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Some Aspects in the Design of Sonar Domes

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Abstract. The importance of vibro-acoustic characteristics in the design of hitherto conventional Sonar Domes is discussed. A practical method of studying full scale domes for their vibro-acoustic characteristics is suggested.

1. Introduction

A large number of ships such as research vessels, fishing crafts, warships, etc. are provided with sonars for different applications. All sonars are mounted inside free-flooding domes. In early days, sonar domes for all sonar applications were designed from mechanical strength and low drag considerations rather than vibro-acoustic characteristics. The dome was viewed as an acoustically transparent streamlined body to avoid direct interaction of flow with sonar array and at the same time offering good mechanical strength to overcome the hydrodynamic forces resulting from movement through water at maximum speed of the vessel in all weather conditions and ensuing ship motions. An attempt is made in this paper to highlight certain aspects to be considered in the design and location of a sonar dome from vibro-acoustic considerations to reduce sonar self-noise and thereby improve its detection capability.

2. Analysis of the Problem

In any ship's sonar system, the main sources of self-noise operating simultaneously are : (i) Machinery generated noise, (ii) Flow noise, and (iii) Propeller noise. Noise sources such as sea ambient noise, electrical noise, general rattles and bangs of loose equipment etc. are however neglected from the discussion. The main paths/mechanism by which the noise from these sources can reach sonar are : (i) Direct mechanical vibration transmitted through the transducer dome mountings, (ii) Direct flow and/or propellar noise excitation, and (iii) Paths through ship's structure radiated into the adjacent water, and then to the dome. Direct mechanical vibration contribution is however not relevant to the discussion because isolation of this vibration can be achieved by proper design and use of antivibration mountings and must be arranged so as to isolate the whole dome structure in the water if they are to be effective.

The other paths/mechanism by which the acoustic energy is carried to sonar inside the dome will interact with dome body in two ways; they are :

(i) Energy will get transmitted into the dome depending upon the acoustic transparency of the dome wall and/or,

(ii) The dome wall will get excited into flexural vibrations causing radiation into the interior of the dome as self-noise.

From the above observations, it can be concluded that dome design, from vibro-acoustic point of view, should follow the principles of good wall design which cannot be easily vibration excited while retaining its acoustic transparency at the sonar operating frequency.

3. Vibro-Acoustic Characteristics

Some of the characteristics of the dome to be considered in this paper are: (i) Boundary layer pressure fluctuations on the dome wall, (ii) Acoustic transparency of the dome wall, (iii) Structural damping properties, (iv) Size of the dome, (v) Dome wall configuration, (vi) Response due to acoustic excitation, (vii) Ocean wave effects on the dome, (viii) Radiation effects in the dome interior, and (ix) Location of the dome in the ship's structure.

The conceptual ideas on the above vibro-acoustic characteristics are briefly discussed below :

(*i*) *Boundary Layer Pressure Fluctuations*

When a fluid flows past the dome wall, a boundary layer, characterized by turbulent flow conditions, involving fluctuating velocities or pressures is formed at certain speed. Lighthill[1], page 13 (1952) published a classic paper giving the theory of sound produced by free-turbulence. Curle[1], page 14 (1955) extended Lighthill's theory to include the effect of rigid body adjacent to a region of turbulence. He showed and Phillips[1], page 15 (1956) confirmed that the intensity of radiation from surface pressure fluctuations on the body is proportional to the 6th power of the mean flow Mach number. This gives an indication that for flows over sonar dome, direct radiation from boundary layer pressure fluctuations adjacent to dome cannot be of importance. However, these pressure fluctuations can excite dome-wall vibrations which are to be looked into for the mechanism of flow noise. The boundary layer pressure fluctuations, amenable to measurement by flush-mounted hydrophones and often called pseudo-sound, is the random function that sets the sonar dome into vibration and consequent acoustic radiation into the interior of the dome. In the absence of a good theory which can account for flow-induced vibration of curved walls of arbitrary-shaped bodies, a recent and most applicable theory of flow-induced vibration with fluid loading is that of Straw-Dermann & Christman[2]. They considered the dome as a plate of uniform thickness. The normal deflection $W(x, y, t)$ of a plate immersed in a fluid and acted upon by a turbulent pressure fluid $P(x, y, t)$ on one side is

$$D\nabla^4 W + \frac{r\partial W}{\partial t} + \mu \frac{\partial^2 W}{\partial t^2} = P_-(x, y, 0_-, t) - P_+x, y, 0_+, t) + P(x, y, t)$$

where $D = \frac{1}{12} \frac{(Eh^3)}{1 - \sigma^2}$ is the flexural rigidity of the plate, h is the plate thickness, E and σ are Young's Modulus and Poisson's Ratio respectively. The terms $P_\pm$ are the acoustic radiation pressures above and below the plate. They derived an expression in acceleration spectral density form.

$$A(W) = P(W) \frac{8.05 \times 10^{-2} W^6}{\pi^2 U^2} \int \frac{\overrightarrow{dk}}{\text{Plate \& turbulence parameters}}$$

It was calculated by Doughlas A. King[3] for various frequencies at free stream speeds for fibre-reinforced plastic plate

$$A(f) = \frac{P(f)\, 4.9 \times 10^{-7} U^2}{(fh)^2} \quad \text{and } P(f) \text{ for plate with zero pressure}$$

$$L \text{ gradient} = \frac{3.16 \times 10^{-5} \rho^2 \delta^* U^5}{\left(1 + \frac{\pi\delta^* f}{U^2}\right)^{3/2}}$$

Where P = mass density of fluid,

δ^* = displacement boundary layer thickness,

$P(f)$ = turbulent boundary layer pressure fluctuation,

h = platic thickness,

f = frequency, and

U = free stream velocity.

Though the above theory is able to explain some of the practical results within some limits, no rigorous theory is yet developed to explain flow-induced vibrations of arbitrary shaped bodies. Hence, there is a necessity to rely more upon practical experiments on sonar dome for such information. The type of experiments to be carried out is explained at the end of this paper.

(*ii*) *Acoustic Transparency of the Dome*

In the well-designed sonar dome, the acoustic transparency should be maximum in the direction of sonar signal transmission and reception at sonar operating frequency, while it should be minimum in the direction of noise entering the dome. While it is somewhat easy to identify direction of signal transmission and reception, it is difficult to attribute a particular direction to noise entering the dome. However, noise enters the dome from all directions, though it is possible to identify a certain area of dome which acts as a noise window for certain intense noise sources and their direction with respect to sonar and sonar dome. For example, a propeller generally constitutes a major source of intense noise at certain speeds insonifying the aft position of the dome. The parameters which affect the dome transmission coefficient or acoustic transparency are :

(a) Type of material of the dome-wall, (b) Thickness of the dome-wall, (c) Direction of incidence, (d) Shape or geometry of the dome, and (e) Type of wall structure etc. The type of material by which the dome is made should in the first place be acoustically transparent at the sonar operating frequency. This being inversely proportional to thickness, a compromise is to be made between thickness required for high acoustic transparency and thickness required for the dome to be mechanically strong to overcome the hydrodynamic forces which are generally encountered at maximum speed of a ship in all weather conditions and resulting ship motions. The acoustic transparency also depends on the direction of incidence and shape or geometry depending upon its location on the ship structure. While calculating the transmission coefficient, it is necessary to consider dome as a body in close proximity to the ship's structure and its position vis-a-vis the ship's propeller or any other intense source. Type of structural configuration such as stiffened structure, sandwich or pre-stressed structure or fibre-reinforced material also effects the transmission coefficient.

It has been found from literature[4], page 181 that below coincidence frequency, the dominent mechanism of sound transmission through plates and walls, involves longitudinal waves. Flexural waves become dominant in wall transmission for frequencies above about $f_c/2$ where f_c is the critical frequency of the isolator i.e. dome-wall.

In case of longitudinal wave, transmission below coincidence frequency through a plate separating water from water like dome-wall, is

$$\frac{1}{\alpha_t} = 1 + \frac{1}{(2\beta)^2}$$

where α_t is related to Transmission Loss (TL) = 10 log α_t, β is called load factor defined as the ratio of specific radiation resistance of the fluid to the mass reactance of the plate per unit area. TL so obtained is less than 3 dB for frequency less than $f_c/4$. For transmission through air to air separation, the TL is purely governed by mass law and increases with frequency and structural density upto $f_c/2$ and is given by $TL = 20 \log \frac{\mu\omega}{2\rho_0 C_0}$ where μ is surface density, ω is angular frequency and $\rho_0 C_0$ is characteristic impedance of the air. For longitudinal waves to be not transmitted the most effective way is to provide an air column inside the dome between sonar and the propeller.

As far as flexural vibrations are concerned the transmission loss depends on 3 terms as shown

$$TL = 20 \log \frac{\mu\omega}{2\rho_0 C_0} + 10 \log \frac{2\eta_T}{\pi} + 10 \log \frac{\omega}{\omega_e}$$

where η_T = total loss factor. In this, the first term is due to mass law, the second (negative term) is due to damping and the third is an additional term dependent on frequency. Applying these principles to sonar dome problems, isolation can be introduced in the dome between the sonar and the propeller. Several things can be done to decrease transmission between the propeller and the sonar. First thing would be to raise the coincidence frequency of the isolator above the frequency range for which high *TL* is desired. ω_c, consider angular frequency, is inversely proportional to thickness and *TL* in the mass law is directly proportional to thickness. As a compromise, Kurtze & Watter's[4], page 184 proposal may be applicable to sonar domes. This method reduces the flexural wave speed without sacrificing mass by using multi-layer plates in which viscous liquid, viscous solid or some material is placed between two elastic layers.

For introducing isolators of this type in sonar domes, extreme care should be taken to isolate the isolator structurally from surrounding vibrating structures, otherwise this baffle will act as an additional radiating surface and give rise to new local source of noise.

(*iii*) *Structural Damping Properties*

The effect of increased structural damping on plate vibration and more pertinently on the resulting radiation is not completely understood. It is Dyer[1], page 76 (1958) who was the first to establish some analytical criterion for effectiveness of structural damping in reducing flow noise.

From his studies, it was established that for frequencies substantially greater than hydrodynamic critical frequency but less than acoustical critical frequency, a transition frequency exists below which a given increase in modal loss factor caused a significant decrease in modal mean square displacement. Above this frequency, further increase of ϵ, the loss factor would mean little effect. The transition frequency as given by Dyer is

$$f_t = \frac{1}{\pi \epsilon \theta} \text{ where } \theta = \frac{30\delta^*}{U}$$

is the temporal decay factor of the turbulent boundary layer; δ^* = displacement boundary layer thickness and U = free stream velocity. Dyer calculated for a typifying sonar application where $U = 20$ ft/sec, $\delta^* = 0.02$ ft and $\theta = 3 \times 10^{-2}$ sec, $f_t = 1000$ Hz. He found that applied damping treatment should be effective for frequencies from that of lowest plate mode to $f_t \simeq 1000$ Hz in this case. By this, it was possible to reduce high *Q*'s of the order 100 to low *Q*'s of the order 10 by using applied damping treatment in case of welded steel structures. Similarly, reduction in the sound pressure levels of the order of 14–20 dB was realised in these modes.

(*iv*) *Size of the Dome*

It has been shown that the external agencies like flow past the dome excites bending waves in the dome-wall structure. Such waves being dispersive in nature, will have velocity of propagation along the plate as frequency dependent. Depending on the thickness of the plate, below-critical frequency for which the phase velocities along the plate will be below that of acoustic velocities in water, near-field radiation will take place. But at critical frequency, phase velocity in the plate and the medium being same, coupling to a wave radiated parallel to the surface of the dome-wall will be experienced. However, above critical frequency, the phase velocities in the structure will be greater than in the phase velocities in the medium and more energy will be radiated at angles other than parallel to dome-wall. The far-field radiation effects being very small, the sonar array will be exposed to near-field radiation effects of dome-wall. The size of the dome should be selected in such a way as to give sufficient clearance of the dome-wall from the array to allow the near-field radiation to decay adequately.

(*v*) *Dome Wall Configuration*

In practice dome walls are being fabricated out of plates with periodically spaced beams or stiffeners or with lot of discontinuities. Any discontinuity or beam attached to a plate has three distinct effects : (i) it changes its resonance frequency, (ii) when a vibrating force excites one region of the plate, it acts to attenuate the vibratory velocities experienced at the other side, (iii) it increases the sound radiated by the plate. Heckel[1], page 177 measured transmission through single 2.5 cm high steel beam on a 1 mm thick aluminium plate in air and found it to vary from 15 to 35 dB. But this value will, however, be small in water due to near-field acoustic disturbances. Similarly Maidnik, page 178 (1962) Plakov[4], page 178 (1967) found that periodically spaced ribs increase radiation from a plate by 6 dB underwater loading.

Now, on the face value, it appears that whether the wall structure for a dome is to be periodically spaced with ribs depends upon whether vibration propagation along the length of the wall is to be attenuated at the cost of increase in radiation. However, if propeller noise excitations or turbulent flow fields closer to the aft of the dome-wall dominate, it will be worthwhile to go in for rib structure beyond mid aft to attenuate vibration propagation from aft end to forward. The increase in radiation due to such rib structure (energy absorbers) being concentrated at the aft end of dome, can be counteracted by suitable isolators incorporated in between sonar and the propeller (inside the dome) as discussed earlier. However, it must be remembered that in case of flow-induced vibration of the dome, such rib structure may be counter-productive due to additional radiation.

(*vi*) *Response Due to Acoustic Excitation*

Propeller noise can easily excite dome-wall vibration. Such excitation is dominant only above coincidence frequencies. The effect of coincidence frequency on dome-wall vibration and self-noise has already been explained in previous paragraphs.

(*vii*) *Ocean Wave Effects on the Dome*

Ocean waves cause impact forces on the sonar domes readily exciting into strong structural vibration generating high self-noise. Repeated impacts can be found to have a frequency spectrum flat upto $\omega \simeq (3\tau)^{-1}$ and decreases 6 dB per octave for $\omega\tau > 3$ where τ is time constant in which the velocity decays to e^{-1} of its initial value. The actual vibration spectrum of the dome structure is, this input spectrum multiplied by the dome-wall response spectrum. Therefore, highest vibratory and acoustic levels can be expected when harmonics of the impact coincides with structural resonances. Because such coincidences are virtually unavoidable, use of structural damping to reduce resonant response is especially important in reducing impact noise in dome.

(viii) Radiation Effects in Dome Interior

So far, the study has been concentrated on dome-wall vibration and their control. It has also been said that vibrations being flextural in nature cause acoustic radiation both outside and inside the dome. The internal radiation is detected at sonar as self-noise. But in reality, how this radiation effects the self-noise as measured by sonar array depends on such factors as reverberation in the dome, specular, reflection, absorption coefficient of the wall etc. Hence the actual self-noise measured by the array is the spatial average of the intensity in all the wave lengths over a given period of response. However, how these factors influence the self-noise is yet to be studied.

(ix) Location of Dome in Ship's Structure

The location of sonar dome also plays a vital part in reducing self-noise. Even if the dome is designed free from turbulent boundary layer on its surface, if the dome is not located beyond the immediate boundary layer surrounding the ship's hull, the dome will still be excited by ship's boundary layer pressure fluctuation giving rise to self-noise. To avoid this, it is necessary to extend out the dome into free-stream water. Another important consideration for location of dome is with respect to propeller of the ship. It has been found that whenever a source and a receiver are placed below a plate, the plate acts as a reflector for large angles of incidence, but at grazing incidence angles, all plates under water loading will transmit the energy through flexural vibrations of the hull. There will be good amount of attenuation in the direct centrinution introduced between the source and the receiver for grazing angles and qualitatively the attenuation is found to be of the order of 4th power of the grazing paths. Close to ship hull, the propeller and the sonar will act as a pair of such source and receiver, the plate being the ship's hull. The direct path between the propeller and the sonar can, however, be isolated by introducing isolators as discussed earlier. From above considerations, since sonar and dome are inseparable, the self-noise generated will depend upon its location on the ship's structure.

4. Practical Approach

All the phenomena discussed in previous paragraphs is not amenable to any simple theory because of their varied manifestations. It is proposed that the best method of analysing the self-noise problems in sonar domes would be to conduct a series of practical experiments and progressively see the effect of each phenomenon on self-noise.

The limitations of such experiments are :

(i) The water tunnels are not useful for carrying out such experiments. This is mostly because full scale domes are to be experimentally studied to evaluate certain phenomenon like reverberation effects, near field effects, effect of sonar transducer which occupy a significant volume, shadowing effects, stiffening effects, direction of radiation etc. due to their complexity in formulating scaling laws.

(ii) The ambient noise is generally quite high either in towing basins or water tunnels which precludes their use.

(iii) The acoustic wave lengths generally encountered in these experiments are so great that the water tunnels are not of much service because of very close boundaries.

After careful study of all the possibilities, it has been realised by the authors that the best way of studying self-noise in domes would be by use of buoyant or gravity-propelled sonar domes. For this purpose an actual-size dome is made to either pop-off under buoyancy or go-down under gravity in a lake of considerable depth and size. Different terminal speeds can be achieved for different loadings. The equation of motion, for gravity propeller dome is

$$mg - SP - \tfrac{1}{2}\, C_D\, PAV^2 = m\frac{d^2x}{dt^2}$$

and for buoyancy propelled dome is

$$mg - SP + C_D\, PAV^2 = m\frac{d^2x}{dt^2}$$

where P = water density, S = volume of the vehicle, C_D = drag coefficient, V = velocity of vehicle, A = surface area, m = mass of the body. If the initial acceleration is zero, RHS will be zero, the motion of the body will be uniform and attain terminal velocity V which can be easily calculated.

For such experiments, sometimes, domes of certain shapes may require slight modification like making them somewhat axisymmetric to ensure uniform flow all around the body. The dome is then to be fitted with sufficient number of flush-mounted pressure transducers for pressure measurement; accelerometers for recording wall vibration and one or two hydrophones in place of sonar array for finding out self-noise for different types of studies such as flow induced vibration etc. If necessary, these experiments can be extended to generate turbulence by artificial means of tripping and observe its effect on self-noise. Similarly, studies on self-noise due to reverberation effects, near-field noise; cavitation-excited noise etc. can be carried out on such models.

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