



**Acoustics 2019**

Sound Decisions: Moving forward with Acoustics

# Acoustic Signature Control on Maritime Platforms

Stephen Moore

Maritime Division, Defence Science and Technology Group, 506 Lorimer St Fishermans Bend VIC 3207, Australia  
Stephen.Moore@dst.defence.gov.au

## ABSTRACT

The Acoustic Signature Management Branch in Defence Science and Technology Group (DST) develops technical solutions to control the active and passive acoustic signatures of Royal Australian Navy platforms. The aim is to improve the operational effectiveness and survivability of the Navy's current fleet, and the Branch also provides technical advice during the acquisition of new platforms. This paper presents an overview of the active and passive acoustic signatures of maritime platforms and the main factors that influence the signatures. Research by the Acoustic Signature Management Branch on modelling and analysis of acoustic signature generation and transmission is discussed with examples of collaborative research programs with academic and commercial partners.

## 1 INTRODUCTION

Acoustic waves propagate in the ocean over much greater distances than electromagnetic radiation (e.g. light, radio waves). This property has been exploited through the development of sonar (SOund Navigation And Ranging) systems, which can detect, localise, and classify targets at far greater ranges compared with technologies relying on other physical processes, such as electromagnetic radiation. The acoustic signature describes the characteristics of a platform (i.e. surface ship or submarine) that allow it to be detected, localised, and classified using sonar systems. The acoustic signature is a significant factor determining operational effectiveness and survivability of maritime platforms used for military purposes, in particular submarines.

Military sonar systems can be broadly categorised as either passive or active sonar systems. Passive sonar systems are designed to detect the acoustic noise radiated by the target; i.e. the target's *passive acoustic signature*. Passive sonar systems include those installed on submarines (e.g. bow, flank, and towed hydrophone arrays); surface ships (hull-mounted sonars, towed arrays and variable depth sonars); deployed by aircraft (sonobuoys dropped by planes and helicopters, dipping sonars on helicopters); and also fixed installations along coastlines and through ocean transit areas or choke points. Active sonar systems transmit an acoustic signal into the water column and detect the return signal or echo reflected from the target. The returned acoustic signal is determined by the target's active acoustic signature, termed the *target echo strength*. Active sonar systems are deployed on surface ships, sonobuoys, dipping sonar, and also on submarines. However, the use of active sonar on submarines is likely to severely reduce the submarine's stealth and would only be used in particular circumstances.

From the platform's point of view, the threat to survivability from an adversary can be separated into a chain of events:

1. Detection.
2. Identification and classification.
3. Localisation, tracking, and targeting.
4. Hit with a weapon.
5. Damage and/or death.

The platform's acoustic signature directly affects the probability of events 1 – 3 occurring, and thus the possibility of being hit with a weapon, sustaining damage, and being killed.

The mechanisms that contribute to the passive acoustic signature of a maritime platform include on-board machinery, the propulsor (i.e. propeller or pumpjet), and noise due to flow over the hull. Target echo strength is affected by the size and shape of the platform, as well as the materials used to coat the hull. The designs of naval platforms, especially submarines, are significantly influenced by technology to reduce the passive acoustic signature and the target echo strength. The advantage that this technology imparts on the operation of the platform means that the details of the research, development, and implementation are usually classified. Nevertheless, fundamental research on noise and vibration control published in the open literature provides some insight into the principles behind control of acoustic signatures on maritime platforms.

The following section provides an overview of the main factors that influence the passive acoustic signature and target echo strength, as well as the methods to control these signatures. A summary of recent research by the Acoustic Signature Management Branch at DST is given in Section 3, and concluding remarks are given in Section 4.

## 2 ACOUSTIC SIGNATURES OF MARITIME PLATFORMS

### 2.1 Passive Acoustic Signature

The noise radiated into the water column by a ship or submarine can be separated into contributions from three main sources: 1) machinery on-board the platform; 2) noise from the propulsor (e.g. propeller, pumpjet, shrouded propeller); 3) noise due to flow over the hull. These occur on both civilian and military platforms, although the absolute levels of radiated noise and the relative contributions from each source will vary between classes of platforms.

The general characteristics of radiated noise from a surface ship or submarine are illustrated by the spectrum of radiation noise shown in Figure 1 (Lurton, 2002). The spectrum is a combination of narrow-band (tonal) and broadband components. The tonal components are more likely to be present at low frequencies, while at frequencies above a few hundred Hertz, the spectrum is mainly broadband with amplitude that decrease at approximately 20 dB/decade (6 dB/octave). The absolute levels of radiated noise from submarines are rarely published in open literature, although some data is given by Lurton (Lurton, 2002) (originally published by Miasnikov (Miasnikov, 1998)), which is summarised in Table 1.  $RN_{SL}$  indicates the highest tonal component and  $RNL_{1K}$  is the level at 1,000 Hz, as shown in Figure 1. Information on radiated noise levels from WWII-era submarines is given by Urick (Urick, 1983).

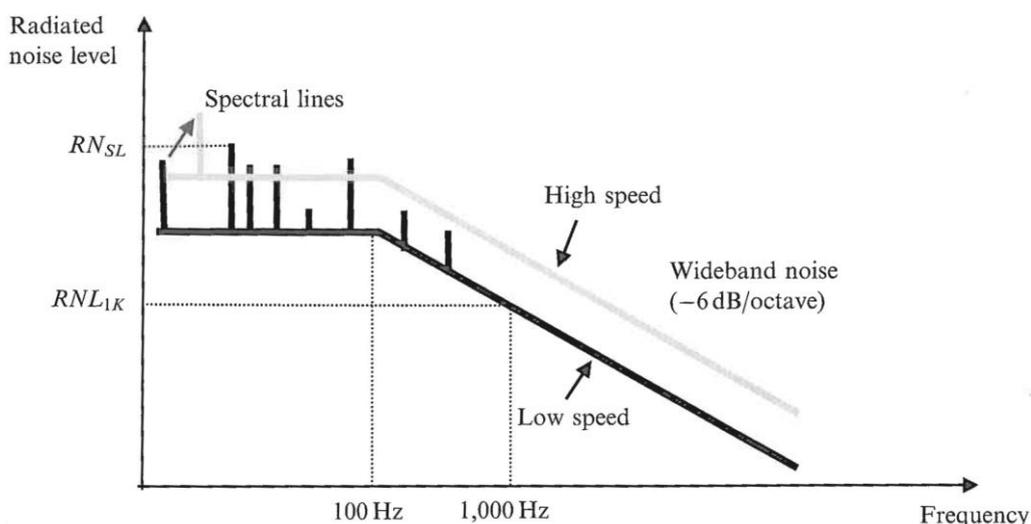


Figure 1 Typical spectrum of radiated noise produced by a surface ship or submarine (Lurton, 2002).

Table 1 Order-of-magnitude levels of radiated noise from submarines at 4 knots (Lurton, 2002).

Submarine Type	$RN_{SL}$	$RNL_{1K}$
World War II submarine (electric)	140	120
Modern submarine (electric)	100	80
Modern submarine (diesel)	140	120
Recent SSN	110	90
Recent SSBN.	120	100

The data in Table 1 indicates that efforts to control the acoustic signature of diesel-electric submarines since WWII have resulted in a 40 dB reduction of tonal and broadband noise. It is also evident from the data that nuclear powered attack submarines (SSN) and nuclear powered ballistic missile submarines (SSBN) produce higher radiated noise than a conventional diesel-electric submarine, except when the conventional submarine is operating its diesel engines to recharge batteries. The radiated noise on SSNs and SSBNs may be attributed to the machinery required to maintain safe operation of the nuclear power plant. In contrast, conventional submarines operating at low speed using power from the batteries can minimise the noise generated by machinery.

The passive acoustic signature varies significantly with vessel speed. Noise from the propulsor and flow along the hull, increases in proportion to vessel speed raised to the fifth or sixth power (Ross, 1987), and flow-generated noise tends to dominate the contribution from machinery at higher speeds. This is illustrated in Figure 2 (Miasnikov, 1998) which shows radiated noise versus speed. At speeds below 8 kts machinery noise dominates the acoustic signature, and increases with speed. Flow noise and propulsion noise begins to dominate above 8 kts and increases with speed at a greater rate than machinery noise. The highest noise levels are produced after the onset of cavitation, although submarine propulsors are designed so that cavitation is unlikely to occur, especially when submerged. The acoustic signature is not only dependent on the machinery line-up and speed; it also changes over time due to the maintenance of machinery (McIntosh, 2014), as well as bio-fouling of the hull which increases drag and consequently propulsion noise and flow noise.

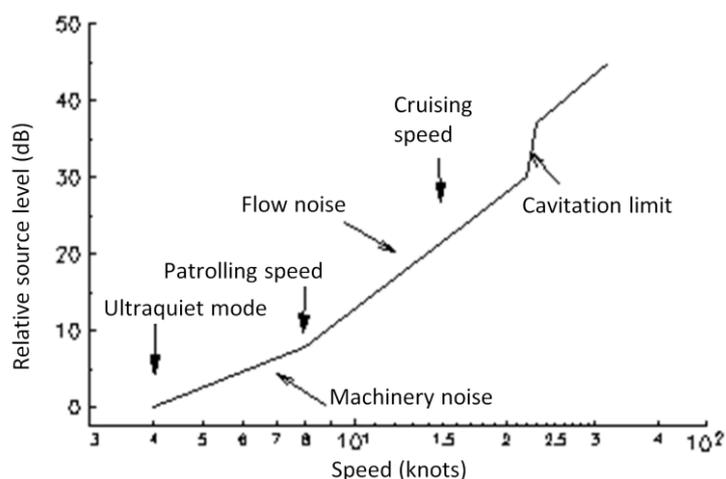


Figure 2 Submarine radiated noise vs. speed (Miasnikov, 1998).

### 2.1.1 Machinery Noise

Noise and vibration is an inevitable by-product of machine operation. Typical machines on naval platforms include diesel engines, gas turbine engines, and/or electric motors used for main propulsion; gearboxes; diesel generators; electric propulsion motors, pumps, fans, and hydraulic power packs. The contributions from machinery noise can be separated into structure-borne, airborne, and fluid-borne components and analysed using a source-path-receiver conceptual framework, as illustrated in Figure 3 for the case of a submarine. This approach is a starting point for analysis as it allows each component and transmission path to be considered in

isolation and then combined in an uncoupled model. A more detailed analysis would account for a degree of coupling between the different components and transmission paths.

Structure-borne source levels for machines are typically described as free vibration levels, and the transmission path comprises machine vibration isolation, machine rafts, decks, foundations, and hull structural elements. Similarly, the airborne contribution is described by the machine's sound power and the acoustic response of the compartment, which is affected by acoustic treatments such as enclosures, shields, and acoustic absorption material. An overview of some recent research on submarine vibration isolation and noise control is given by Howard (Howard, 2011). Pumps and hydraulic machinery generate fluid-borne noise and source levels are quantified in terms of pressure pulsation amplitudes. The main fluid-borne transmission paths are fluid-filled pipes, which can radiate noise directly into the water column or induce structure-borne vibration through supporting structures.

In general, it is desirable to treat machinery noise as close as possible to the source though the selection of machinery with low noise and vibration characteristics. The use of vibration isolation, acoustic barriers or enclosures, and flexible pipe elements limit the transmission of vibration or acoustic energy to surrounding areas. Despite these treatments some proportion of structure-borne, airborne, and fluid-borne noise will excite vibration in the hull, which is subsequently radiated as acoustic noise into the water column.

In addition to the mechanisms described above, diesel generators on submarines may expel exhaust gasses into the water column. The radiated noise is due to pressure pulsations from the engine combustion process, bubble formation, and the interaction of the bubbly flow with nearby structures.

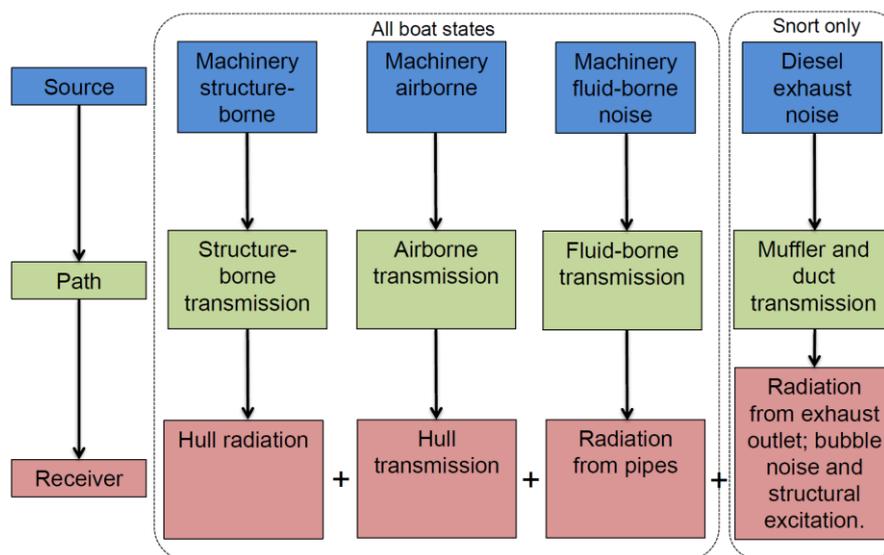


Figure 3 Source-path-receiver conceptual framework applied to machinery noise radiated from a submarine.

### 2.1.2 Propulsion Noise

Propulsion noise is generated by the action of the propulsor generating thrust to propel the platform. Propulsion noise can be separated into a number of mechanisms:

1. Narrow-band or tonal components at the blade-pass frequency and its harmonics. This is generated by unsteady thrust due to the rotation of each propulsor blade through the non-uniform wake from the hull.
2. Low frequency broad-band noise due to the turbulent inflow into the propulsor.
3. High-frequency broadband trailing- and leading-edge noise.
4. Vortex-induced noise and excitation of propulsor blade resonances. A common example is propeller singing.
5. Cavitation noise, which is broadband and typically results in a large increase in the radiated noise, as indicated in Figure 2.

Mechanisms 1 – 3 are largely unavoidable, and the aim during design is to reduce these contributions as much as possible while achieving suitable hydrodynamic performance. Submarine propellers typically have a relatively large number of blades with a swept back profile compared with surface ship propellers, and are designed to provide sufficient thrust at low rotation speeds, to help reduce noise generation (Ozden, 2016). Mechanisms 4 and 5 may occur at certain operating points; however, for submarines this is highly undesirable because of the detrimental effect on the acoustic signature. Comprehensive studies using computational fluid dynamics (CFD), model testing and full scale trials, are necessary to optimise both the hydrodynamic and hydro-acoustic performance of the propellers (Tani, 2016).

Some proportion of propulsion noise is radiated directly into the water column and some noise is generated through interaction of the propulsor with the hull, as shown in Figure 4, which illustrates the arrangement of a submarine propeller. Unsteady thrust and blade vibratory forces are transmitted to the hull via the propeller shaft, journal and thrust bearings and these forces will excite the hull to radiate noise. The structural-dynamic properties of the propeller, propeller shaft, shaft bearings, and the hull will determine the level of propulsion noise radiated by the hull. Studies have investigated the dynamics of the propulsion shafting system and aft-end structures and demonstrated the potential for optimising the designs to reduce radiated noise (Dylejko, 2007; Qi, 2016). Radiated noise from the propeller also excites the hull, which then re-radiates the noise. On surface ships the propeller may be relatively close the ship hull compared with a submarine and pressure pulsations from the propeller and cavitation can cause significant hull vibration.

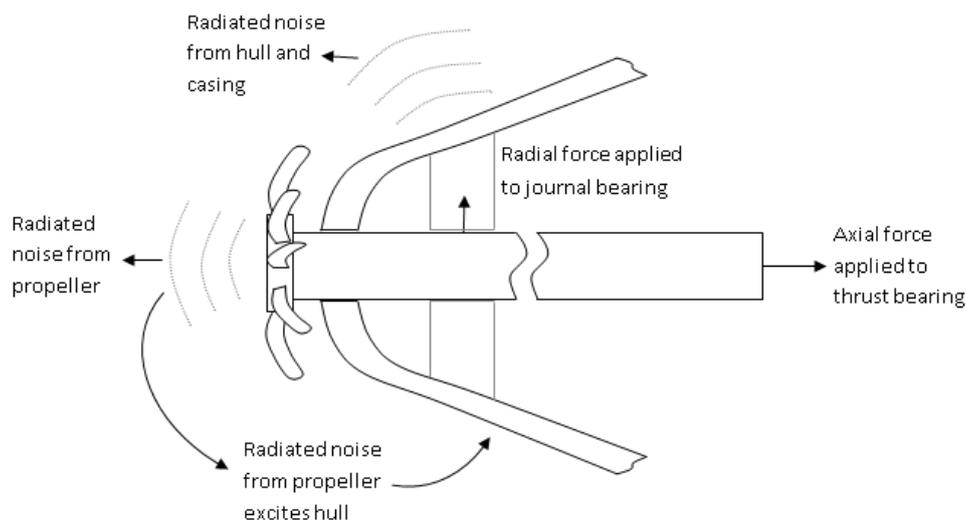


Figure 4 Mechanisms of noise generation by a propeller on a submarine.

### 2.1.3 Flow Noise

Flow over the hull generates broadband noise through the interaction of the turbulent boundary layer with the hull. This process is relatively inefficient such that other noise sources are likely to dominate noise radiated into the far-field. However, flow over sonar system hydrophones gives rise to 'self-noise' and this reduces the signal-to-noise ratio of the sonar system. Domes and covers over sonar transducer arrays (e.g. over the bow sonar on ships and submarines and the flank array on submarines) are designed to minimise self-noise and cavitation while also being transparent to acoustic waves.

Flow over appendages such as rudders, control surfaces and struts can also generate noise due to mechanisms 2 – 6 listed in the previous section. Vortex-induced excitation of structural resonances will produce tonal radiated noise, and in some cases can induce fatigue damage in the structure. Tonal noise may also be generated by flow over cavities along the hull, such as pipe or tank openings. In these cases flow generates vortices that excite resonances in the cavity and structural elements bounding the cavity.

Experimental measurement of flow generated noise is challenging given that in most situations where flow exists considerable noise is generated by other mechanisms. Experimental studies have been done in wind and

water tunnels and also using buoyancy driven models (Haddle, 1969; Fischer, 2017; Yen, 2018). Numerical modelling is increasingly being used to optimise hull forms for hydrodynamic performance and to minimise flow noise and self-noise (Chen, 2012a; Chase, 2013).

### 2.1.4 Transient Noise

Many of the mechanisms described above produce steady noise. Transient noise is also an important component of the acoustic signature and is generated by a range of processes on-board a platform including crew activities, weapons handling, operation of periscopes and masts, start up and shutdown of machinery, and manoeuvring of control surfaces. In contrast to steady noise sources, transient noise is more difficult to characterise using just radiated noise spectra. Some recent work by Leissing (Leissing, 2014) discusses alternative signal processing techniques for the characterisation and assessment of transient noise.

## 2.2 Target Echo Strength

The target echo strength (TES) is a measure of the active acoustic signature that is sensed by active sonar systems. It is essentially a quantitative measure of the acoustic reflectivity of the target, defined as  $10 \cdot \log_{10}(I_{ref}/I_{inc})$ .  $I_{inc}$  is the intensity of the incident wave, which is assumed to be a plane wave as consequence of the source and target being far apart, and  $I_{ref}$  is the intensity of the reflected wave, which will radiate in all directions. In *monostatic* sonar operation (see Figure 5 (a)) the source and the receiver are in the same location, e.g. on a surface ship, and the TES is a function of the angle of incidence of the incoming wave relative to an axis on the target (i.e. aspect). In *bistatic* sonar operation the source and receiver are not co-located and the TES is a function of the incident direction ( $\theta_i$ ) and the direction of the receiver ( $\theta_r$ ), as shown in Figure 5. In principle, TES is also a function of elevation angle between the source, target, and receiver, although shallow elevation angles are usually of most concern due to the typical distances separating source and receiver, relative to the depth of the water column.

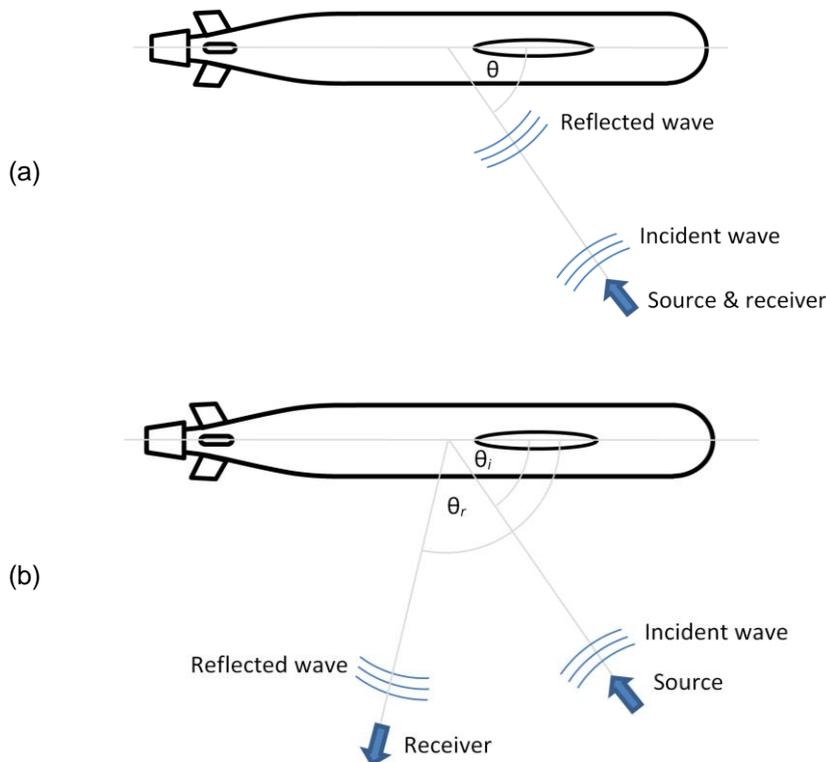


Figure 5 A plan-view schematic of monostatic (a) and bistatic (b) sonar operation.

TES can be measured in full-scale trials or using scale models (*Physics of Sound in the Sea*, 1969; McLeary, 1994). Results from full-scale measurements for two WWII-era submarines are shown in Figure 6 (Urick, 1983), and a feature typical of submarines is evident: target strength at beam aspects ( $90^\circ$ ,  $180^\circ$ ) is significantly greater than around stern and bow aspects, mainly due to the elongated cylindrical geometry of submarines. The TES of a submarine at beam aspect is dominated by specular reflection from surfaces with acoustic impedances very different to water. This includes 'hard' surfaces like steel plate but also 'soft' surfaces like an air volume in a tank. In addition to specular reflection, scattering of the incident wave by protuberances, corners, and edges with small radii of curvature relative to the wavelength of the incident wave will contribute to TES. It should also be recognised that the incident wave may penetrate parts of the structure and undergo multiple reflections from structures within the exterior casing of a submarine.

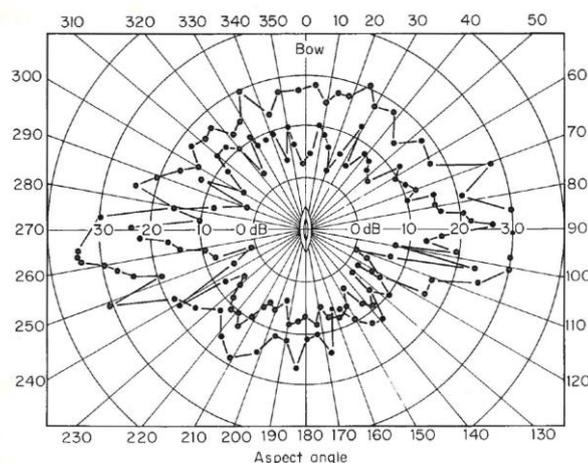


Figure 6 Measured target strength for two submarines (Urick, 1983).

Control of TES is achieved through optimising the shape of the body and the use of anechoic coatings. Optimising the shape involves reducing the radii of curvature of surfaces (i.e. avoiding large flat surfaces) and angling surfaces away from the horizontal elevations. Modelling is used to assess design options and the application of a number of approximate analytical and numerical approaches is described by Schneider (Schneider, 2003). Anechoic coatings were first developed by Germany during WWII (Meyer, 1950) and were designed to reduce the intensity of the reflected wave by absorbing the incident acoustic energy. The German 'Alberich' tile was made from an elastomer with an array of macroscopic holes of two sizes. The tile material properties, thickness, size and shape of inclusions can be optimised to minimise the reflection coefficient across particular frequency ranges (Zeqiri, 2010). Maintaining the coverage of anechoic tiles throughout the life of a submarine is important, as illustrated by Figure 7, which clearly shows the pattern of tiles on the sail of the UK submarine HMS Triumph, as well as areas where tiles are missing.



Figure 7 The UK submarine HMS Triumph. The outlines of anechoic tiles are visible as are areas where tiles are missing (Wikipedia, 2019).

### 3 RESEARCH AT DEFENCE SCIENCE AND TECHNOLOGY GROUP

The Acoustic Signature Management Branch conducts research to control the active and passive acoustic signatures of Royal Australian Navy platforms. The aim is to improve the operational effectiveness and survivability of the Navy's current fleet, and the Branch also provides technical advice during the acquisition of new platforms, for example Australia's Attack Class Submarine and Hunter Class Frigate. The Branch works closely with the Royal Australian Navy, Capability Acquisition and Sustainment Group (CASG), and other parts of the Defence Department. Support to Australia's current Collins Class Submarine fleet is facilitated through a strategic alliance between DST and ASC Pty Ltd, the company that constructed and now maintains the Collins Class Submarines.

#### 3.1 Technical Disciplines and Research

The Acoustic Signature Management Branch employs scientists, engineers, mathematicians, and mechanical and electrical trades and the Branch's capability is complemented by collaborative projects with universities and with commercial companies. Technical disciplines include:

- Acoustics (airborne and waterborne);
- Vibration of structures and machinery;
- Fluid mechanics (hydrodynamics and hydroacoustics);
- Materials;
- Vibration and acoustic measurements;
- Laboratory based experimentation and field trials;
- Analytical and numerical modelling.

This expertise is applied to the full range of areas that affect a platform's acoustic signature, summarised in the previous section, and the Branch endeavours to publish fundamental aspects of its research. For example: on machinery noise and vibration isolation (Dickens, 2000; Forrest, 2006; Dylejko, 2014; Dylejko, 2017); hull radiation and active control of hull radiation (Forrest, 2007; Forrest, 2011; Forrest, 2016; Pan 2008a; Pan 2008b; Pan 2013); propulsion noise (Dylejko, 2007); flow noise (Do, 2011; Chen, 2011; Chen, 2012a; MacGillivray, 2017); diesel engine exhaust noise (Bowden, 2016); bubble noise (Chen, 2012b); vibro-acoustics of novel materials (Sharma, 2019), and target strength modelling (Schneider, 2003; Zhang, 2003). A significant part of this work has been done in partnership with Universities through formal research agreements and the support of graduate research students.

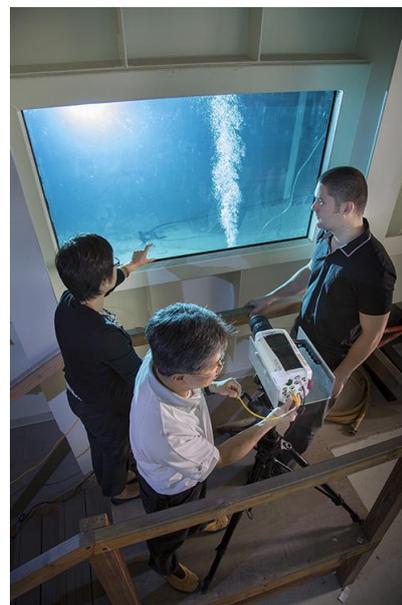
DST also leverages expertise in industry, and an example supporting acoustic signatures research is the development of AUSRAT, a software tool for modelling the acoustic signature of a platform from the concept design stage through to detailed design (Norwood, 2017). The software was developed by Frazer-Nash Consultancy in partnership with DST and includes tools for modelling machinery noise, propulsion noise, and also hull radiation.

#### 3.2 Facilities

DST has extensive laboratory facilities to support acoustic signatures research. The laboratory at Fishermans Bend, Victoria houses a  $10 \times 10 \times 6$  m open water tank shown in Figure 8 (a). The tank is used to measure the sound radiation from structures, the acoustic transmission and reflection of materials, and also in the study of bubble plumes (Figure 8 (b)) (Chen, 2012b). Testing of small scale buoyancy driven models has also been carried out in the tank (Yen, 2018), with acoustical measurements in the tank, acceleration measurements inside the model, and high speed video recording of the ascending model.



(a)



(b)

Figure 8 (a) Water tank at DST Fishermans Bend; (b) experiments on bubble plumes.

A temperature-controlled pressure tank shown in Figure 9 (a) is available to simulate hydrostatic pressure, and has been instrumented with hydrophones to facilitate measurement of acoustic transmission and reflection from material samples. DST developed a facility for measuring the dynamic stiffness of vibration isolators (Figure 9 (b)) (Dickens, 2003); and a  $4 \times 4 \times 3$  m anechoic chamber is available for vibro-acoustic measurements in air (Figure 9 (c)).

Research at DST often involves a staff and facilities from number of different Branches and Divisions. Figure 10 (a) shows modal testing of DST's Hedemora V6 diesel engine, which has been mounted on a vibration isolation system used for acoustic signatures research. The diesel engine test facility was set up by the Maritime Platform Performance Branch in DST. Figure 10 (b) shows the experimental apparatus for flow noise measurements in DST's low speed wind tunnel, which is managed by Aerospace Division. An acoustic beam forming measurement technique developed by researchers at UNSW was used to localise sources of flow noise (Fischer, 2017). The microphone array can be seen mounted in the side wall of the tunnel test section.

#### 4 CONCLUSIONS

The acoustic signature is a significant factor determining operational effectiveness and survivability of maritime platforms used for military purposes, in particular submarines. The main mechanisms that influence the passive and active signature have been discussed, with examples of research in this area done by the Acoustic Signature Management Branch at DST.

#### ACKNOWLEDGEMENTS

This paper summarises work by the Acoustic Signatures Management Branch at DST. The author is grateful for contributions from Branch members, in particular Li Chen, Paul Dylejko, James Forrest, Ian MacGillivray, Xia Pan, and Alexei Skvortsov.

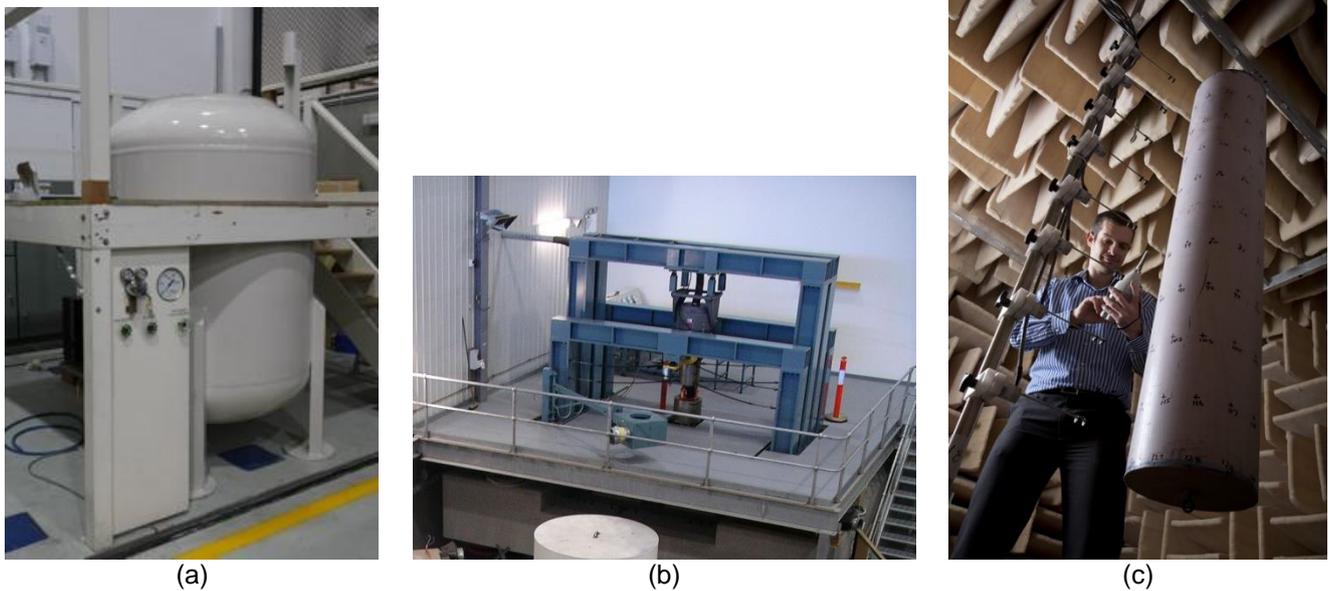


Figure 9 (a) Pressure tank; (b) vibration isolator test facility; (c) anechoic chamber

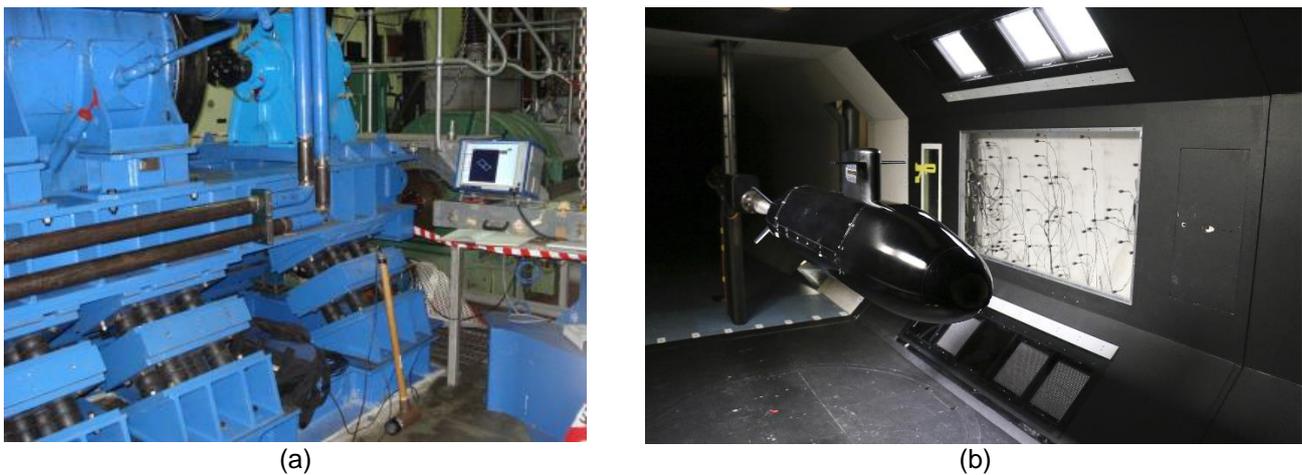


Figure 10 (a) Modal testing of the DST Hedemora V6 research diesel engine; (b) Flow noise measurements in the DST low speed wind tunnel (Fischer, 2017).

## REFERENCES

- Bowden, D. R., 2016. Development of a large experimental acoustic transmission loss test bench suitable for large marine diesel exhaust system components. *Proc. Acoustics 2016*. Brisbane, Australia.
- Do, T., Chen, L., Forrest, J.A., Tu, J. 2011. Numerical experiments of forced cylinder oscillations at an angle to oncoming flow, *Engineering Applications of Computational Fluid Mechanics*. 5(4): 579-594.
- Chase, N., Carrica, P.M., Submarine propeller computations and application to self-propulsion of DARPA Sub-off. *Ocean Engineering*. 60: 68-80.
- Chen, L., MacGillivray, I.R. 2011. Characteristics of sound radiation by turbulent flow over a hydrofoil and a bare-hull SUBOFF, *Proc. Acoustics 2011*. Gold Coast, Australia.
- Chen, L., MacGillivray, I.R., Tso, Y.K. 2012a. Radiation characteristics of turbulent flow noise from an underwater vehicle, and a feasible prediction method. *Proc. Pacific 2012*. Sydney, Australia.
- Chen, L., Wood, S., Moore, S., Nguyen, B. 2012b. Acoustic emission of bubbly flow and its size distribution spectrum. *Proc. Acoustics 2012*. Fremantle, Australia.

- Dickens, J.D. 2000. Dynamic model of vibration isolator under static load. *Journal of Sound and Vibration*. 236(2): 323-337.
- Dickens, J.D., 2003. Development of a facility to dynamically test vibration isolators. *The Shock and Vibration Digest*. 35(4): 265-271.
- Dylejko, P.G., Kessissoglou, N.J., Tso, Y., Norwood, C.J. 2007. Optimisation of a resonance changer to minimise the vibration transmission in marine vessels. *Journal of Sound and Vibration*. 300: 101-116.
- Dylejko, P.G., MacGillivray, I.R. 2014. On the concept of a transmission absorber to suppress internal resonance. *Journal of Sound and Vibration*. 333: 2719-2734.
- Dylejko, P.G., MacGillivray, I.R., Moore, S.M., Skvortsov, A.T. 2017. The influence of internal resonances from machinery mounts on radiated noise from ships. *IEEE Journal of Ocean Engineering*. 42(2): 399-409.
- Fischer, J., Rowan, M., Jacquemin, P., Lamos, D., Skvortsov, A., Doolan, C. 2017. Wind tunnel flow noise measurements of a generic submarine model. *Proc. Acoustics 2017*. Perth, Australia.
- Forrest, J.A. 2006. Experimental modal analysis of three small-scale vibration isolator models. *Journal of Sound and Vibration*. 289: 382-412.
- Forrest, J.A. 2007. Moment control of the sound radiated from an axially excited cylindrical shell. *Proc. ICSV14 14<sup>th</sup> International Congress on Sound and Vibration*. Cairns, Australia.
- Forrest, J.A. 2011. Structural vibration transmission in stiffened structures. *Proc. Acoustics 2011*. Gold Coast, Australia.
- Forrest, J.A. 2016. Sound radiation from a submerged stiffened cylinder with acoustic excitation. *Proc. Acoustics 2016*. Brisbane, Australia.
- Haddle, G.P., Skudrzyk, E.J. 1969. The physics of flow noise. *J. Acoust. Soc. of Am.*, 46(1): 130-157.
- Howard, C.Q. 2011. Recent developments in submarine vibration isolation and noise control. *Proc. 1st Submarine Science Technology and Engineering Conference*. Adelaide, Australia
- Lurton, X. 2002. *An Introduction to Underwater Acoustics*. Springer.
- Leissing, T., Audoly, C., Lachambre, H., Stempf, G. Advanced signal processing methods for the analysis of transient radiated noise from submarines. *Proc. InterNoise 2014*. Melbourne, Australia.
- Miasnikov, E.V., 1998, 'What is known about the character of noise created by submarines?'. *The Future of Russia's Strategic Nuclear Forces – Discussions and Arguments*, Moscow: Center for Arms Control, Energy and Environmental Studies, Moscow Institute of Physics and Technology.
- MacGillivray, I., Skvortsov, A., Dylejko, P. 2017. Vibroelastic Models for Flow Noise Estimation. *Proc. ICSV 24 24<sup>th</sup> International Congress on Sound and Vibration*. London, United Kingdom.
- McIntosh, D.J., 2014. Real variability in ship systems' noise and vibration. Design and through-life management implications for underwater noise and habitability. *Proc. InterNoise 2014*. Melbourne, Australia.
- McLeary, R., Witcher, R.E., MacGillivray, I.R. 1994. Scattered field distributions from the near to the far field using an acoustic lens. *J. Acoust. Soc. of Am.*, 95(5): 2560-2566.
- Meyer, E. (ed), Kuhl, W., Oberst, H., Skudrzyk, E., Tamm, K. 1950. *Sound Absorption and Sound Absorbers in Water (Dynamic Properties of Rubber and Rubberlike Substances in the Acoustic Frequency Region)*. Translated by Charles E. Mongan Jr., Department of the Navy, Bureau of Ships, Washington, DC, Report NavShips 900,164, Vol. 1. Manuscript delivered 1946, published 1950.
- Norwood, C., Moore, S. 2017. A unified approach to modelling the acoustic signature from concept to build. *Proc. Maritime/Air Systems & Technologies MAST Asia 2017*. Chiba, Japan.
- Özden, M.C., Gürkan, A. Y., Özden, Y.A., Canyurt, T.G., Korkut, E. 2016. Underwater radiated noise prediction for a submarine propeller in different flow conditions. *Ocean Engineering*. 126: 488-500.
- Pan, X., Tso, Y., Juniper, R. 2008a. Active control of low-frequency hull-radiated noise. *Journal of Sound and Vibration*. 313: 29-45.
- Pan, X., Tso, Y., Juniper, R. 2008b. Active control of radiated pressure of a submarine hull. *Journal of Sound and Vibration*. 311: 224-242.
- Pan, X., MacGillivray, I., Tso, Y., Peters, H. 2013. Investigation of sound radiation from a water-loaded cylindrical enclosure due to airborne noise. *Proc. Acoustics 2013*. Victor Harbor, Australia.
- Physics of Sound In The Sea*. 1969. National Defence Research Committee Division 6 Summary Technical Report 8, reprinted by U.S. Department of Navy.
- Qi, L.B., Wu, Y.S., Zou, M.S., Duan, Y., Shen, M.X., Acoustic and vibrational characteristics of a propeller-shaft-hull coupled system based on sono-elasticity theory. *Journal of Vibration and Control*. 24(9): 1707-1715.
- Ross, D. 1987. *Mechanics of Underwater Noise*. Peninsula Publishing.
- Schneider, H. G., Berg, R., Gilroy, L., Karasalo, I., MacGillivray, I., Ter Morshuizen, M., Volker, A. 2003. Acoustic scattering by a submarine: results from a benchmark target strength simulation workshop, *Proc. ICSV10*, Stockholm, Sweden.

- Sharma, G.S., Skvortsov, A., MacGillivray, I., Kessissoglou, N. 2019. Sound absorption by rubber coatings with periodic voids and hard inclusions. *Applied Acoustics*. 143: 200-210.
- Tani, G., Viviani, M., Hallander, J., Johansson, T., Rizzuto, E., Propeller underwater radiated noise: A comparison between model scale measurements in two different facilities and full scale measurements. *Applied Ocean Research*. 56: 48-66.
- Urick, R.J. 1983. *Principles of Underwater Sound*. 3<sup>rd</sup> Edition, McGraw-Hill.
- Wikipedia. 2019. [https://en.wikipedia.org/wiki/Anechoic\\_tile](https://en.wikipedia.org/wiki/Anechoic_tile). (accessed 3 October 2019).
- Yen, J.S.Y., Butler, D., Lamos, D., Seers, J., Clarke, D.B., Cairns, R., Rowan, M., Skvortsov, A. 2018. Experiments and simulations of an accelerating buoyancy-driven model. *Proc. 21<sup>st</sup> Australasian Fluid Mechanics Conference*. Adelaide, Australia.
- Zeqiri, B., Gélat, P., Norris, M., Robinson, S., Beamiss, G., Hayman, G. 2010. Design and testing of a novel Al-berich anechoic acoustic tile, *Proc. Inter-Noise 2010*, Lisbon, Portugal.
- Zhang, Z. Y., MacGillivray, I., Nguyen, B., Wood, S. 2003. Measurement and modelling of acoustic scattering from submerged objects. *Proc. Undersea Defence Technology Asia 2003*. Singapore.