull vibration, U.A. Shimansky presented an approximate procedure based on extrapolation of results obtained for the two- and three-noded modes to be applied to the usual methods such as the method of successive approximations. An approximate formula for this purpose was derived by the author of the present review from known formulas of Hohenemser and Prager for the frequencies of higher modes of nonuniform beams.[6] It should be noted that A.A. Kurdiumov[3] in 1951 generalized the formula of Hohenemser and Prager, accounting for deformation due to shear.

The well-known formula of Schlick for the approximate calculation of the fundamental frequency of a ship's hull was modified by Todd and Marwood[7] in 1948 by introducing the concept of effective beam depth with a view toward accounting for the effect of long double-deck superstructures on the natural frequency of the hull.

Thus at the present time the structural mechanics of a ship encompasses reliable means of calculating the first five modes of free vibration. Logically it seems desirable to develop methods for calculating still higher modes. However, caution should be exercised that in going to higher modes the distance between adjacent modes is at least equal to the lateral dimension of the hull and the frequency of the vibration of the hull girder as a whole does not reach the frequency of local structures such as bottom and deck sections with attached machinery, bulkheads, shell plating panels, and dampers, for then the theory of slender beams is inapplicable.

Thus in considering the frequencies and modes from the sixth up, it is necessary first to estimate the effect of the above-mentioned factors and only then to select with caution the method of calculation and the accompanying mathematical apparatus.

As to other unclarified points in the theory of free vibration of ships, it is necessary to mention the problem of torsional vibration for which we do not yet have practical methods of calculation (if we neglect Horn's work published in 1925),[8] and the interaction of these vibrations with horizontal vibrations which up to the present time are treated as independent of torsional vibrations.

PROPELLER-EXCITED SHIP VIBRATION

The experimental work of F.M. Lewis on this problem should be pointed out first. Results of his work, published in 1935 and 1936, can serve only for qualitative evaluation of the phenomenon of propeller vibration.[9] Moreover, as was established later, Lewis underestimated the effect of variation of the velocity field in the oncoming flow to the propeller and somewhat overestimated the role of forces on appendages such as struts and bossings.

An attempt to fill this gap was made in works published in 1948–1953.[10] The main results obtained on the basis of these investigations, and also of a series of practical computations made by S.K. Dorofeiuk and L.V. Medvedovska in 1953–1954 are the following.

Propeller-excited vibration of a frequency equal to the product of the number of blades and the rpm is due principally to the pressure pulsations which are transmitted through the water to the hull. Part of the forces (approximately 25 percent) due to periodic changes in hydrodynamic forces on the propeller blades during operation of the propeller in a nonuniform velocity field, is transmitted to the hull directly through the bearings. The fraction of the forces impressed on the bossings is negligible. The location of the bossings determines the magnitude of periodic propeller-exciting forces only insofar as the bossings disturb the oncoming water flow. An effective means of decreasing the pulsating pressure, aside from increasing the clearance between the propeller and the hull, is obtained by increasing the number of propeller blades and by equalizing the velocity field in the propeller disk.

The experimental verification of calculations made on models and full-scale ships have shown satisfactory accuracy for these methods.

It should be mentioned that at the present time multibladed propellers; particularly five-bladed, are widely used in foreign practice for combating vibration on commercial vessels, and also special fins are installed in the region of the propellers for equalizing the flow to the propellers. This is indicated in the works of Baier and Ormondroyd, also Beguin and Brehme,[11] published in 1952–1954. In passing it should be mentioned that a new work of Lewis was published in 1954, showing how the forces transmitted from a propeller through the water to the hull of single-screw ships were measured by methods similar to those used in his previous investigations. It should be noted that this work confirmed the conclusion previously reached by Lewis on the important role of forces transmitted from the propeller through the water.

As to the question of possible causes of first-order vibration, until recently there existed an impression that a vibration of this type is due to shaft misalignment during installation. The works of Shimansky as well as of other investigators [13] have shown that only initial permanent set of shafting members could set up such forces. With existing tolerances in the manufacture of shafting it would be impossible for hull vibration to reach the magnitudes encountered in practice due to such imperfections of shafting.

A.N. Kalmakov [14] gave in 1941 the physical explanation of the origin of first-order periodic forces as due to inequality of pitch of separate propeller blades. The calculations made by the author of this review in 1952 on the basis of a quasi-stationary condition verified the assumptions of A.N. Kalmakov and indicated the necessity of tightening the specification for permissible deviation in pitch of individual blades.

As to the forces which are transmitted to the hull through the bearings, one should take into account the possibility of a resonance phenomenon in the propeller-shafting system. A check on this system for resonance can be made by a method presented by Shimansky.

Besides the periodic forces acting in a direction normal to the longitudinal axis of the ship, there are forces acting along the shaft axis arising from thrust variation due to the operation of the propeller in the nonuniform wake at the stern of the ship. This phenomenon was investigated in works of Rigby and Kane and McGoldrick. [15] The authors of these works, referring to cases of longitudinal vibration in the propulsion-shafting systems of battleships and aircraft carriers, present methods of calculating resonant vibration of these systems and means of reducing intolerable vibration of this type by increasing the number of propeller blades, installing the thrust bearing further astern, etc.

FORCED HULL VIBRATION

From the point of view of the mathematical theory of vibration, the problem of forced vibration of an elastic system presents no difficulty if the exciting forces, frequencies, and principal modes of free vibration are known and if, in the case of the ship, the frequency of the exciting force does not coincide with one of the natural frequencies of the hull. However, even the frequency of the fifth mode usually falls considerably below the frequency of third-order exciting forces. As the calculation of a resonant amplitude of a hull, it is necessary to have information on damping resistance which prevents unlimited amplitudes at resonance. At the present time considerable attention is given to the problem of forced vibration of elastic system in the technical literature. It suffices to mention the known works of N.N. Davidenko, E.S. Sorokin, G.S. Pisarenko and others.

In all these investigations, regardless of the hypothesis assumed as to the nature of the elastic forces, there are considered the vibrations of simpler beam systems, in which case it is sufficient to consider only the internal damping of the material. The corresponding experimental work is also limited to the investigation of the energy loss in different materials as such, and not to structures as a whole. However, a ship presents a more complicated mechanical system in which the damping forces do not correspond either quantitatively or qualitatively with those of simple beam systems. From what has been said it is clear that present methods of calculating forced vibration of elastic systems (such as the so-called normal mode method or the known method of Shimansky) permit calculating forced resonant vibration only for the first three or four modes, which generally fall in the range of the first-order exciting forces. The calculation of vibration of higher orders, such as the third in the case of a three-bladed propeller, is not possible by these methods. At the same time it should be pointed out that we do not have a reliable method of evaluating the resonance magnification factor which indicates the degree of damping. For determining its magnitude we can only refer to the formula presented in Volume III of the Handbook of Naval Architecture, and also the formulas recommended by U.A. Shimansky and N.V. Mattes.[1] These formulas do not yield the same results, which apparently is due to the use of experimental data from different types of ships in deducing them.

This problem must be treated differently, namely by a closed form solution rather than by a series of normal modes as when normal coordinates are used. For this purpose the actual nonuniform beam such as a ship's hull must be replaced by some arbitrary beam of the same length and mass but with a constant area moment of inertia of its cross section along its length. The magnitude of the moment of inertia should be based on the equality of frequencies of the higher modes of vibration of both beams. For this purpose the method recommended by Hohenemser and Prager should be employed. Further, it is necessary to set up the differential equations for lateral vibration of a prismatic beam accounting for internal damping, assuming this for simplicity as proportional to the first power of the velocity of deformation. By considering one of the ends of a beam as free and the other as driven by a concentrated sinusoidal force it is not difficult to find the amplitude of forced vibration in closed form and the corresponding pattern of elastic deflection of the ship. The coefficient of internal damping should be chosen in such a way that the form of the elastic line corresponds to that encountered in practice when large vibration of the hull is limited to the stern. A series of calculations gave amplitudes for the ship differing considerably from those measured during trials. At the same time, however, one important feature was clarified, namely that the ratio of calculated to measured amplitudes is constant for a given type of ship. This permits using a single correction factor for a given type of ship. The correction factor apparently takes care of such effects as rotary inertia, shear deflection, nonprismatic form, and variation of internal damping with amplitude and frequency, which are not taken into account in the method of calculation. We may assume that for ships of the same type, built of the same material, and having similar principal dimensions the influence of the factors mentioned will be the same.

It should be noted that the method presented applies only to ship vibration in the vertical plane, in which case this type of vibration can be considered independently of other types. It is obviously possible to extend it also to horizontal vibrations by assuming that to a first order of approximation these are independent of torsional vibrations. However, it is difficult to say at present to what degree this is valid. In general the mechanism of propeller-excited horizontal vibration of a ship's hull, the amplitudes of which are in some cases quite high, has not been thoroughly investigated up to the present. We may assume that it is due to the combination of the horizontal component of force transmitted through the bearings and the torsional vibration of the hull resulting from the pressure pulsations due to opposite phasing of the blades of the rotating propellers.

In concluding this section we may note the work of K.K. Melnikov[16] in which an attempt is made to solve a problem of forced vibration of a hull. The hull is in this case considered as an equivalent prismatic beam with frequencies close to the principal frequencies of the free vibration of the hull.

VIBRATION OF LOCAL HULL STRUCTURES AND EQUIPMENT

One important hull structure is a deck consisting of a system of plating and stiffeners. The vibration of decks can result from vibration of their edges due to the general vibration of the hull and also from the direct action of periodic forces arising from the operation of unbalanced machinery installed.

In reviewing the work in this field, it must be stated that the investigations by A.S. Lokshyn, M.G. Krane, and I.L. Nudelman, as well as A.P. Filipov, published during the period 1935–1940, did not find use in shipbuilding because of the difficulty of direct application of their calculations to decks.

In 1941, Shimansky recommended applying the graphical method of Rayleigh, to the calculation of natural frequencies of decks, assuming beam modes.

In works of A.A. Kurdiumov[17] published in the period 1948–1954, solutions are given for finding the frequencies of free vibration for the practically important case of decks composed of identical equally spaced stiffeners in the longitudinal direction, and rigidly or elastically attached at their ends, and of transverse stiffeners differing in mass and rigidity and hinged at the ends. In work published in 1950[18] there are presented approximate methods of calculating natural frequencies of decks, these decks having a sufficiently large number of identical stiffeners in both directions, assumed fixed at the ends, and for decks having a a large number of longitudinal stiffeners with one or two transverse stiffeners.

In 1954 V.K. Egupov[19] presented a method of calculation of natural frequencies of decks based on the use of series. The author asserts that his method giving the exact solution for decks having similar stiffeners in each direction permits an approximate solution for decks having a limited number of stiffeners which are different in the two directions.

As follows from this brief review, the problem of free vibrations of decks may be considered as having been adequately investigated. When it comes to forced vibration including resonant vibration of this type of an elastic system it must be said that practically nothing has been done in this field. The main obstacle is the absence of experimental data as to the magnitude and nature of the internal damping of the structure as a whole.

Closely associated with the problem just reviewed is the problem of the vibration of of decks, panels of which, bounded by stiffeners, can be treated as rectangular plates.

The pecularities of ship construction involving the use of plates in shaping the configuration of a hull introduces factors which require special consideration in vibration calculations. In many cases the boundaries of plates cannot be considered rigid; some plates are under tension or compression in their neutral plane due to bending of the ship as a whole; moreover, it is often necessary to take account of the curvature of the plate.

At present the majority of the problems enumerated above with regard to ship plates can be considered satisfactorily solved owing to the works of N.V. Mattes, V.S. Chuvikovsky,* and also due to investigations of I.F. Sharov, V.M. Krishen, V.G. Baburin, and other authors.

As is known, ship plates are at times in contact with fluids–the surrounding water, or fuel or lubricating oil in tanks. Formulas for computing the so-called entrained mass of fluid during vibration of rectangular plates at the frequency of the fundamental mode are given in Reference 20 for width-to-length ratios in the range 0.5 to 1.0. N.V. Mattes [21] has obtained a corresponding solution for a long plate and thus the entire range of plate dimension ratios has been covered.

In addition to the problems reviewed above, shipbuilding practice has been concerned with the problem of the vibration of masts. Methods of calculating free vibrations of masts are adequately presented in books of Shimansky and Kurdiumov.[22] Problems of vibration of masts due to gunfire are also presented there. There are also given methods of calculating the vibration of masts due to vibration of the whole ship.

We do not consider here the vibration of periscopes and other unusual structures because these involve special problems in hydrodynamics which are outside the scope of this review.

EXPERIMENTAL MEANS OF INVESTIGATING HULL VIBRATION

In the last 10 to 15 years means of investigating vibration have been greatly developed. Mechanical vibrographs of the Geiger type and portable vibrographs of the Askania type have found wide application in shipbuilding. However, this equipment has the drawback of not yielding simultaneous records for far distant points on the ship. Such measurements can be made successfully only with the aid of an electrical recording system. For this purpose wide use is made of electrodynamic vibrographs VL–50 and vibrometers Shch–30, designed by N.A. Leptin, the main feature of which, aside from simplicity of construction, low weight, and reliability in operation, is the possibility of recording directly on an ordinary oscillograph without special electronic amplifiers.

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*Chuvikovsky, V.S. "The Local Impedance of Ship Structures to Vibratory Loading." Paper presented at the Scientific Technical Conference on Seagoing Qualities and Structural Mechanics of a Ship, dedicated to the memory of academician A.N. Krylov.

Experience in measuring vibration on ships shows that in the majority of cases there is increasing vibration of local structures and machinery but that excessive vibration of the ship as a whole is at present seldom observed. As a rule intense local vibration is due to coincidence of natural frequencies of ship structures with the operating exciting frequencies. Since such troubles are disclosed only during ship trials and require additional work on the ship in question, there is a need for discovering such possibilities during the final period of ship construction prior to the trials. This can be done by applying to the stationary hull by artificial means periodic exciting forces similar to those encountered in operation of the ship. For this purpose so-called vibration generators are used at the present time which consist of a set of four rotating eccentric masses, the speed and eccentricity of which can be varied over sufficiently wide ranges. The description of such machines and also the methods of using them are given by V.G. Lentiakov, who developed with N.G. Chupelin the first vibration machines in domestic shipbuilding, applying them successfully in practice.

It should be mentioned that a vibration machine, in addition to simulating vibration under trial conditions, can also be utilized for the investigation of damping characteristics. A comparison of the amplitudes of forced vibration of a hull produced by periodic forces of known magnitude from the vibration machine with the amplitude during operation of the ship due to propeller-exciting forces permits an evaluation of the latter forces.

It is known that vibration machines have found application also in foreign shipbuilding. The results of such investigations are described, for example, in the works of Richards[23] and Johnson.[5]

In concluding this review of the problem of ship vibration, some consideration should be given to current problems in this field.

With effective methods of calculating vibration and apparatus for experimental investigation of its mechanism available we should look into the problem of prevention of vibration in the design stage and of eliminating it on ships already in service by the use of vibration dampers, etc. Since standards for vibration on completed ships have been established on the basis of statistical norms, we should give more attention to the problem of improving present methods and developing new methods of calculating forced vibration. For this purpose we must expand our knowledge of the damping characteristics of the structure as a whole and and other factors limiting the resonant amplitude.

It is necessary to continue the investigation of pulsating pressures due to propeller action extending this to propellers working under conditions of highly developed cavitation and also to propellers for new types of cargo ships. If in the near future we shall be able to solve these problems and also a series of new ones arising from the rapid development of shipbuilding techniques, we will thus in the best way advance the work which was begun more than a half-century ago by academician A.N. Krylov and we will contribute practically to the development of our science.

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David Taylor Model Basin. Translation 291.
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1. Ships – Vibration
I. Babaev, N.N.

David Taylor Model Basin. Translation 291.
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1. Ships – Vibration
I. Babaev, N.N.

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1. Ships – Vibration
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