LONGITUDINAL STIFFNESS OF MARINE PROPULSION THRUST BEARING FOUNDATIONS

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THE AUTHOR

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THE PROLOGUE

PERHAPS no other organization in the world offers the diversity of engineering billets found in the Navy's Bureau of Ships. It is the agency charged with the design, construction, and maintenance of the United States' Fleet. And a modern man-of-war may be likened to a fortified and extremely mobile industrial city. There is probably no art or science that isn't reflected in the completed warship. After all, naval fighting ships are mightier in some respects than the Grand Coulee Dam; yet as small and sensitive in others as a delicate Swiss watch. Whatever the scientific specialty—there is a corresponding challenge in the Bureau of Ships.

Foremost among challenges is the continuing problem of keeping the assorted ship design experts acquainted with each other's efforts. It's easy to imagine that Solomon himself wouldn't today enjoy the excellent reputation that he does, had he ever been challenged to reconcile the often conflicting interests of the physicists, scientists, and engineers involved in warship design. And the latter is, of course, precisely the problem that confronts anyone having the temerity to discuss main thrust bearing foundations.

THE PRINCIPALS

First, there is the physicist. He is interested in the frequency and amplitude of longitudinal vibration excited by propeller thrust. These are, among other things, a function of the thrust bearing foundation stiffness. He therefore sets about positively determining this elusive foundation spring constant.

Then there is the hull scientist, an expert on structural mechanics. He is concerned more directly with foundation problems, since he must actually design the supporting members for the components of the shafting system (including the thrust bearing itself), and must moreover provide for absorption of the transmitted propeller thrust by the hull structure. He thinks in terms of dynamic loads and static loads, and bending moments and shearing forces. Still, it's quite possible that he has never worried about the thrust bearing foundation longitudinal spring constant.

Finally, there is the marine engineer. His concepts serve to bridge the gap between the precept of the scientist and the precept of the artisan or craftsman. This is particularly true as regards the problem of providing an adequate thrust bearing foundation. After all, it is the marine engineer who is responsible for accommodating and arranging the propulsion machinery within the confines of the hull.

THE PURPOSE

While the physicist may desire a specific minimum foundation stiffness, and the hull scientist may design the best practicable foundation under the circumstances; it's entirely possible that neither is aware of what the other is doing. Moreover, as we shall endeavor to show, only the marine engineer can assure that the one can fulfill the desires of the other, by so arranging his equipment as to allot sufficient space for accommodating the proper foundation. Accordingly, this paper is not intended to serve as a technical treatise for the enlightenment of physicists or hull designers. The literature is already replete with such material. The real problem concerns the marine engineer's failure to fully understand or appreciate his design requirements. Therefore, the purpose of this article is to apprise the propulsion plant designer of the inter-related foundation design interests of the physicist and hull designer; acquaint him in general terms with the basic principles underlying their efforts; and especially, to provide him with a simple but practical design technique which will assure his automatically satisfying their needs and desires.

THE PROBLEM

The longitudinal stiffness of propeller thrust bearing foundations (usually denoted as the foundation spring constant, k_f) is very important in the design of high-powered vessels, particularly those employing propulsion components of large mass coupled to long shafting systems. This results from the fact that the longitudinal frequencies of a propulsion mass-elastic system are (unlike the torsional frequencies) a function of foundation stiffness as well as of the component masses involved. At the same time, the magnitude of the fore and aft thrust of the propellers, plus any margins for fore and aft shock impact, plus (in the case of submarines) the axial hydrostatic load on the propeller hub at deep submergence—all combine to make the longitudinal load on the thrust bearing foundation a most severe loading condition.

Excessive vibration amplitudes in the longitudinal or axial direction of the propeller shaft system may occur when the natural frequency of the system (as determined by the masses of the propeller, entrained water, shafting, and connected gear wheels; and the flexibilities of the shaft and thrust block) is such that resonance is excited in the operational range of propeller revolutions by the thrust alternations occurring at blade frequency. A determination of longitudinal frequencies with relation to the maximum propeller rpm of the vessel therefore becomes an important factor in the design of large high-powered vessels, if unacceptable longitudinal vibration amplitudes are to be avoided. When calculations undertaken in the early design stages indicate that these longitudinal criticals lie in or near the rpm range of the propeller, it is possible to shift the criticals with respect to the propeller speed range by changing shaft dimensions, the longitudinal location of the thrust bearing, the number of propeller blades, or the foundation stiffness.

As regards the thrust block foundation itself, it should be noted that the maximum practicable stiffness is fairly well fixed by considerations apart from the vibration problem, such as the approximate location of athwartship condensers or other large machinery items which interrupt the fore and aft continuity of the thrust foundation. At the same time, while the stiffness of the thrust bearing foundation may greatly influence the calculated critical frequencies, the massiveness of the structure, plus the fact that frequency varies as the square root of the spring constant, suggest that an impractical extent of reinforcement would be required to appreciably shift calculated frequencies. Thus, foundation stiffness is not determined with a view to strengthening it, if critical system frequencies and propeller blade frequency coincide, but rather, it is estimated only as an incidental step in the predicting of natural longitudinal frequencies.

THE PRACTICE

It follows from the foregoing that it usually isn't necessary to know the foundation stiffness with a high degree of accuracy. As a matter of fact, the customary procedure in new design is to investigate the sensitivity of calculated criticals to experimentally determined ranges of longitudinal foundation stiffness, so as to determine the limits of permissible error in the estimated foundation spring constant. It should be further noted that the estimated spring constant is normally derived solely from experimental data previously obtained for comparable installations. Thus, k_f ranges from 5 to 20 million (inch-pounds per radian) for thrust bearing foundations located adjacent to the propulsion reduction gear casing, and k_f ranges from 20 to 40 million for thrust foundations located well aft and separate from the propulsion machinery.

It is fortunate that reasonable estimates of k_f are all that is required, since the flexibility of bearing supports is the most indeterminate factor entering into the calculation of longitudinal criticals. Detailed analysis and calculations of k_f are possible only after thrust bearing mounting, foundation, and propeller shafting system drawings have been developed. This very fact emphasizes again that k_f is not a truly variable factor in the design process. Even in the advanced design stages the calculations, though quite involved, represent only educated guesses, due to the indeterminate nature of the end-fixity of the various members of the foundation, and the resilient nature of the hull of the vessel itself.

Even those experienced in the art of estimating spring constants find the determination of k_f extremely difficult, and widely varying opinions among the experts are the rule rather than the exception. One famous research organization required a month to estimate k_f for a complete vessel, for which all the physical data were known. A large shipbuilding concern found reasonably accurate estimates of k_f to be impossible, and therefore calculates the variation in frequency for values of k_f ranging from 7.5 to 30 million, which they consider to be representative of the worst and best possible foundations, respectively.

THE PROPOSAL

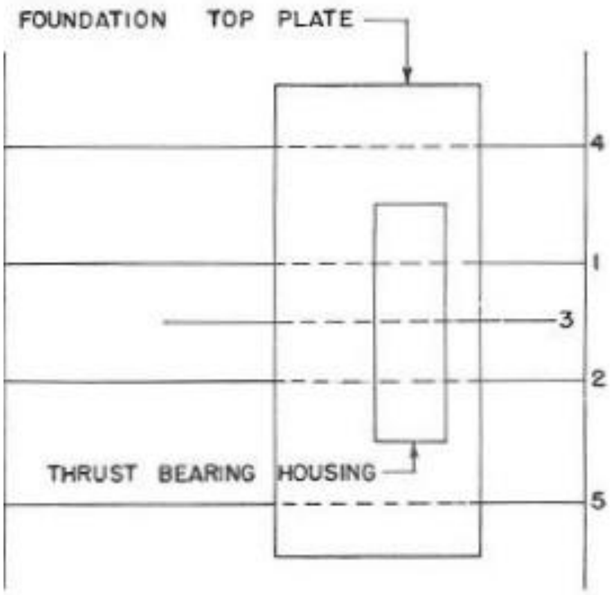
In any case, k_f can be accurately determined only experimentally, by shaker tests, after a vessel is completed. Nevertheless, an estimated k_f is required in the early design stages for purposes of vibration analysis. Moreover, since substantial improvement in the completed foundation is normally impossible or impracticable, there is even more reason for developing some simple procedure for predicting k_f values in advance of completing a new ship design.

The procedure envisioned should enable the arrangement engineer to advise the physicist at an early stage as to the apparent practicable limits of k_f achievable in a given location for a given design. Again, it should permit the ready evaluation of the relative merits of alternate foundation location possibilities. Above all, it should serve to guide the arrangement engineer, such that he will allot adequate space for the hull designer, with a view to enabling a foundation design that will incorporate the stiffness characteristics that vibration analysis indicates are necessary or desirable.

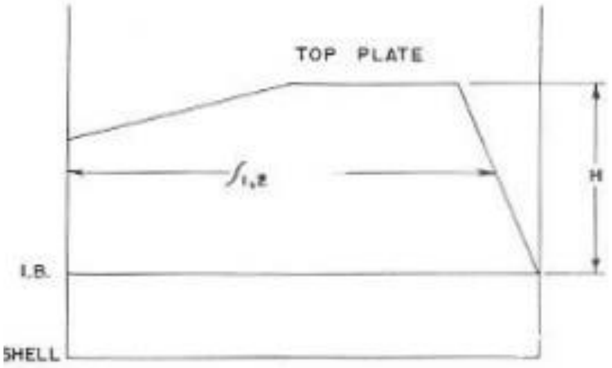
Accordingly, a simple but reasonably valid method for predicting k_f is presented herewith. It, should be noted that the procedure described does not apply to those instances wherein the numerical value of "R" (a term to be defined below) is less than approximately 0.33 (at which point, bending deflection—which the proposed method neglects—is more critical than the shear deflection). Nor does it apply to those foundation arrangements in which the top plate is extended to and joined with a longitudinal bulkhead or the rising shell of the ship. Furthermore, the admitted accuracy of the proposed procedure is on the order of plus or minus 8 percent. However, the speed of application of the method is considered to far outweigh the limitations on its accuracy, especially in view of the generally acknowledged indeterminate nature of the entire “science" of estimating k_f.

THE PROCEDURE

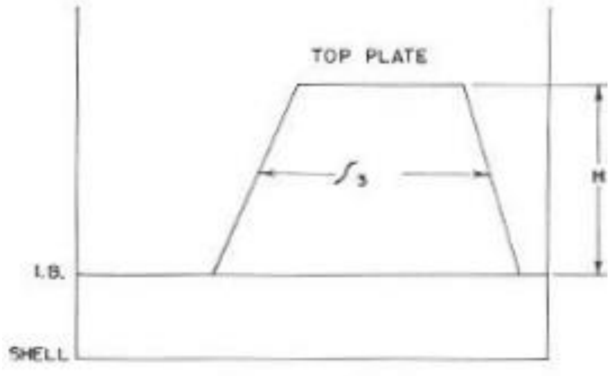
(1) Determine “H,” the maximum height of the top plate above the inner-bottom. See Figure I-c.
(2) Determine "L," the average of the mean lengths of all the girders fully effective in shear.



(a)
Plan



(b)
Elevation (Girders No. 1, 2)



(c)
Elevation (Girder No. 3)
Figure 1. FOUNDATION SKETCHES

  a. Fully effective girders are those that transit directly below the bearing housing, e.g. No. 1, 2 and 3 per Figure 1-a.
  b. X Mean lengths (1, 2, 3) are as indicated in Figures 1-b and 1-c.

(3) Determine “R,” which is the ratio of ' 'L' divided by “H.”

(4) Determine “k_f” as a function of "R," utilizing the appropriate curve presented in Figure 2.

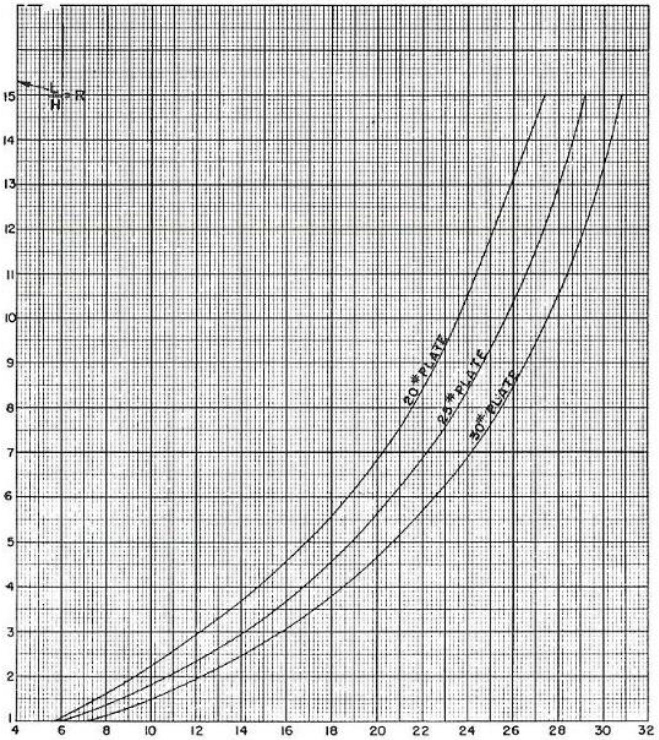
That is all there is to it. And it should be noted that this procedure may be applied even before foundation plans are developed. For example, reasonable maximum practicable values of "H" and “L” can be estimated for any given location directly from preliminary shafting or machinery arrangement plans.

THE PRINCIPLES

The foregoing procedure is based upon the fact that the two principal factors entering into longitudinal foundation stiffness are the shear deflection in the central girders fully effective in shear, and the deflection due to rotation of the inner-bottom. It is realized that additional parallel girders (i.e., those parallel to the centrally located fully effective girders) that are tied into the foundation by the top plate, and the transverse floors, also contribute to the stiffness of the foundation. However, the literature suggests that the over-all effectiveness of these members is relatively minor, even as common sense would suggest that these outlying members are going nowhere until the strongest link in the system, the central fully effective girders, start to deflect.

It is also realized that bending deflection as well as shear deflection occurs in the central fully effective girders. However, where the length of the girders is not less than approximately one-half the height of the girders, this effect too appears to be minor. In any case, the additional complication involved in calculating bending deflection (which involves moments of inertia of assumed configurations with assumed degrees of end-fixity) is not warranted by the effect on the accuracy of the estimate.

As for the deflection due to inner-bottom rotation, the curves (Figure 2) reflect an assumed inner-bottom stiffness of 40 million which appears to be reasonable for vessels of conventional inner-bottom structure. At any rate, the accuracy of the results of the foregoing procedure seems to justify and confirm the reasonableness of the assumed inner-bottom stiffness. The latter acts in series with the girder (shear) stiffness in resisting deflection, and these two values are therefore combined reciprocally.



Plan
Figure 2. Longitudinal Foundation Stiffness

The foregoing principles constitute the basis for the proposed procedure. It might be well to note that the longitudinal stiffness is independent of the number of girders, since the acting force (thrust) is assumed to divide equally between all the central fully effective girders. The corresponding deflections reflect this pre-proportioning of acting forces; the ratio of force to deflection (which is “the stiffness”) being constant as a function of the geometry and physical properties of the materials involved. Of course, the value of the deflection, and hence the vibration amplitude, is a function of the number of girders, but this need not concern the marine engineer.

THE PROSPECT

It is to be hoped that the ideas presented herein may prove useful to all those concerned with thrust bearing foundations. For the machinery arrangement engineer it emphasizes the importance of allowing for longitudinal girders four to five times as long as they are high (from inner-bottom to top plate), in the area immediately below the thrust bearing, if a normally acceptable value of stiffness is to be achieved. The method also affords a quick means by which the hull designer can corroborate estimates of k_f submitted by design agents. It further provides an early index of practicable ranges of k_f in any given case for use in early design stage vibration analysis. Finally, the novel nature of the presentation permits the ready addition of check points for refining the curves as actual shaker test experience and results accumulate.