SOUND INTENSITY MEASUREMENTS ON BOARD SUBMARINES

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ABSTRACT

In the early days of steam propulsion, life on board ship was often equated with a living and working environment of high noise levels. There is little doubt that excessive noise levels in the engine room and other compartments caused some degree of hearing loss to unprotected members of the crew. On a positive note, however, subjective evaluations of even small differences of sound often gave the first indication that a machine was not functioning properly. Nowadays, with health and safety regulations relating to environmental noise in general becoming ever more stringent, greater attention is now being paid to the control of airborne noise within ships of all types including naval vessels.

One of the important aspects of noise control is noise source identification. This article outlines some of the ways in which sound intensity measurements have been used as a diagnostic tool in identifying the source of noise problems in submarines. The benefit that this method has over traditional sound pressure measurement techniques, in identifying the contribution of machines or machine components in the presence of high background levels, is also highlighted.

Introduction

A submarine submerged on patrol for several months at a time is both the workplace and home for the crew on board. Airborne noise is one of the many factors which needs to be addressed, in order to provide a suitable environment in which the crew can work and rest. Excessive airborne noise poses a potential threat to the safe operation of a submarine and the efficiency of the crew, and from an environmental point of view its control is driven by the following aspects:

- To protect the crew from high noise levels so that their hearing is neither temporarily impaired nor permanently damaged.
- To ensure that noise does not interfere with clear audible communication.
- To prevent noise from disturbing the crew's rest and sleep.

Taking each of the above factors into account, maximum overall dBA sound pressure noise target levels are assigned to each compartment whether manned continually or occasionally. Such target levels have been developed over the years in response to measured onboard levels, and are based on how the compartments will be used and the activities that will be performed in them:

- For continually manned areas of the submarine, the highest noise target level (85 dBA) is assigned to compartments containing machinery where there are many noise sources and noise needs to be controlled to avoid hearing damage.
- Medium target levels are set for control and command areas where noise must not be allowed to interfere with speech and communication (60 to 70 dBA).
- The lowest target levels are reserved for the accommodation areas where noise must be prevented from disturbing the crew from their rest and sleep (less than 60 dBA).

At the design stage of each new class of submarine, calculations are made to achieve an early estimate of the airborne noise levels that will be encountered onboard. This allows identification of acoustic treatments that will be necessary for compartment target levels to be achieved, and saves much time and effort during the build and avoids possible costly reworking to include treatments once construction has been completed.

The computerised methods used to calculate submarine compartment air-borne noise levels and to assess the effectiveness of acoustic treatments have been developed and used successfully by the UK submarine construction industry for over 10 years. These methods have their foundations in standard acoustic theories, and have been enhanced with empirical data resulting from onboard testing[1].

During the submarine build, and once the submarine is completed and undergoes sea trials, onboard sound pressure measurements are taken to determine compartment levels and to check on the effectiveness of acoustic treatments that have been installed. Where compartment target levels are exceeded or other problems are identified, then further investigative trials, including the use of sound intensity, are conducted.

Design and airborne noise control

Reduction of noise at source is the most effective form of noise control. For submarines this can be achieved by selecting machines and other equipment, at the design stage of a submarine, which have low emission levels but can also meet the required operational duties and can fit in the space available.

Different forms of palliative measures are used, some of which are now installed as a matter of course (some treatments were initially developed from the need for vibration reduction), such as:

- Applying acoustic absorption material to the inner surface of the hull and other compartment boundaries to reduce reverberant sound and standing wave resonances within compartments, and to reduce any focusing effect of noise by the hull.
- Enclosing noisy machines by situating them in compartments dedicated solely to these units (e.g. main air conditioning fans, diesels, LP blowers.).
- Separation of noisy and quiet compartments by locating an intermediate compartment between the two.
- Isolating machines from compartment structure using resilient mounts to reduce transmission through the structure.
- Installation of damping panels on compartment boundaries to reduce noise transmission between compartments.
- Fitting silencers and acoustic lagging to fans and other machines, and acoustic lining of ventilation ducts.

Many of the above noise control features are based on experience aimed at preventing noise problems arising in the first place. Unfortunately the confined submarine environment is not always suited to their implementation. In reality the result is a compromise between the ideal situation and what can be practically achieved within constraints of space and cost.

Measurement techniques

Sound pressure, the pressure fluctuations in air which we define as sound and are detected by the human ear and microphones, are caused by sound sources radiating acoustic power. Sound pressure is dependant on the distance between the noise source and the receiver, and the acoustic absorption properties of the environment in which the source and receiver are located. Sound pressure levels due to a noise source will therefore vary, depending on its acoustic environment. Sound power, however, is independent of the acoustic environment and a noise source will radiate the same sound power irrespective of its location.

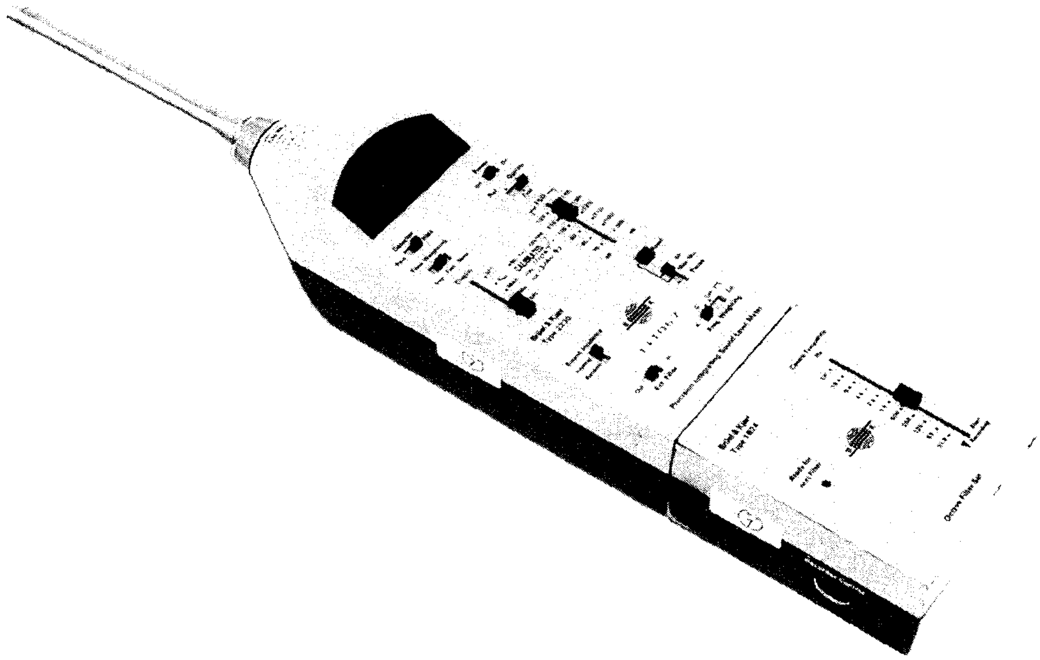

FIG. 1—SOUND LEVEL METER (B&K)

Since sound pressure is a scalar quantity, sound pressure measurements taken by a sound level meter fitted with a microphone (FIG.1) at selected locations in any environment, will be the sum of all contributions of noise sources in that area. Sound pressure is the quantity measured during compartment airborne noise surveys, for example during sea trials, to determine total compartment levels for comparison with the relevant target levels.

In submarine compartments where there is a single dominant noise source or very few sources in total, it is possible to determine the contribution to compartment levels of each source using sound pressure measurements by running each machine individually. Where there are many sources such as in a machinery compartment, and it is not possible to switch all machines off, the sound pressure contribution of a single machine can only be measured if the sound pressure sum of all other sources present is less than the contribution of the unit under investigation. In areas of high background noise, where unwanted machinery noise sources cannot be eliminated by switching them off or by screening them using acoustic enclosures, the only measurement technique to obtain the contribution of individual machines onboard is to use sound intensity.

Whereas sound pressure measurements have been used for many years, sound intensity measurement devices have only been available as commercial items within the recent past few years. In the UK submarine construction industry, sound intensity measurements have now been used for 5 years. Sound intensity measurements are normally carried out using an analyser linked to a probe consisting of two microphones mounted face to face with a solid spacer of fixed length between them (FIG.2). In order to obtain sound intensity measurements, a series of imaginary measurement surfaces enclosing the machine under test are first defined. Sound intensity measurements are then taken at selected locations on these surfaces, or by sweeping the probe over the surfaces[2].

FIG. 2—SOUND INTENSITY PROBE (B&K)

Sound intensity is defined as the average rate of sound energy flow per unit area. Sound power levels can therefore be obtained by multiplying the intensity measurements by the area of the surfaces enclosing the machine under test. Sound intensity, being a vector quantity, not only enables the level of sound power to be determined but also its net direction. Unlike sound pressure measurements, this method is therefore useful in identifying which machine in a compartment or even which component of a machine radiates the most noise even in the presence of relatively high background noise levels. Measurements are valid as long as the background noise is steady, is external to the measurement volume over the machine under test and there is no absorbent material inside this volume. Under these circumstances the sound energy flow of background noise into the measurement volume will equal the background noise energy flow out of the volume, and has been demonstrated to be the case[3].

The case studies outlined below are a selection of onboard investigations in which sound intensity has been used. Included are examples where noise problems have arisen and sound intensity has been used as a diagnostic tool to identify noise sources where it was not possible to do so with sound pressure measurements.

CASE STUDIES

Case study 1

Having obtained the sound power of a machine using sound intensity measurements, one can calculate the sound pressure levels at specific locations in a compartment due to these machines if the distance and orientation of the source relative to the receiver is known, and the acoustic absorption of the environment in which it is located can be measured or calculated. This first study shows how sound pressure levels derived from sound power levels by this method compare with actual sound pressure measurements.

The study concerns two hydraulic oil pumps within a machinery compartment. Swept sound intensity measurements were made over imaginary measurement surfaces forming a box shape over each pump. Knowing the surface area of these box shapes, sound power levels of both pumps were determined by multiplying the sound intensity measurements by these areas. The resulting levels are shown in Table 1 and indicate that each pump emitted similar levels.

TABLE 1— *Hydraulic oil pumps sound power levels*

Noise Source	Sound Power Levels (dBA ref. 10^{-12}W)								
	Overall	63Hz	125Hz	250Hz	500Hz	1kHz	2kHz	4kHz	8kHz
Pump 1	89	55	65	79	81	83	80	82	82
Pump 2	90	64	66	81	81	79	83	82	84

Sound pressure levels due to the two pumps were then calculated using predictive software knowing the distance and orientation of the pumps relative to a selected receiver location in the compartment, and information relating to the acoustic absorption afforded by the surfaces of the compartment's boundaries, the surfaces of objects within the compartment and the volume of air in the space under investigation. The calculated sound pressure levels are shown in Table 2 where they compare favourably with measured sound pressure levels.

TABLE 2—*Hydraulic oil pumps sound pressure levels*

Method	Sound Pressure Levels (dBA ref. $2x10^{-5}$Pa)								
	Overall	**63Hz**	**125Hz**	**250Hz**	**500Hz**	**1kHz**	**2kHz**	**4kHz**	**8kHz**
Measured: Pumps 1&2	78	44	51	65	70	72	72	71	71
Predicted: Pumps 1&2	79	54	55	68	69	71	73	73	72

Exercises such as this give an indication of the confidence that has been gained in the accuracy of sound intensity measurements and the calculation methods used.

Case study 2

This study concerns an investigation into ventilation noise within a control/command area. Sound pressure measurements taken during a compartment airborne noise survey indicated that the compartment target level was exceeded. Subjective comments had also been made by the crew to the effect that noise was interfering with speech communication. An initial investigation involved taking sound pressure levels with and without the main air conditioning fans in operation. These measurements identified that the ventilation system was the dominant source of noise in this compartment with noise being greatest in the starboard aft corner. Unfortunately, with there being many noise sources in the control area, sound pressure measurements could not be used to discriminate between the contribution of each duct opening and hence the dominant noise source could not be identified.

In order to establish which part of the ventilation duct system linked to the main air conditioning fans was emitting most noise in the control area, swept sound intensity measurements were taken over each of the supply and exhaust duct openings in this compartment (FIG.3). The resulting sound

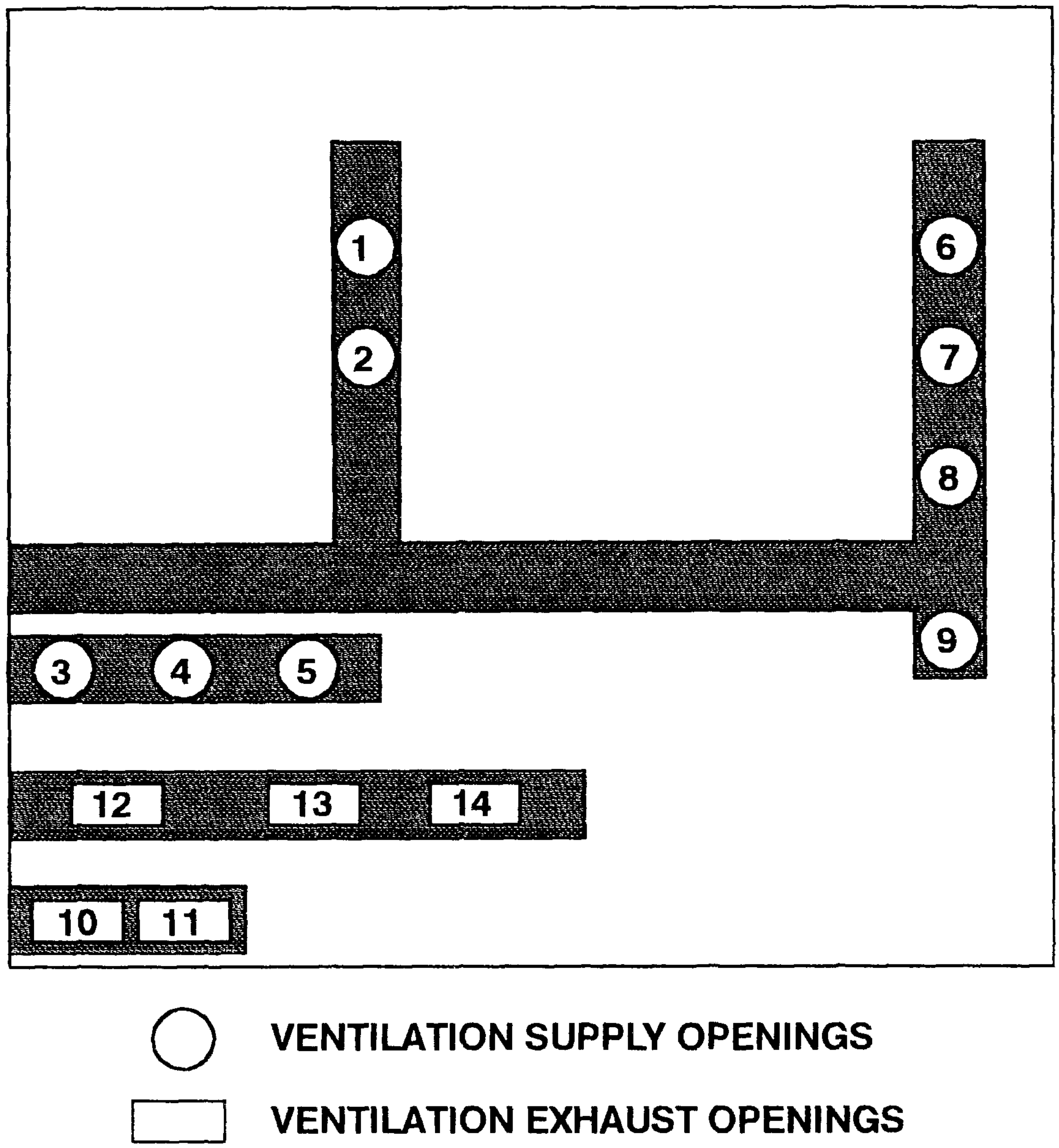

FIG. 3—CONTROL AREA VENTILATION DUCTS (PLAN VIEW)

power levels of this survey are shown in Table 3. This table indicates that more noise was generally emitted from the exhaust duct openings than the supply duct openings, and that exhaust duct opening 12 emitted most noise. This duct opening was also located in the corner of the compartment where the highest sound pressure levels had been measured previously.

TABLE 3—*Control area ventilation duct sound power levels*

Duct No. (See Fig.3)	Sound Power Levels (dBA ref. 10^{-12}W)								
	Overall	63Hz	125Hz	250Hz	500Hz	1kHz	2kHz	4kHz	8kHz
Supply 1	49	25	37	43	41	44	32	36	36
Supply 2	50	37	40	41	47	39	34	39	35
Supply 3	54	32	45	43	48	48	46	39	38
Supply 4	56	39	33	44	46	45	54	47	43
Supply 5	49	38	40	40	40	38	43	42	32
Supply 6	50	35	39	45	40	44	38	24	37
Supply 7	49	39	39	42	41	43	35	29	38
Supply 8	48	38	36	42	41	43	36	33	23
Supply 9	52	40	40	44	43	46	38	45	36
Exhaust 10	55	36	41	41	48	47	45	51	43
Exhaust 11	53	26	39	39	40	40	51	44	41
Exhaust 12	70	38	51	51	57	60	66	65	61
Exhaust 13	67	33	42	53	55	57	64	60	59
Exhaust 14	66	37	36	49	55	58	62	58	56

The source of the high noise levels was traced to the presence of a nearby orifice plate used to control airflow within the duct in question. By their very nature, orifice plates restrict air flow and consequently generate a great deal of flow related noise. The orifice plate was later removed and re-positioned further upstream with the result that sound pressure levels in the control area were reduced to a satisfactorily level and the compartment target achieved.

Case study 3

This study involves airborne noise investigations carried out in a compartment containing gyro compass equipment. An initial investigation had identified that noise from the ventilation system was the dominant source of noise in this compartment, and as a result, the offending duct opening had been covered with an acoustic silencer box. Unfortunately, after the duct had been treated, sound pressure measurements indicated that the compartment noise levels had not been reduced as expected with the acoustic box in place.

It was then realised that various electronic processing units of the gyro compass equipment suite in this compartment, which operated during certain operating states of the submarine, could have a significant effect on compartment noise levels. These units were sensitive to being switched on and off and so the opportunity of taking sound pressure measurements to obtain the contribution of each unit was not possible. Instead, swept sound intensity measurements were taken over each of the processing units and over the attenuated duct opening. The sound power level contributions of each noise source are shown in Table 4.

TABLE 4—*Gyro compass area sound power levels*

Noise Source	Sound Power Levels (dBA ref. 10^{-12}W)								
	Overall	63Hz	125Hz	250Hz	500Hz	1kHz	2kHz	4kHz	8kHz
Processing Unit 1	76	44	61	64	68	74	66	63	54
Processing Unit 2	72	52	50	58	65	70	64	57	49
Processing Unit 3	68	29	55	59	64	64	57	56	38
Processing Unit 4	68	43	64	63	52	54	59	48	45
Ventilation Duct	73	68	71	60	54	61	56	50	45

These results confirmed that the acoustic box over the ventilation duct opening was functioning as expected, and that one of the processing units was dominating compartment levels now that noise from the ventilation duct had been reduced.

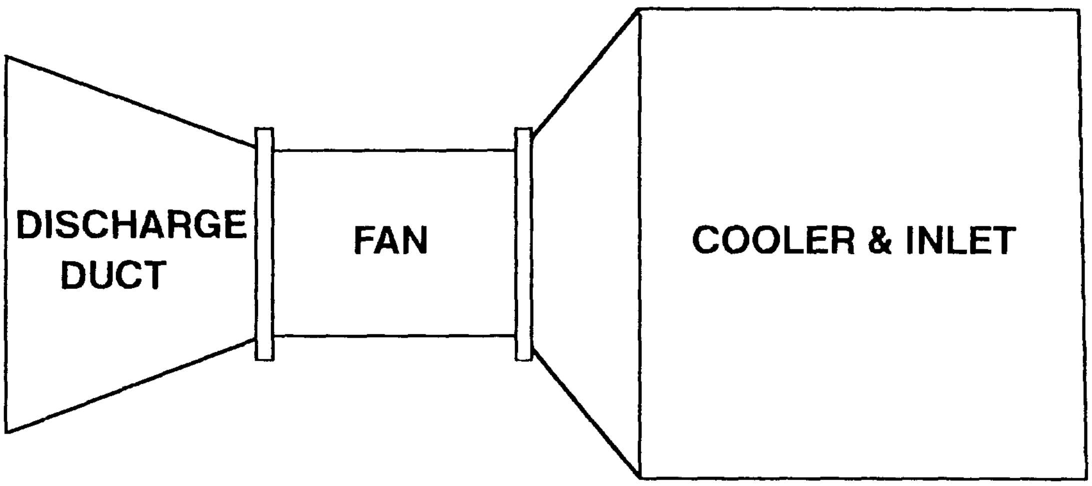

FIG. 4—AIR TREATMENT UNIT

Case study 4

This study is an example of how sound intensity measurements have been used to identify which components of a machine emit most noise. The machine discussed here is an air treatment unit (FIG.4) located in a machinery compartment and was identified as one of the dominant sources of noise within this compartment. In order to propose the most effective acoustic measures for the air treatment unit, it was first necessary to identify those parts of the unit that were emitting most noise. This could not be achieved using sound pressure measurements because these would only give the sum of the contributions of all components of the unit, and hence sound intensity measurements were utilized instead.

Swept sound intensity measurements were taken over imaginary surfaces enclosing the cooler and inlet, the fan casing, and the discharge duct of the air treatment unit. The sound power levels determined using this method are shown in Table 5, and indicate that most noise was emitted from the inlet and discharge.

TABLE 5—*Air treatment unit sound power levels before treatment*

Component (See Fig.4)	Sound Power Levels (dBA ref. 10^{-12}W)								
	Overall	63Hz	125Hz	250Hz	500Hz	1kHz	2kHz	4kHz	8kHz
Cooler & Inlet	93	60	66	78	87	89	87	81	67
Fan Casing	78	52	54	66	70	75	71	63	54
Discharge Duct	91	77	78	77	83	86	86	80	72
Total	96	77	78	81	89	91	90	84	73

In order to reduce noise levels it was decided to reconfigure the cooler and inlet to allow a smoother airflow to be incident on the fan, and to attach silencer resonators to the fan discharge. Sound intensity measurements were then re-taken once the treatments had been installed and the results are indicated in Table 6.

TABLE 6—*Air treatment unit sound power levels after treatment*

Component (See Fig.4)	Sound Power Levels (dBA ref. 10^{-12}W)								
	Overall	63Hz	125Hz	250Hz	500Hz	1kHz	2kHz	4kHz	8kHz
Cooler & Inlet	85	57	60	67	79	77	82	76	59
Fan Casing	68	49	52	55	64	59	63	53	50
Discharge Duct	86	74	72	73	77	81	82	76	67
Total	89	74	72	74	81	82	85	79	68

These indicate that although most noise was still being emitted by the inlet and discharge, the total overall levels from the unit as a whole had been reduced by 7 dBA.

Conclusions

This article has shown through the case studies, some of the ways in which sound intensity has been used as a diagnostic tool in identifying problem noise sources in submarines. The benefits of using sound intensity techniques over sound pressure measurements in identifying the contribution of machines or machine components in the presence of high background noise, are of particular note.

References

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