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DYNAMIC POSITIONING CONFERENCE

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DESIGN SESSION

Thruster Noise

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NAB & Associates, Inc. & Offshore Model Basin

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INTRODUCTION

Trainable Kort-nozzle thrusters are being installed in increasing numbers to provide the dynamic positioning (DP) of drilling ships and semi-submersibles operating in deep water. These thrusters are large and have high powers; they invariably operate with cavitation. Without the baffle effect formerly furnished by transverse tunnel thrusters, the underwater noise radiated by this cavitation threatens to interfere with the operation of the DP systems. The consequences of loss of position control during drilling operations remain very costly.

In this paper we discuss the nature of thruster propeller cavitation noise and means for estimating its intensity, as well as engineering means to reduce this noise. We show that the worst noise outputs which can be expected are estimable with reasonable accuracy. At least three means of noise reduction: hydrodynamic design to minimize cavitation, baffling, and air emission, have been applied in the past, but it appears that only hydrodynamic design is useful for quieting the modern, high-powered, trainable thrusters.

UNDERWATER RADIATED NOISE ESTIMATION FOR THRUSTERS

Basis for Underwater Noise Estimation

On the basis of early work in Naval ship noise [(1)] and our own analyses, we have found that propeller or thruster cavitation noise intensity has an asymptotic behavior. This limiting noise intensity, for which we presume cavitation is fully developed, is found to vary simply as:

$$I \propto B\,D\,V_t^3\,\sqrt{H}$$

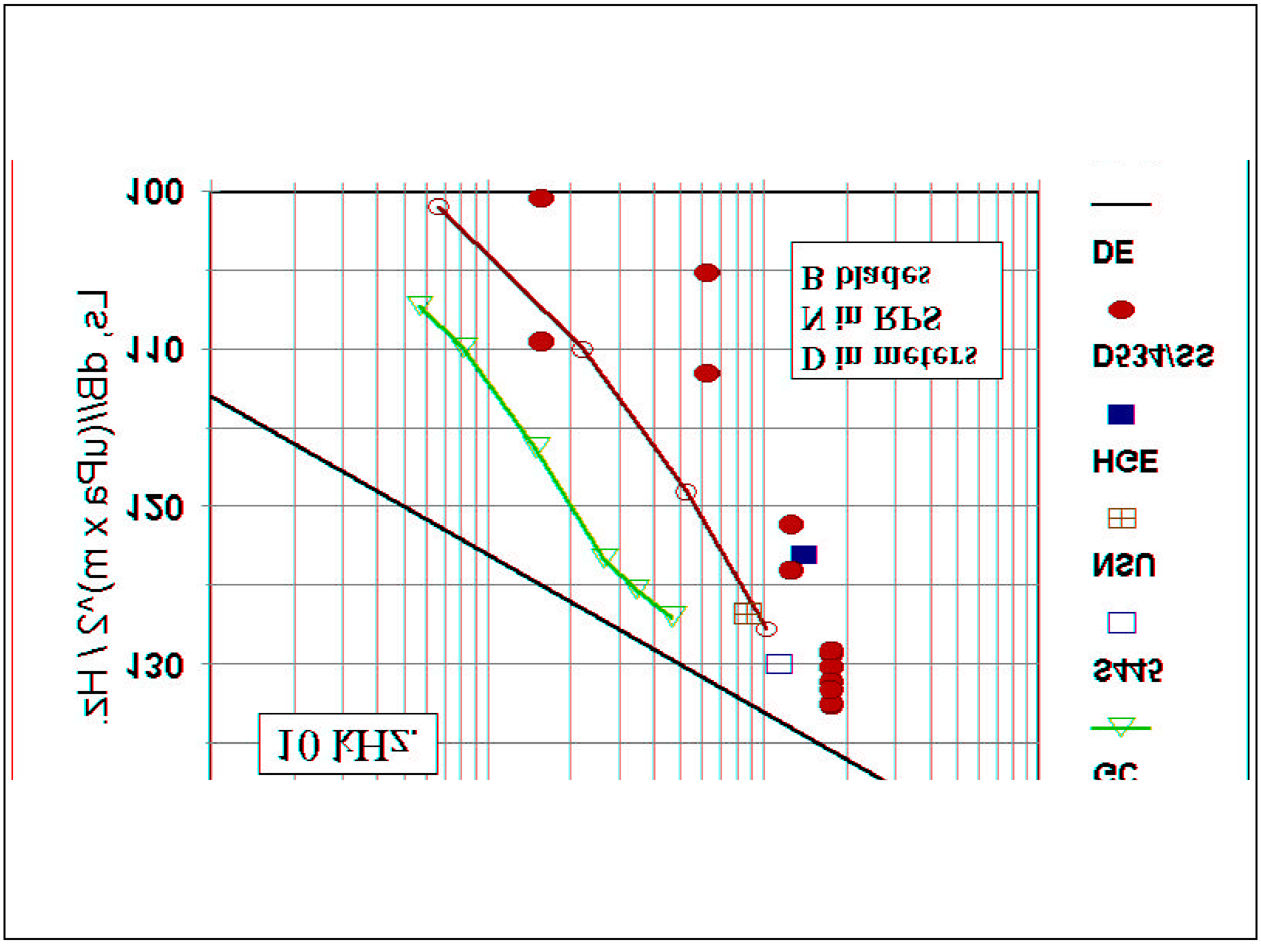
where: I is the acoustic intensity, B is the number of blades, D is the diameter, V_t is the tip speed, and H is the absolute head above vapor pressure.

The above assumes a fixed frequency. We have found by measurement and review of the literature that the frequency dependence of cavitation noise at mid to high frequencies is typically between f^{-1} and f^{-2}, that is, between -3 dB/octave to -6 dB/octave when considered in constant bandwidths.
We believe the former is more typical and is certainly the more conservative when scaling upward in frequency. We recommend the assumption of the f^{-1} spectral shape for noise prediction purposes.

In figure 1, we have collected the measured radiated noise source levels of several different thruster installations and compared them to the asymptotic limit discussed above. The abscissa is the BDV^3 parameter; the head factor, H, is ignored as its square-root is nearly equal for these units. The drillships involved are identified by the following key:

Symbol	**Drillship**
GC	GLOMAR CHALLENGER
S445	SEDCO 445
NSU	NSU (?)
HGE	HUGHES GLOMAR EXPLORER
D534/SS	DISCOVERER 534, SEVEN SEAS
DE	DISCOVERER ENTERPRISE

All but the last of these ships or semi-s are at least 25 years old. The particulars of their noise data are discussed in the Appendix. The new data for ENTERPRISE is found to agree well with the trends of the old cases, which lends confidence to the estimation procedure. Discussions of the ENTERPRISE and the seemingly anamalous SEVEN SEAS are found below.



The source level ordinate is a measure of the radiated noise intensity. When measured at a distance R, in meters, from the thruster, the sound pressure level is increased by the law of simple spherical spreading; namely 20 log R in decibels. The result is the sound pressure level that would be measured at a distance of one meter from the thruster noise source if replaced by a point source with the same acoustic power output.

The source levels shown are for those aspect angles where the observer is looking directly into the thruster duct. For other angles, a certain amount of baffling may occur yielding apparent reductions of source level.

Similarly, in those situations where the acoustic propagation law does not follow R^{-2} other errors may be introduced in the measurement of source level. The Asource level@ is a construct but is the accepted representation in underwater acoustics.

The point of figure 1 is that all of the data shown approach, but do not exceed, the asymptotic limiting line. This approach to the limiting line with thrusters of widely varying sizes and speeds encourages us to believe that we can predict the highest source levels to be expected of a new thruster design with fair accuracy. This is important because it is those highest values which threaten the integrity of acoustic DP systems.

Estimation Formula

We interpret the difference between the asymptote and the data for any given thruster as the fraction of the propeller disc area which is not swept by cavitation. On the limiting line, the cavitation is presumed fully developed or sweeping 100% of the disc area. To be more specific, we may write that the one-meter

$$L_s = 133 + 10 \log (B D^4 N^3 f^{-1}) + 10 \log (A_C / A_D)$$

source spectrum level for thrusters at frequencies above 10 kHz. is estimable by:

where: B is the number of blades, D is the propeller diameter in meters, N is the operating revolution rate in rps, A_D is the propeller disc area, A_C is the swept area of cavitation, and f is the frequency in Hz. No baffling is interposed.

The last term makes the estimate pertinent to a particular thruster design and operating condition where the swept area of cavitation is either estimated or known from observation of a model test. The ratio A_c/A_D being less than one, this term is always negative. When $A_C = 0$, i.e. before cavitation inception, there is no cavitation noise. If the basic parameters shown in the second term have already been selected, then the reduction or minimization of the cavitating area, A_C, becomes the appropriate design objective for reducing - noise.

Cavitation in the tip clearance gap is not implicitly included in the formulation but must of course be considered. If this is done, the ratio A_c /A_D can be greater than unity in extreme cases. For tip cavitation, a value $A_C/A_D = 0.1$ can reasonably be assumed.

Some of the thrusters shown in figure 1 approach to within about 3 dB of the asymptote. This corresponds to cavitation from the blade tip down to the 70% radius over the full periphery. Finally, it has been observed that both bubble type cavitation associated with blade section thickness and intermittent cavitation associated with blade passage through the wakes of struts etc. is noisier than simple leading edge type cavitation. This is undoubtedly true but is not explicitly recognized In the above formulations or plot. Thickness cavitation is avoided by all designers because of' erosion problems; hence it should not be of concern in estimating noise. Unsteady cavitation is considered to contribute to the quantity A_C in the above, but with equal weight in comparison with steady cavitation.

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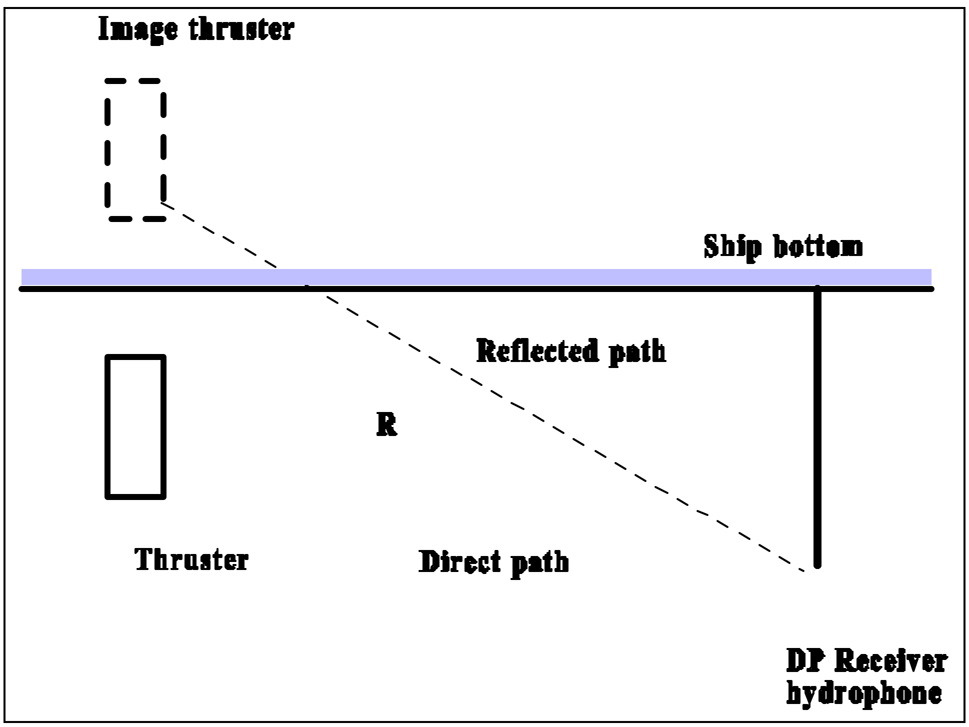
New Data The points in figure 1 identified as ADE@ (DISCOVERER ENTERPRISE) represent new data, very recently acquired.[3, 4] The six thrusters on this large drillship are below bottom, trainable, variable speed, fixed pitch, Kort-nozzle type. They are each rated at 7000 horsepower at 150 RPM, and have four-blade propellers of 4.1 meters diameter. Interference noise levels were measured through the DP system receivers at various thrust levels and training angles of several thrusters while in deep water in the Gulf of Mexico. The data were analyzed in the following manner, which illustrates the Asource-path-receiver@ paradigm.

From the geometry of the locations of the various thrusters and DP system hydrophones [3] the slant range from each operating thruster or thruster group (of two) to the receiving hydrophones was calculated, along with the elevation angle, and the corresponding spherical spreading transmission losses were



estimated. Note that, because of efficient reflection from the ship=s bottom at shallow grazing angles, there are two paths for noise transmission for each thruster-hydrophone pair; see figure 2. Effectively, the number of thruster sources is doubled, but the reflected Atwin@ has a transmission path approaching the hydrophone at a higher elevation angle.

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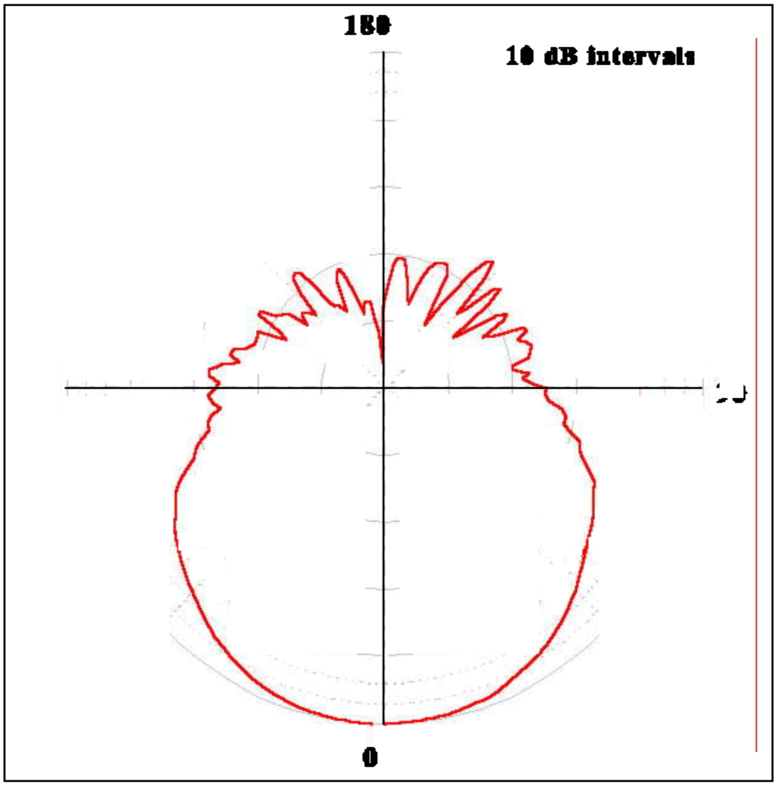
The elevation angles of the various noise paths (the upper extreme of the propeller is considered the strongest source area) are applied to a polar plot of the receiver hydrophone sensitivity. The pattern for the receivers on ENTERPRISE is shown in figure 3. (4) Clearly, a major reducer of apparent noise levels is found in the strongly reduced sensitivity of the receiver at angles above the horizontal. As the apparent sound



pressure level is based on the on-axis sensitivity of the receiver and its measured voltage output, the true SPL at the receiver location is found by adding to the apparent level the attenuation, in decibels, shown by the pattern at the angle of sound incidence. The Aone-meter source level@ of the thrusters= radiated noise is then found by adding to the SPL at the hydrophone location the transmission loss over the path from the thrusters= locations. The single thruster source level is estimated by removing the contribution of the ship bottom-reflected path, or image thruster; a reduction of typically 2 to 3 dB. (It would be 3 dB if the direct and reflected path contributions were equal.) Of the new data shown in figure 1, source levels at the lower thrust levels have undoubtedly been elevated by ambient noise in the through-system measurement. Note that there may not be a significant reflected path on a semi- when the thruster and receiver are on different pontoon-bottoms. The sea suface may then enter in, however, but probably at a larger elevation angle.

NOISE REDUCTION

Design for Cavitation Reduction

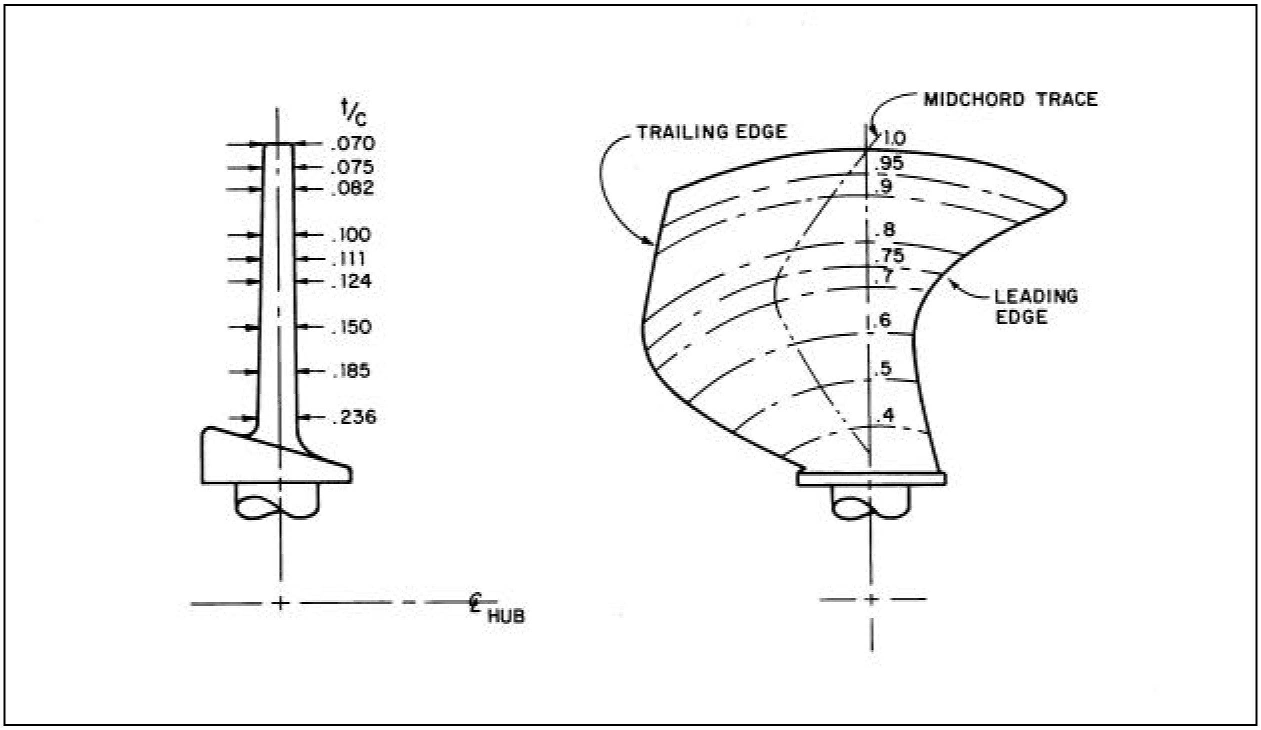
As the above discussion has made clear, the reduction or elimination of cavitation, both steady and unsteady, sheet, bubble and tip type, is the most direct and effective way of reducing the underwater radiated noise of thrusters. In this regard it is instructive to examine the point in figure 1 identified as AD534/SS.@

This represents a measurement of one of the lateral thrusters on SEVEN SEAS when operating at rated power. This ship, and its sister DISCOVERER 534, has six of these 2500 HP transverse tube-thrusters located below the keel. They are unusual in that they are AC motor driven at constant rotation rate, with controllable, reversible pitch (CRP) propellers for varying the magnitude and direction of their thrust.

The requirement of port-starboard symmetry of perfromance with uni-directional rotation required that the blades be Aflat,@ that is, have no twist. Consequently, when pitched for producing thrust in either direction the blades= pitch distribution was all wrong; the tips were over-pitched and the blade roots under-pitched relative to the ideal helical surface. Further, the discrepancy increased with thrust level, making these thrusters potentially poor performers from a cavitation noise standpoint. But a difficult noise requirement was invoked for these acoustically DP=d vessels; the Offshore Company demanded 10 dB of noise reduction relative to conventional reversible DC motor-driven thrusters at DP frequencies.

The solution was found in a design concept combining increased blade thickness and a radical swept-forward blade outline; both of which provide tolerance against cavitation due to incidence angle (angle of attack). The blade design is shown in figure 4.(2)

To make a long story short, this design concept worked rather well, as may be seen by comparing the point marked AD534/SS@ with the limit line and with its neighbors in figure 1.



Now it may be argued that this acoustic performance was achieved by reduced loading relative to, for example, the modern high-powered trainable Kort-nozzle thrusters of the Transocean DISCOVERER ENTERPRISE. There is merit to that argument as witness that the SEVEN SEAS units have only about 45% of the power per unit disc area of the ENTERPRISE units. Now, as then, maintaining modest loading with increasing installed thruster power is not an economic option. Rather, loading must increase to limit cost, size and weight.

However, extensive cavitation tunnel model testing of the forward-swept blade CRP thruster design showed major improvements relative to conventionally designed blades at the same maximum thrust values. Leading edge and blade surface cavitation was virtually absent on the thick, swept blades whereas it was copious on the thinner, straight blades. Only tip-gap cavitation remained. The full scale acoustic results are consistent with the model observations. Thus, this case becomes Athe exception which proves the rule.@ It may further be noted that the forward-swept blade concept has been incorporated into mixed-flow and axial pumps in noise sensitive applications with notable success.[5]

It is concluded that a useful noise reduction can be achieved on modern, highly loaded trainable thrusters by careful design, incorporating unconventional features.

Baffling

The duct, tunnel, or nozzle of a thruster may serve as an acoustic baffle to reduce the underwater noise radiated in certain directions, namely those perpendicular to the thrust axis. The angular extent of the "shadow zone" depends greatly on the length-to-diameter ratio, L/D, of the thruster duct. With relatively long ducts and fixed transverse thruster orientation, the older generation of drillships often benefitted greatly from baffling of the cavitation noise.

For thruster ducts with L/D less than 1.0, we can expect little baffle effectiveness; the shadow zone will become narrow and shallow. In practice, It would be unwise to rely on the baffle effects of a trainable thruster unless the range of its allowable training angles were severely restricted; a highly undesireable situation.

Pressure Release Material

Examination shows that any practical application of pressure release or compliant materials in the thruster interior will have no important effect on high-level cavitation noise at the frequencies pertinent to acoustic positioning systems. The basic idea of having a low impedance, compliant material in the vicinity of an acoustic source, like a cavitation bubble, is that the source tends to be Ashort circuited@. A hydrodynamic velocity is created, which does not radiate, rather than an acoustic pressure when a volume source works near a compliant boundary. To explain this behavior, one may examined the radiation from a volume source in the vicinity of an infinite plane wall of compliant pressure release material. It will be found that noise reduction, relative to the same source without the wall, only occurs if the source is located within about 1/6th of an acoustic wave-length from the pressure release surface. For the frequency range 15 to 60 kHz that is a distance of 20 mm to 5 mm respectively. Therefore if the inside of a thruster duct could be lined with compliant material, It would reduce the noise only of cavitation occurring within perhaps 20 mm of the wall. Noise from cavitation in the tip clearance gap would be reduced but there would be no effect on noise from cavitation over most of the screw blade at these frequencies. Therefore, the noise at low thrust values would be reduced but not at the rated thrust unless the thruster were to achieve almost cavitation-free operation. In that case, further noise reduction would probably not be needed.

Air Emission Systems

Naval experience has demonstrated that nozzle and propeller air emission systems yield a very large reduction of cavitation noise in the frequency range of interest. We expect not less than 5 dB and perhaps as much as 20 dB of noise reduction by this method. Some manufacturers offer air-emission noise reduction for tunnel thrusters on cruise ships, which systems are effective in the lower frequeny, audible ranges. These are aimed at reducing structureborne noise excited by cavitation.(6)

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However, great care must be taken that air emission-equipped thrusters do not carry air bubbles to the vicinity of the ship's DP system hydrophones. Gas in the water near the hydrophones not only generates noise but introduces serious position errors by effecting the local speed of sound in the water. This problem can be avoided by locating the hydrophones sufficiently far below the ship's bottom. This, with the expense and complication of added air systems in trainable thrusters, makes air emission for DP noise reduction a poor prospect for drillships.

Conclusions

Recently measured noise data on DISCOVERER ENTERPRISE agrees well with expectations based on a cavitation noise prediction formula and a collection of old data. DP systems with trainable thrusters do not benefit from the baffle-effect noise reduction furnished by the transverse tunnel thrusters which were formerly common. However, because of the favorable directionality of DP system receiver hydrophones, apparently only the highest levels of thruster noise threaten to interfere. Those highest levels may be predicted with confidence.

As there is not now a need to reduce lower levels of thruster noise (those occuring at all but near-max rated thrust levels) means for reducing lower levels of noise, such as that due to tip-gap cavitation, are not called for. Noise reduction by means of air emission appears dangerous to acoustic DP systems. Since trainable thrusters typically have short Kort-nozzle ducts their baffle-effect is small, no matter how Aacoustically opaque@ the duct structure. Since they are trainable, baffle-effect noise reductions cannot be counted on in any event.

The highest levels of cavitation noise in ducted thrusters can be reduced adequately by application of some advanced blade-form concepts; specifically swept-forward leading edge outlines and more rounded blade section leading edge profiles.

References

(1) @An Analysis of the Cavitation Noise Characteristics of Ships, Submarines, and Torpedoes,@ D. Ross and B.W. McCormick, Jr., Symposium on Hydraulic Propulsion, Washington, D.C., March 1950.

(2) AThruster Design for Acoustic Positioning Systems", N.A. brown, J.A. Norton, San Diego Section, Society of Naval Architects and Marine Engineers, April, 1974

(3) Data supplied by Transocean, September 1999.

(4) Data supplied by Sonardyne International Ltd., September 1999.

(5) "Impeller Vane-Edge Design for Improved Cavitation Performance," N.A.Brown, Second ASME Pumping Machinery Symposium, Washington, DC, June 1993.

(6) AKAMEWA Conquers Noise,@ Excellence in Propulsion, No. 3, May 1998.

APPENDIX

The Old Data

In figure 1, all items are shown at 10 kHz. frequency for comparative purposes. The four points for AGC@ (GLOMAR CHALLENGER) are taken from a report by Schneider(A1). His smoothed source level spectra, derived from measurements at a distance from the ship of from 100 yards to l/4 mile, have here been reduced by 3 dB to eliminate the effects of reflection from the sea surface. Such corrections to the case of an effectively infinite fluid medium put all the data on the same basis.

Data for AS445" (SEDCO 445) thrusters was reported at 20 kHz by Honeywell(A2). We have Increased the level by 3 dB to account for a frequency shift to 10 kHz, as discussed above. The levels were then reduced by 3 dB to eliminate the effects of reflection from the hull bottom, resulting in zero net correction. Corrections for directivity of the thrusters have been applied by Honeywell however, and these corrections are not small.

Data for AHGE@ (HUGHES GLOMAR EXPLORER) were measured by Bolt Beranek & Newman, Inc. during builders trials of that ship. Noise from the skeg mounted stern thrusters was measured at a distance and depth that precluded substantial contributions from reflection paths. Measurements were made over a wide frequency band using calibrated hydrophones with omnidirectional sensitivity The point shown corresponds to 210 rpm as compared to 213 rpm at the rated thrust. The measurements for AHGE@ agree very closely with the prediction made for these thrusters during the design stage.(A3) All the thrusters discussed above are of the fixed pitch type with variable speed, bi-directional D.C. motor drive.

There is one data point, marked ANSU@, for a constant speed, CRP type thruster This Is a trainable unidirectional Kort nozzle configuration with high power. The data point shown is not from the actual machine, however, which had not yet been built, but from measurements made on a scale model in the NSMB vacuum tank facility.(A4) The measured data was scaled in frequency and level from the model to the prototype according to a law developed by the Dutch organization TPD(A5) (which be shown equivalent to our prediction scheme under certain conditions) and reported at 25 kHz. We have shifted the result to 10 kHz. according to the inverse frequency rule and have reduced level by 3 dB to account for water surface reflection; assuming that this contribution was not accounted for in the measurement.

References, Appendix

(A1) Report of Noise Measurements Made During Leg 17 of Deep Sea Drilling Program, for Global Marine Inc. and Scripps Institute of Oceanography, Wm. P. Schneider, September 1971.

(A2) Data supplied by Roy Pierson, Honeywell Marine Systems Div., Seattle, Washington.

(A3) Estimated Cavitation Noise Interference Levels at DOMS Positioning System Sensors, BBN Technical memo. No. 114, 31 Jan. 1972.

(A4) Data supplied by T. ten Wolde, Institute of Applied Physics, TNO-TH, Delft, The Netherlands.

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