AIRBORNE NOISE PROBLEMS IN SUBMARINES

INVESTIGATION USING PREDICTIVE MODELS

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ABSTRACT

Acoustic models can be useful in identifying potential airborne noise problems at the design stage in submarine construction, and in reducing existing airborne noise problems in those boats already in service. Such work is directed mainly at providing the crew with a suitable environment in which to work and rest, free from the risk of hearing damage and related fatigue and communication difficulties. The article commences with a discussion on some of the basics of acoustic modelling and noise control in submarines. Using selected case studies, it is then demonstrated how computer models have been used in identifying those areas where acoustic measures were required, and those treatments necessary to reduce noise levels and practical to install.

Introduction

Sound is an inevitable but often controllable consequence of everyday life and during an average day one expects to be subjected to various levels of noise. Airborne noise is usually measured with microphones linked to a set of standard electronic filters designed to mimic the frequency response of the ear to sound.

Such filters are known as the 'A' weighting network and the sound processed in this way is quoted as an 'A' weighted level on the logarithmic decibel scale (dBA). This then provides a good estimate of how damaging a particular noise is likely to be and legislation exists which establishes the noise levels at which one can work and rest in safety and comfort.

In an enclosed environment such as inside a submarine, one can appreciate that the ship's crew will be subject at times to high levels of noise. An individual's exposure to noise will depend on which duties he has to perform, the areas of the boat he has to carry them out in and the time duration of the allotted tasks. An unfortunate fact resulting from the confined nature of a submarine is that it is not possible to obtain complete respite from noise. Even in the crew's quarters, where one would expect a reasonable degree of quietness, levels can at times be well above those acceptable in residential suburbia. There are standards for noise control on board submarines but any cost-effective method that allows current noise levels to be reduced further will undoubtedly improve the quality of life of submariners. In general, the consequences of reducing noise will allow the risk of hearing damage to be lowered, fatigue lessened and communication difficulties eased.

With the advent of more stringent and enforceable noise limits, greater emphasis is now being given to the prediction of noise levels before submarine construction takes place. By doing so, potential noise problems can be identified at an early stage and the appropriate noise control measures incorporated in the design of the product. Experience has shown that this will reduce time and cost during submarine build, avoid the need to retrofit noise control treatments after final construction and reduce potential claims for hearing damage by ship's personnel. Even so, where airborne noise problems already exist, predictive work also offers the possibility of selecting the appropriate noise control measures, without the need to perform actual trials on each treatment fitted in turn.

The term 'acoustic modelling' is used to encompass all aspects of predictive noise work including the calculation of noise levels, and the determination of the effects of acoustic treatments. This article discusses examples of how acoustic modelling has been used to identify problem noise sources in submarines, and the practical treatments necessary to reduce levels.

The Acoustic Model

Acoustic Elements

All acoustic models are built up of three basic acoustic elements:

- Noise sources (moving machinery).
- Receiver points (compartments).
- Transmission paths between sources and receivers (airborne and structural).

Sources

Sources of noise in a submarine are many and varied, and examples include turbines, pumps, fans, computers and switchboards. Compartments such as machinery spaces contain many noise sources, while other compartments contain few sources or none at all. Some sources dominate noise levels not only in the compartment in which they are located but also in adjoining spaces, while other sources are less significant and only have a localized effect. Other machines operate intermittently during a submarine patrol and hence compartment noise levels will differ according to the operational state of the boat.

Receiver Points

In a whole boat acoustic model, noise levels need to be calculated for each compartment which will either be continuously manned or where personnel require access from time to time. The receiver points in each of these compartments are chosen at positions that will allow representative estimates of noise levels to be determined for the entire compartment. Positions too close to noise sources will be dominated by localized effects and where possible such positions are avoided. Receiver points are normally located near the geometric centres of each compartment supplemented with others at particular watch-keeping positions.

Transmission Paths

The final element of the acoustic model is the set of airborne noise transmission paths linking the sources to the receiver points. There are numerous transmission paths between each source and each receiver point, but not all will be significant. In very general terms there are three main types of transmission path, as shown in FIG. 1:

(*a*) Through the air along the line of sight between the source and receiver within a compartment, supplemented by diffraction and reflection effects of noise incident on surfaces within that compartment.

(*b*) Via bulkheads, decks and other structures when the source is contained in a compartment adjacent to the receiver area.

(*c*) Through connected systems such as ventilation ducts and pipes. Noise passing along these can be easily transmitted to numerous compartments throughout the boat.

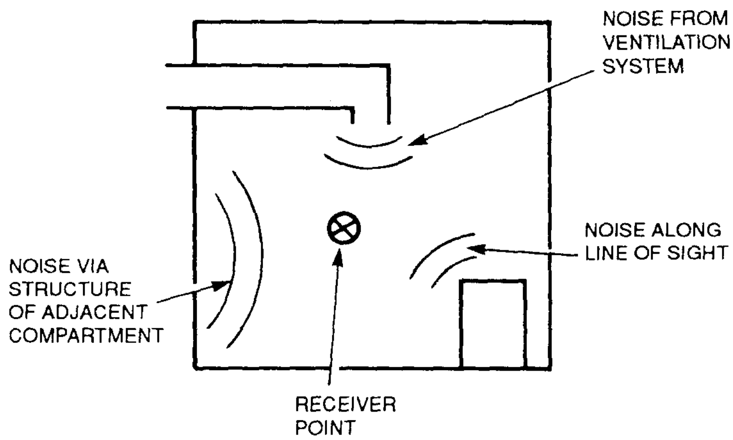

FIG. 1—ACOUSTIC TRANSMISSION PATHS

Noise Control

Common-Sense Guidelines

Although the term 'acoustic modelling' conveys thoughts of complicated matrix algebra and graphic output, which are of course used in computer acoustic modelling and simulation, the most effective noise control measures are actually based on common-sense guidelines based on experience aimed at preventing noise problems from arising in the first place. Three examples of such guidelines are:

(*a*) Avoid placing noisy machines in designated quiet areas.

(*b*) Avoid situating potentially noisy compartments adjacent to quiet ones.

(*c*) Avoid linking noisy compartments and quiet areas with connected systems such as ventilation ducts.

Although, at first sight, guidelines such as these seem rather obvious, the confined environment which exists inside a submarine is not always suited to their implementation. In reality the result is a compromise between what is ideal and what can be practically achieved. Fortunately the siting of noisy machines in quiet compartments is generally avoided but as will be discussed later in the case studies, the lack of space often overrides the noise control ideals outlined in the latter two guidelines shown above.

Target Levels

Ideally, aspects of noise control need to be included at the very beginning of the design stage of a submarine in the layout of compartments, when a noise target level can be assigned to each space. Such target levels should be based on how the compartment is used and the activities that will be performed in it. A low target level will thus be given to compartments such as bunkspaces, cabins and the sickbay where noise levels must not disturb rest or sleep. Medium target levels will be given to offices and control rooms where noise must not interfere with audible communication. The highest target levels will be reserved for machinery spaces where noise hazards need to be controlled to avoid hearing damage.

One may argue that it would be desirable to set low target levels for all compartments, but in reality this is not possible. As long as an individual's daily noise 'dose' does not exceed statutory limits then it is neither necessary nor cost-effective, even if it were practical, to reduce noise levels say in a machinery space to those acceptable for a bunkspace.

Sources

Knowing the noise target level of a compartment, plans can be made concerning the location of individual items of machinery and other potential sources of noise. The highest concentration of noise sources will be matched to those machinery spaces with the highest airborne noise target levels, and the siting of machines in low target areas avoided. Compartments with a special function such as the wireless office or control room will have noise sources appropriate to that compartment, and the noise target for these compartments will hopefully have been set to take the presence of such sources into account.

Compartment Layout

Once the individual compartment target levels have been set, one can then assess the compartment layout of the boat as a whole to check if the planned layout has quiet areas sited adjacent to potentially noisy compartments. Where such situations exist it is best to try and re-locate either of the compartments, for example by siting a compartment with an intermediate target level between the two. Noise transmitted from a high level area to a quiet area via an intermediate compartment is naturally attenuated much more than across a single boundary common to the original pair of compartments. It is thus much easier and more cost-effective to use the compartment plan to one's advantage in noise control matters, than to have it work against you. Where it is not possible however, to separate compartments in this way at the design stage, one must make allowances for the space and resources required for special acoustic treatments which it may be necessary to incorporate in the actual build of the submarine.

Connected Systems

Again where target levels are known the routes of ventilation systems and pipework can be planned. Unless there are special reasons for doing so, one can design the ventilation network for instance, so that noisy and quiet areas are not linked with the same ventilation duct run. An example of this is shown in FIG. 2

where high noise level compartments such as machinery spaces have separate supply and exhaust ducts from those linking quiet compartments such as cabins. Should special acoustic treatments be required because of the impracticality of achieving this, then the design stage is again the point to allocate the necessary resources to allow them to be fitted at the build stage.

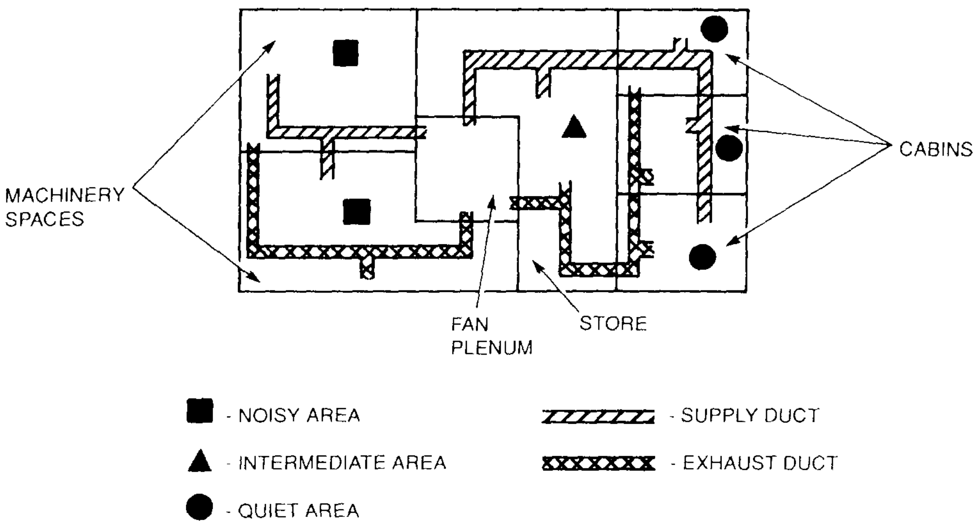

FIG. 2—ROUTEING OF VENTILATION DUCTS TO AVOID LINKING QUIET AND NOISY AREAS

Predictions

Sound Pressure and Sound Power

Sound can be defined as the pressure variations in air that can be detected by the human ear. In acoustic terms this is known as sound pressure and can be measured at receiver points using microphones. Sound pressure is caused by a noise source emitting acoustic power, also known as sound power. A noise source will generally radiate the same sound power irrespective of the environment in which it is located. The sound pressure on the other hand is dependent on the size and shape of the compartment in which the source is located, the amount of acoustic absorption in that compartment, the effects of reflective surfaces including objects and people, and the distance the receiver point is from the source.

Sources

In all aspects of noise prediction at the design stage of a new boat, one needs initially to determine the sound power of each source. For items of new machinery, sound power levels during pre-installation tests can be obtained by correcting sound pressure level measurements with the acoustic factors relevant to the environment in which the machine was tested. Alternatively, sound power levels can be measured directly using special sound intensity techniques. For similar machines used on previous boats, then predictions can be based on their sound power levels which will have been determined previously.

Receivers

Knowing the sound power level of a machine one can then predict the resulting sound pressure level in the compartment in which it will be sited, assuming that information on the acoustic properties of that compartment is available and the distance between the source and relevant receiver points is known.

If it is required to predict sound pressure levels in a compartment adjacent to the source area, in addition to the sound power level of the source and the acoustic properties of the source room, one also needs to know the acoustic properties of the receiver room and details of the intervening structure.

Transmission Paths

The amount of noise that will be transmitted between compartments will depend on the size, thickness and composition of the boundaries of the source and receiver compartments. In addition to the common boundary between the two compartments, one also needs to take structural flanking paths into account, as shown in FIG. 3. Noise transmitted along these paths can sometimes dominate over the noise transmitted along the direct path.

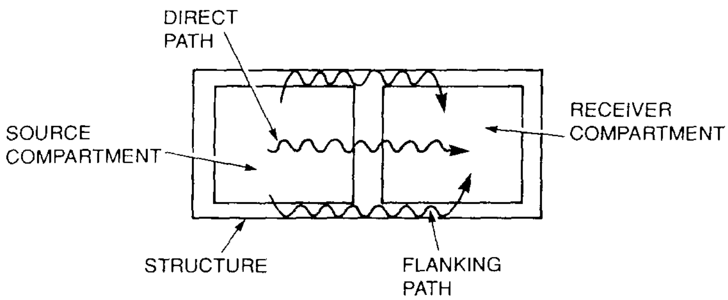

FIG. 3—DIRECT AND FLANKING NOISE PATHS

To calculate the noise transmitted along, say, the ventilation system, one needs to consider:

(*a*) The attenuation that noise will encounter as it passes from the fan through each duct.

(*b*) Noise generated by the flow of air through the ducts.

(*c*) Noise which breaks in or breaks out through the duct walls or openings.

Each duct will therefore contribute individually to the compartment total level, and have an effect on the noise levels in each of the other ducts in the same ventilation lead.

Acoustic Treatments

Choice of Source

How can the level of noise sources within a compartment be reduced? If it is possible, one must at the outset take noise into consideration in the purchasing of equipment. From a noise point of view one should aim to obtain the quietest piece of machinery that is able to carry out all the necessary requirements that will be placed upon it.

Within a Compartment

If it is determined that noise levels due to a particular machine will be excessive at the receiver points in a compartment, there are several possibilities for noise reduction:

(*a*) If the source is close to the receiver point, then either the source could be moved further away, or an acoustic screen constructed between the source and receiver. If the source is to be moved, one must be careful not to re-position it in a confined location, such as a corner, because localized reflections may well cause its contribution to noise levels in this compartment to increase.

(*b*) When a problem source is some distance away from the receiver, then acoustic absorption material can be fitted to the compartment boundaries to reduce noise reflected from them.
(*c*) Enclose the source or clad different parts of its casing.
(*d*) Fit silencers to fans.
(*e*) In a machinery space sound-proof booths could be constructed for personnel who have to be present in that space for any appreciable time.

If one requires acoustic measures such as these, then including them in the design of the boat will save much time and effort over trying to fit them once the compartment is built, since by then it is often found that the required space is unavailable.

Between Compartments

Where predictions show a noise source in an adjacent compartment to be a problem, and it is not possible to separate the source and receiver compartments with an intermediate space, there are other options that can be considered:
(*a*) Enclose the source.
(*b*) Fit acoustic absorption materials to the boundaries of the source or receiver compartment.
(*c*) Reduce the transmission of noise through the common or flanking structure, by optimizing the thickness and composition of the structural materials.
(*d*) Apply damping materials to the structure in order to increase its attenuation characteristics.

Systems

If the problem noise source is identified, for example, as the ventilation system, its noise contribution can be reduced in several ways:
(*a*) Noise which breaks out from the duct walls can be reducd by altering the wall thickness, or lagging it externally with an acoustic insulant. This will also reduce break-in noise.
(*b*) Noise generated by the air flow itself within the ducts can be reduced by lowering the flow rate through the duct by increasing the duct dimensions, in addition to smoothing constrictions and bends in the system.
(*c*) Noise transmitted along a duct can be attenuated by lining the internal surfaces of the ventilation ducts with acoustic insulation usually held in place with a perforated plate.
(*d*) By reducing the level of the source of noise, the fan, then this will reduce noise throughout the whole duct system.

Similar treatments to these can also be envisaged for pipe systems.

Case Study A

Initial Prediction

The first case study concerns a fan located in Compartment A shown in FIG. 4. In the design of the boat this compartment was sited underneath Compartment B with an open hatchway linking the two providing a natural air return to the fan. Knowing the types of compartment concerned, an airborne noise target of 75 dBA was assigned to Compartment A and 67 dBA to Compartment B. Having specified the duty requirements of air flow, pressure drop, motor speed, physical size, etc. for the fan, fan manufacturers were invited to bid to supply the required unit and eventually a tender was finally accepted.

The successful manufacturer estimated that the overall airborne sound power level of the fan would be 98 dBA. Using the frequency spectrum noise information supplied by the manufacturer, a computer acoustic model of the two compartments was made, and this predicted an overall sound pressure level of 86 dBA in Compartment A and 72 dBA in the Compartment B. This showed that the airborne noise targets of both compartments would be exceeded.

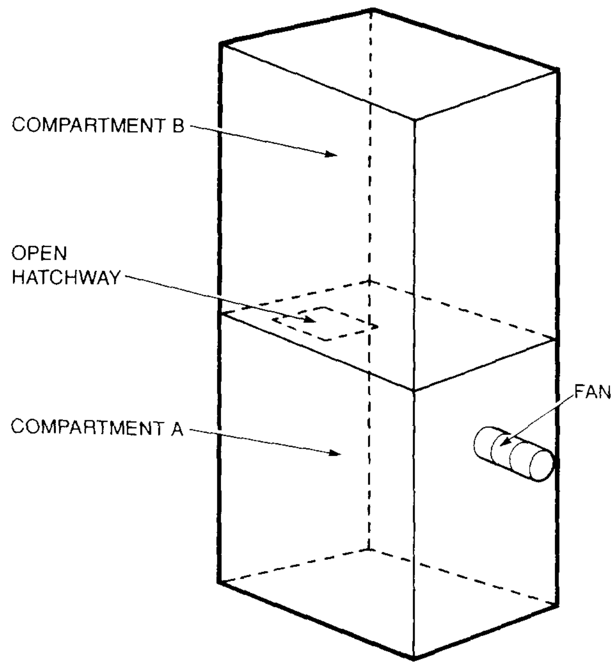

FIG. 4—CASE STUDY A

Silencers

Noise from a fan or any other air moving device is mainly transmitted through its inlet and discharge openings. Lesser amounts of noise are generally radiated from the unit's casing. The first stage therefore in reducing the noise from the fan was to determine the effect of fitting silencers to its inlet and discharge. The fan manufacturer supplied details of the appropriately-sized silencers and this information was entered in the acoustic model which was then re-run. This time predictions showed that levels due to the fan in Compartments A and B would be 77 dBA and 63 dBA respectively. Compartment B's target level was therefore achieved and, although the target for Compartment A was exceeded by 2 dBA, this did not give undue cause for concern.

Test Measurements

Once the fan had been constructed it was noise tested during its routine pre-installation test. Unfortunately it was found that its overall sound power level was 107 dBA without silencers, 9 dBA above the level estimated by the manufacturer, and that its frequency spectrum was also different from that which the manufacturer had envisaged. This measured data was fed into the acoustic model, and predictions of 82 dBA and 68 dBA resulted for Compartments A and B respectively. Although these levels were only 5 dBA above the previous predictions because of the change in the fan's frequency spectrum, the target levels of both compartments were now exceeded.

Final Solution

It was then decided to determine the effect of placing a hatch cover over the open hatchway between the two compartments. Return air would be provided with a small ventilation duct which would bypass the closed hatch. The acoustic model was altered to reflect this change and predictions showed that this arrangement would improve the levels in Compartment B by 10 dBA, to within its target level. This change was accepted.

Once the fan with its silencer had been installed, on-board measurements were then taken with the unit *in situ*. These measurements showed that levels in Compartment A due to the fan to be 81 dBA, only 1 dBA less than the final predicted level; they also indicated that the silencers had performed better than expected. The silencers had in fact reduced the fan's inlet and discharge noise contributions by such a degree that the casing was now actually the dominant source of noise. In order to reduce levels in Compartment A, several acoustic treatments were then incorporated in the computer acoustic model and this concluded that cladding the fan casing would be the most effective treatment. It would also be the easiest treatment to install. A lagging material composed of a fibreglass mattress with a flexible lead core was selected and wrapped around the fan casing. Measurements taken with the lagging in place indicated an overall sound pressure level in Compartment A due to the fan to be 73 dBA, 2 dBA within the compartment target level.

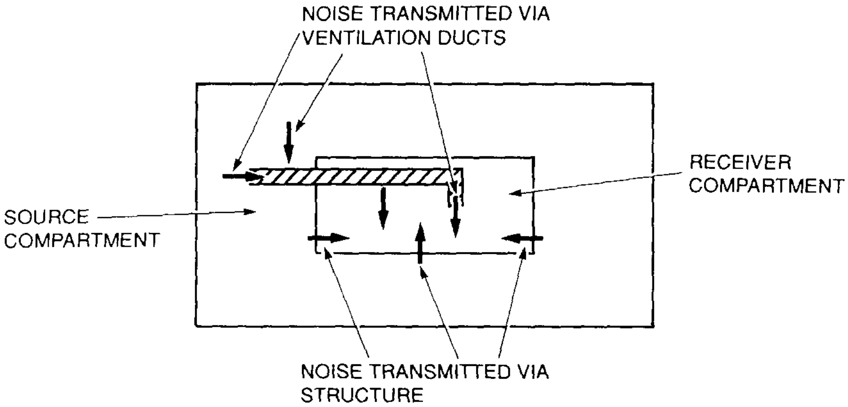

FIG. 5—CASE STUDY B

Case Study B

Initial Prediction

The second case study again shows how acoustic modelling can be used to reduce noise transmitted from one compartment to another. Two adjacent compartments are considered, as shown in FIG. 5, with the source space completely surrounding the receiver compartment. The transmission paths involved were through common structural boundaries and via ventilation ducts linking both compartments.

A possible construction material of the bulkheads and ceiling of the receiver compartment was 3 mm aluminium, and for the ventilation ducts 1.6 mm aluminium plus 6 mm cork. Although the cork attached externally to the ventilation ducts in this case was specifically chosen for thermal reasons, it does increase the acoustic transmission loss through the duct walls. The target level of the receiver compartment was designated as 70 dBA.

Having identified the relevant transmission paths between the two compartments, and knowing the source levels of the machines in the source space and the acoustic properties of the two compartments from geometric data, a computer acoustic model of the compartments was formed. Predictions using the model showed that the expected level in the receiver compartment to be 72 dBA, 2 dBA above the target level, with the transmission path via structural boundaries contributing 71 dBA and the ventilation ducts 67 dBA.

Acoustic Treatment Selection

Having created the acoustic model it was then a simple task to incorporate various acoustic treatments into the model to determine their effect on levels in the receiver compartment. Various treatments were considered and the predicted levels in this space for some are shown in TABLE I. One can appreciate that each treatment has both benefits and drawbacks. For instance, fitting acoustic insulation inside the receiver compartment reduces the available space in that compartment, while altering the thickness of the various boundaries produces a considerable weight penalty.

Of the treatments considered in TABLE I, the damping panels were deemed to be too expensive, the insulation took up too much space, the double thickness materials were not held in stock on site, and the internal lagging of the ventilation ducts would have caused air flow speeds in the duct to be above acceptable limits. The actual solution was to construct the original aluminium structure and the ventilation ducts from the same thickness of steel. When actual measurements on board were obtained, an overall sound pressure level of 67 dBA was recorded in the receiver compartment (3 dBA within its target level), which agreed with the appropriate predicted level.

TABLE I—*Effects of acoustic treatments*

Contribution	*Acoustic Treatment*	*Predicted Overall Sound Pressure Level in Compartment* dBA
Compartment Boundaries	nil	71
Ventilation Ducts	nil	67
Total	—	72
Compartment Boundaries	double thickness	66
Ventilation Ducts	nil	67
Total	—	70
Compartment Boundaries	double thickness	66
Ventilaiton Ducts	double thickness	62
Total	—	67
Compartment Boundaries	damping panels	63
Ventilation Ducts	nil	67
Total	—	68
Compartment Boundaries	insulation	65
Ventilation Ducts	nil	61
Total	—	66
Compartment Boundaries	nil	71
Ventilation Ducts	internal lining	62
Total	—	72
Compartment Boundaries	aluminium to steel	65
Ventilation Ducts	aluminium to steel	62
Total	—	67

Case Study C

As explained earlier, when a source and receiver point are in the same compartment, one of the major and rather obvious transmission paths is through the air along the line of sight between the two. If a barrier could be placed between them, or if the source or receiver point could be hidden from view, then noise along the line of sight will obviously be reduced.

This case study concerns the situation shown in FIG. 6, with a machine at Position A in the line of sight of a receiver point. Using the known source sound power levels of the machine and the computer acoustic model for this compartment, it was found that an overall level of 72 dBA would be expected at the receiver point. The acoustic model was re-run with the source at different locations and it was found that a 2 dBA reduction could be achieved with the machine hidden behind a bulkhead at Position B. The machine was sited at this position and when actual measurements were taken onboard, an overall level of 70 dBA was obtained, which agreed with the prediction. This again demonstrated how one can use the boat's layout to one's advantage in noise control matters.

Although only a small improvement was gained in this particular case, many similar instances can be identified throughout a whole boat and the combined benefits of such changes can soon accumulate. Obviously it is best to perform this type of analysis at the design stage of the boat because, once fitted, machines are unlikely to be moved.

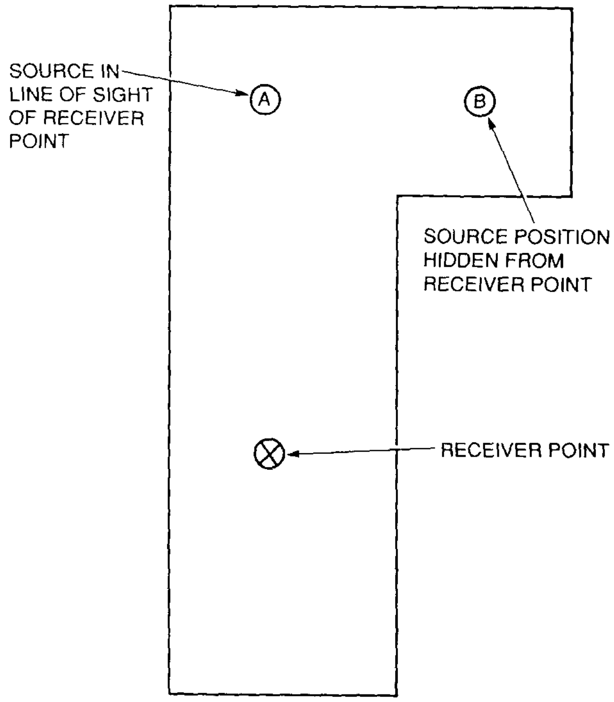

FIG. 6—CASE STUDY C

Conclusions

This article has shown, through the case studies, how acoustic modelling has been used to reduce airborne noise in submarines. Common-sense guidelines of noise control have been highlighted, and suggested acoustic treatments discussed. Identifying potential airborne noise problems at the pre-build stage of a submarine allows the required treatments to be included in the design of the boat, thus avoiding costly retrofits once the boat is built. In all aspects of noise control one should attempt to utilize the inherent acoustic attenuation properties due to the boat's layout before suggesting acoustic treatments which may cause a space or weight penalty.