HEAR
TO LISTEN
ACOUSTICS ADELAIDE - SOUTH AUSTRALIA
6 - 9 NOVEMBER
2018

Free-Field Acoustic Source Levels from Measurements conducted in a Water Tank

Vinh Trinh, Li Chen and James Forrest

Maritime Division, Defence Science and Technology Group, Victoria, Australia.

ABSTRACT

Measuring acoustic radiation from underwater sound sources at sea is expensive. Therefore, it would be highly desirable if the acoustic source level could be obtained accurately and easily in a water tank. Building an anechoic water tank for the audio frequency range is not practicable. In this paper we present a method that can be used to obtain source level from measurements that are conducted in a reverberant water tank with known reverberation time (T60). The T60 is used to calculate the critical radius where the direct field and reverberant field of the source are equal. The measured reverberant sound pressure level (SPL) of an object can then be used to give the direct field and therefore the source level at 1m. Very good agreement was obtained between the known levels of an underwater sound source and it source level calculated using this technique.

1 INTRODUCTION

Measuring acoustic radiation from underwater sound sources at sea is expensive. Therefore, it would be highly desirable if the acoustic source level could be obtained accurately and easily in a water tank. Building an anechoic water tank for the audio frequency range is not practicable. In this paper we present a method that can be used to obtain source level from measurements that are conducted in a reverberant water tank.

The measurement method is based on room acoustics for air, but only a few underwater applications have been found (e.g. Cochard, 2000). It requires a highly reverberant confined sound space and an accurate measurement of reverberation time (T60). A previous paper (Cochard, 2000) applied this technique to a large water tank successfully by using a single broadband T60 (1kHz-20kHz). The current method utilises the reverberation time in one-third octave bands. The reverberation time was indeed found to be a function of frequency. The T60 is used to calculate the critical radius where the direct field and reverberant field of the source are equal. The measured reverberant sound pressure level (SPL) of an object can then be used to give the direct field and therefore the source level at 1m. To illustrate the accuracy of this method, measurements from an underwater sound source in a reverberant water tank are compared to its known source level.

2 A BRIEF OVERVIEW OF REVERBERANT ENCLOSURE ACOUSTICS

In this section we state some established results of room acoustics that are relevant to the discussion in this paper. The results originally developed for room acoustics can be applied more generally to any reverberant enclosure, including water tanks with acoustically reflecting walls. A comprehensive discussion of room acoustics, or the acoustics of an enclosure, can be found in (Kuttruff 2009).

2.1 Sound field inside a reflective enclosure

When a sound source is placed in an enclosure with highly reflecting boundaries, at steady state different types of sound fields are developed within that enclosure, such as the near field, the direct field and the diffuse or reverberant field. The near field is the region which is either close to a sound source or close to a large reflecting surface such as a boundary of the enclosure. The near field close to the sound source is characterised either by (i) evanescent waves in the region immediately adjacent to the vibrating surface of the source, or (ii) a large fluctuation of sound pressure level because of sound wave interference within this region. For case (i), there is no energy propagation to the far field due to the acoustic pressure being out of phase with local particle velocity. For case (ii), no regular decay relationship such as the 6 dB attenuation rule (see below) can be applied. Usually the near field surrounds the whole source as it is confined to very close to the source; the extent of this kind of near field is approximately the dimension of the source or half of the lowest wavelength of interest (Bies, 2003; Hopkin, 2007).

For the near field close to a large reflecting surface, every point in this region is characterised by a non-random phase relationship between the incident and reflected waves, where they are combined and an interference pattern is developed. After accounting for all angles of incidence, it is found that the mean-square pressure at the rigid boundary is doubled when compared to a point in the diffuse field. This pressure difference becomes smaller as we move away from the boundary and it is governed by $\left(1+\frac{\sin(2kd)}{2kd}\right)$ where d is the distance from the boundary and k is the wavenumber (Hopkins, 2007). The largest pressure difference occurs within a quarter of a wavelength from the boundary. Therefore the near field close to any large rigid boundary is considered as a quarter of a wavelength of the lowest frequency of interest from that surface. No measurement should be made inside this region (Rossing, 2007).

The direct field is defined as the region where the sound field radiated by the source has no interference effect from any reflection or diffraction. The sound pressure at a point in this field is solely due to the direct sound wave from the source, as it dominates any of the other effects in this region. In the direct sound field, the inverse square law holds which is characterised by 6 dB attenuation in sound pressure level for every doubling in distance from the source, i.e. the same as for a free field. A purely direct field hardly exists in practice, with the exception of a source in an anechoic chamber where all of the surrounding surfaces are lined with almost totally absorbent materials. In an acoustic enclosure the total sound pressure at a point is the combination of both the direct field and the diffuse field, which is discussed below.

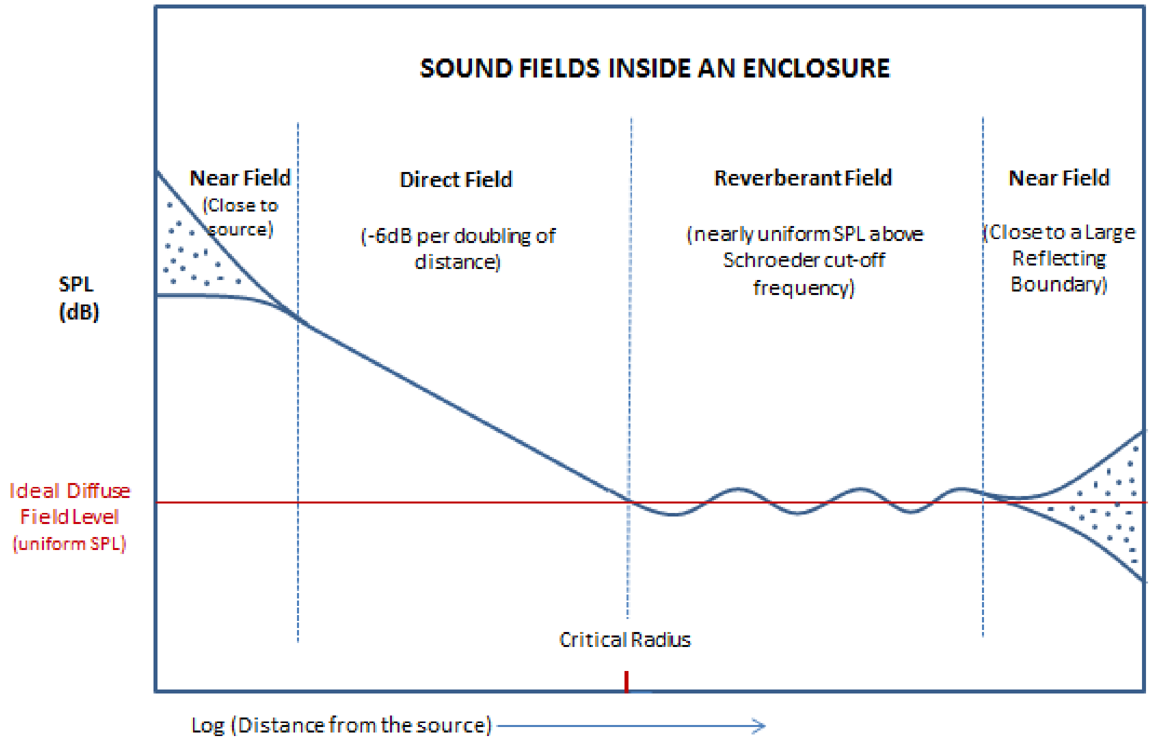


Figure 1: Schematic of the different types of sound field as a function of distance from the source. The dotted regions indicate a highly fluctuating SPL in the near fields which is complex and difficult to predict.

When a sound source is placed in a highly reflective enclosure there will be a vast number of sound wave reflections from its boundaries and the sound field generated by these reflections of the sound waves is known as the diffuse field or reverberant field. A perfectly diffuse sound field is produced when the reflected and diffracted sound waves combine to create a uniformity of sound energy throughout the region of consideration. Theoretically, a perfectly diffuse field must have the following properties: (i) at any position within this field, sound waves arriving at this point will have random phase, and there will be equal probability of a sound wave arriving from any direction, and (ii) the intensity hence sound pressure of the diffuse sound field is the same everywhere regardless of position. A perfectly diffuse field only exists in concept as is not achievable in practice. Practically, this means the sound pressure level must be measured in several locations inside the enclosure, and then averaged to characterise the diffuse field. The diffuse field for an enclosure can be approximated by a highly reverberant field from and above a certain cut-off frequency (Hopkin, 2007) which is given by (Jones, 1996).

$$f_{cut-off} = [c^3 T_{60}/4Vln10]^{1/2} \tag{1}$$

where c is the speed of sound in the medium and V is the volume of the enclosure. An enclosure is regarded as highly reverberant if its boundaries are acoustically hard. It will create a reverberant field which dominates most of the space except for small regions near the source and adjacent to the boundaries.

2.2 Critical radius as an energy balance between direct and reverberant sound fields

When a continuous sound source is placed in an enclosure, at steady-state two dominant types of sound fields are generated: the direct sound field from the source and the reverberant sound field created by reflections. (The near field is not considered as its sound field is locally confined and unpredictable.) The energy density as well as the sound pressure at any point in the room is due to contributions from both fields. Note that the following discussion can be applied to each band of a set of one-third octave bands, as long as the enclosure has sufficient modal density in each band considered to create a reverberant field.

For an omni-directional point source with sound power output Ws, sound speed in the medium c, the direct-field energy density E_{dir} is given by (Kuttruff, 2009)

$$E_{dir} = Ws/4\pi cr^2 \tag{2}$$

The energy density of the diffuse field with an equivalent (or Sabine) absorption area A is given by

$$E_{diff} = 4Ws/cA \tag{3}$$

The total energy density at a point in the enclosure is the sum of contributions from both the direct field and the diffuse field

$$E_{tot} = E_{dir} + E_{diff} = Ws(1/4\pi cr^2 + 4/cA) \tag{4}$$

The relationship between the mean squared sound pressure $< p^2 >$ and energy density E is given by $E = < p^2 >/\rho c^2$, where ρ is the density of the acoustic medium. Therefore, the total mean squared sound pressure at a distance *r* from the source is given by

$$< p^2 >_{tot} = < p^2 >_{dir} + < p^2 >_{diff} = Ws\,\rho c(1/4\pi r^2 + 4/A) \tag{5}$$

This means the measured sound pressure level is indicative of the energy density, and from Eq. (4), that it can be directly related to contributions from both the direct and diffuse fields. A distance $r = R_c$ from the source is defined as the critical radius or reverberation radius such that the contributions from the direct and diffuse fields are equal. It is obtained by equating the two terms on the right-hand side of Eq. (5) as

$$R_c = [A/16\pi]^{1/2} \tag{6}$$

The critical radius R_c can also be expressed in terms of the reverberation time using the Sabine equation $T_{60} = 55.26V/cA$ (Kuttruff, 2009)

$$R_c = [55.26V/c16\pi T_{60}]^{1/2} \tag{7}$$

From Eq. (7) we observe that (i) the size of critical radius is independent of the strength of the sound source and (ii) the magnitude of the critical radius depends on how weak or strong the sound absorption at the boundary is, or equivalently, how long or short the reverberation time of the enclosure is. A stronger diffuse field means a smaller dominant region of the direct field and vice versa.

3 CALCULATION OF SOURCE LEVEL FROM REVERBERANT FIELD MEASUREMENTS

As shown in section 2.1 the total sound pressure at any point inside the enclosure is a combination of sound pressures from both the direct and reverberant fields:

$$P_{TOT} = P_D(r) + P_R(r) \tag{8}$$

At the critical radius R_c from the source there is an equal contribution from both direct & reverberant fields:

$$P_D(R_c) = P_R(R_c) \tag{9}$$

In the direct field of a point source, we have the relationship between SPL at two different locations r_1, r_2:

$$\mathrm{L_{p1}}(r_1) - \mathrm{L_{P2}}(r_2) = 20\log 10(r_2/r_1) \tag{10}$$

If we let $\mathrm{L_{p1}}$ be the source level at 1m ($r_{1\,=}$ 1m) and $\mathrm{L_{P2}}$ be the sound pressure level at the critical radius ($r_2 = R_c$) then Eq. (10) can be expressed as:

$$\mathrm{L_{PD}}(1\mathrm{m}) - \mathrm{L_{PD}}(R_c) = 20\log 10(R_c/1) \tag{11}$$

Rearranging Eq. (11) and substituting $\mathrm{L_{PD}}(R_c)$ with $\mathrm{L_{PR}}(R_c)$ using Eq. (9) gives

$$\mathrm{L_{PD}}(1\mathrm{m}) = 20\log 10(R_c) + \mathrm{L_{PR}}(R_c) \tag{12}$$

For an ideal diffuse field the stationary reverberant sound pressure level should be the same everywhere inside the enclosure. Therefore, the last term in Eq. (12) will be independent of location, leading to the following expression

$$\mathrm{L_{PD}}(1\mathrm{m}) = 20\log 10(R_c) + \mathrm{L_{PR}}(\mathrm{anywhere}) \tag{13}$$

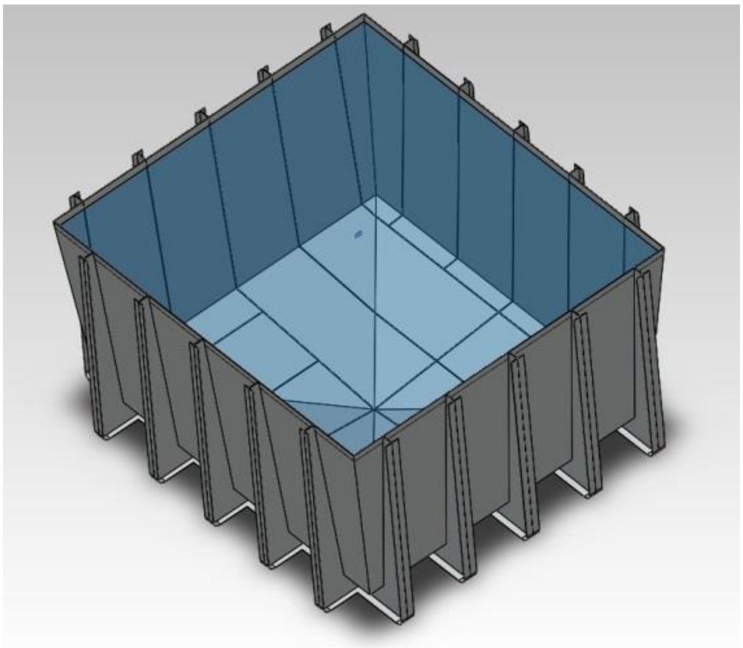
For a given critical radius, one can obtain a direct-field sound pressure level at 1 meter away from the source by measuring the reverberant sound pressure levels anywhere inside the enclosure. As discussed above, the critical radius can be calculated from the known reverberation time of the enclosure. Note that when a source level is calculated based on the reverberant field, the directivity of the source will be lost and cannot be retrieved. Essentially Eq. (13) allows us to calculate the source level of an equivalent omnidirectional point source that will generate the same reverberant sound field as the source under consideration.

Eq. (13) is obtained with the assumption of a perfectly diffuse field where the $\mathrm{L_{PR}}$ is uniform. In practice, when the perfectly diffuse condition is approximated by a highly reverberant sound field above the critical frequency, a small variation of $\mathrm{L_{PR}}$ in the reverberant space will be observed. In order to minimise the location dependence, the averaged SPL using SPLs measured at different locations is used.

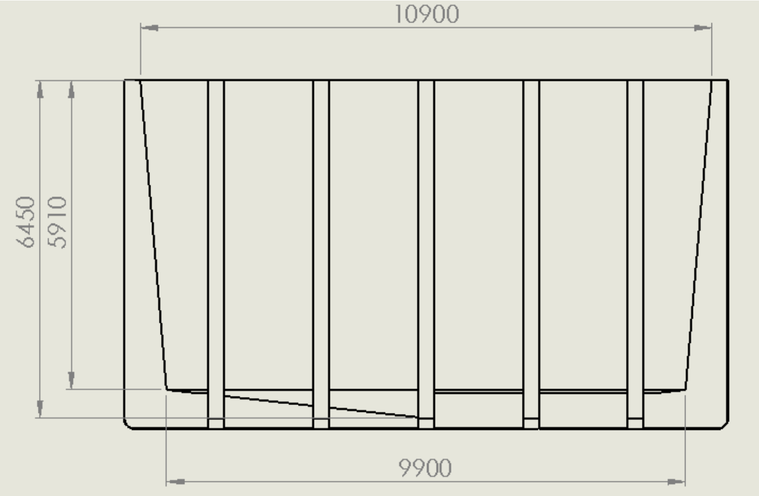
4 VALIDATION RESULTS AND DISCUSSION

4.1 The Maritime Division water tank

The Maritime Division water tank at DST Group considered here (MD tank) is a mild steel construction with drawing and picture as shown below. It has an inverted pyramidal shape on the bottom and slightly sloped sides with top dimensions of 11m x 10m, bottom dimensions of 10m x 9m and a depth of 6m (Figure 2(b)). This shape is intended to partly avoid the standing waves generated directly across tank dimensions with perfectly parallel and opposite walls of the water tank. Because of the high impedance of the tank walls (water – steel – air) and the water surface at the top (water-air) it is considered as a highly reverberant acoustic enclosure with water as the acoustic medium.



(a) Construction drawing



(b) Dimensions

(c) Picture of the water tank's top view

Figure 2: the MD water tank.

The reverberation characteristics of the MD water tank have been previously determined and the following information is readily available for our discussion:

1. The reverberation time of the water tank in one-third octave bands, up to 16kHz centre frequency;
2. The critical radius corresponding to each one-third band is calculated from Eq.(7). These values are used in Eq.(13) as correction factors to the measured reverberant SPL for obtaining the source level;
3. The tank cut-off frequency is computed for each one-third octave band. The highest cut-off frequency of all bands is found to be 830 Hz and it is regarded as the tank lower frequency limit. For a wideband assessment, the cut-off frequency was also found to be about 800 Hz.

4.2 Comparison with known source

The experimental measurement was set up for validation of equation (13). A sound source with known output level was used to compare with the source level calculated from the sound pressure levels measured in the reverberant field of the water tank. Swept-sine and random white noise were used as excitation signals. The reverberant field SPLs were measured using four hydrophones randomly placed inside the water tank. The average of these hydrophones is used as the approximation of the uniform reverberant field SPL.

The following equipment was used in the experimental setup.

- A J9 sound source which is primarily designed as a sound projector with an omnidirectional characteristic to 5 kHz. The J9 was placed at the volume centre of the water tank.
- Excitation signal: swept sine and random white noise were used to drive the J9 source.
- Source output levels: Four one-third octave bands were used (2 kHz, 2.5 kHz, 3.15 kHz and 4 kHz) for comparison with calculated results. These bands are selected to be within the lower frequency limit of the water tank as well as it is within the omnidirectional range of the J9 source.
- Hydrophones: Reson TC4013 (x4) were used as underwater sound pressure sensor.
- Hydrophones were calibrated using the B&K Hydrophone Calibrator (type 4229).

As noted the MD water tank cut-off (Schroeder) frequency is about 830Hz, which corresponds to a wavelength of $\lambda \approx 1.8$m and a quarter wavelength of $\lambda/4 \approx 0.45$m. Accordingly, from the discussion in section 2, the hydrophones were placed at least 1m away from any walls, edges or corners of the water tank to avoid any near field effects.

To ensure that measurements were conducted in the dominant reverberant sound field of the water tank, the hydrophones were placed at a distance (~3m – 5m) much larger than the maximum critical radius which is 0.75m based on the reverberation time of the MD water tank. Applying the 6dB rule to the measurement locations, the direct-field SPL should be 12 to 18 dB weaker than the SPL of the reverberant field to be measured. This distance is also outside of the near field of the source itself.

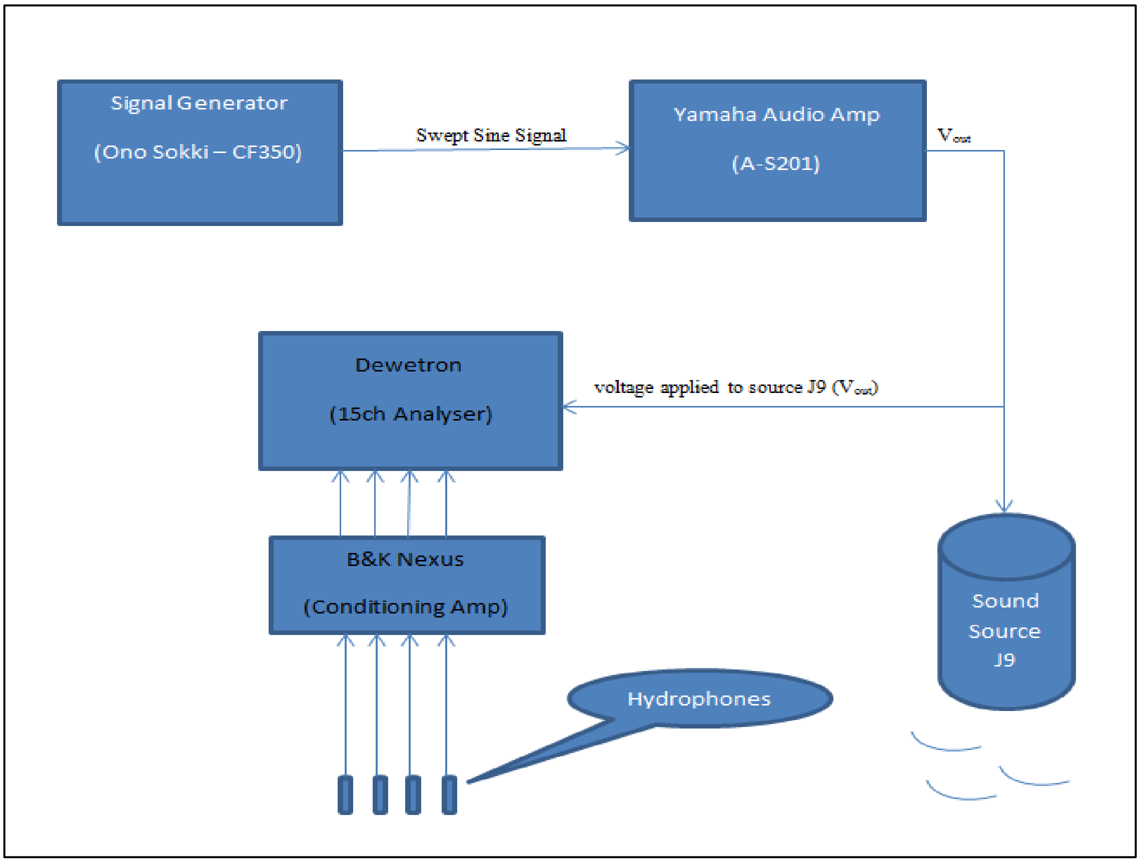


Figure 3: Equipment setup in MD water tank for experimental validation.

Measurements were performed and results obtained were used to calculate the source level using equation (13). They were then compared with the source output level at four one-third octave bands (2, 2.5, 3.5 and 4 kHz). Eight sets of calculated source levels vs one-third octave frequency were obtained, each with different parameters such as different source output levels, excitation signals and hydrophone positions. The differences between the calculated source levels and the known source levels for each measurement set was calculated as the measure of error in this technique. Figure 4 show plots of the reverberant SPL (after averaging of 4 hydrophones), the calculated source level and the known source output level for a typical set of measurement data. Table 1 shows the error mean and standard deviation for each one-third octave band as the result of assessment from all eight sets of measurement data. In this table we observe that the error between the calculated and known source output level is around 0.5 to 1.5dB which is very good agreement between the reverberant-field based calculation and the known source output levels.

The error or difference in level between the calculated and the source output level can be attributed to a combination of the following:

1. The assumed uniform sound pressure level of the reverberant field is approximated by the average of four hydrophones;

2. The accuracy of the calculated source level is also dependant on the accuracy of the reverberation time T60 used in equation (13);
3. As total sound pressure at a point is a combination of both direct-field and reverberant-field sound pressures, the inclusion of a residual direct-field sound pressure at points of measurement is unavoidable, even though the sensors were located well inside the dominant reverberant field;
4. Uncertainty in measurement equipment including the known source J9.

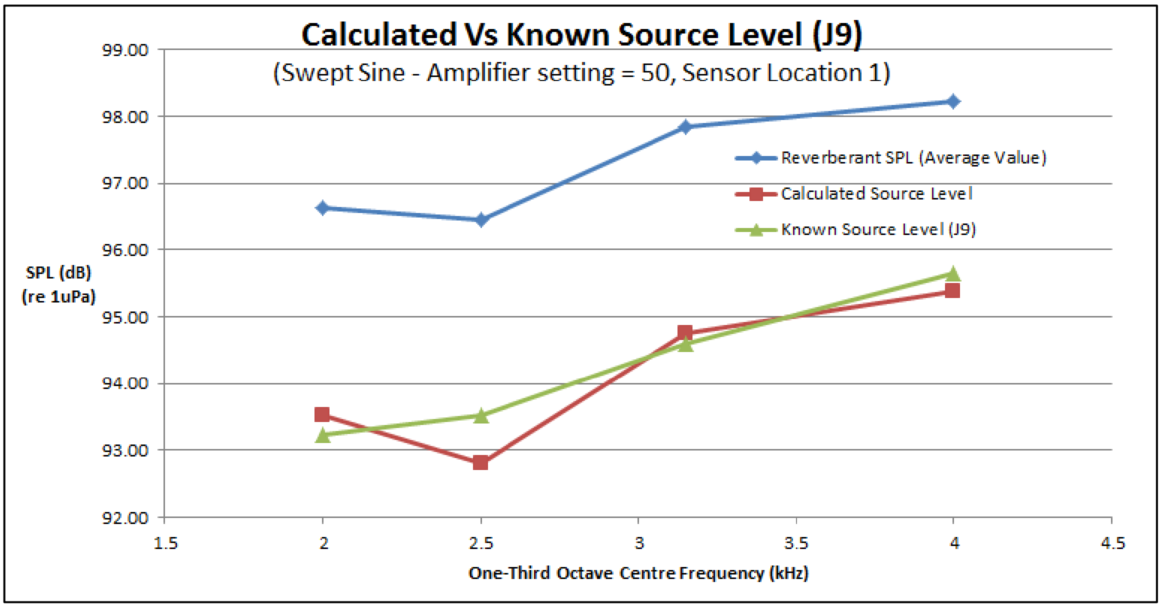


Figure 4: Plot of calculated vs known source levels for a typical measurement set.

Table 1: Analysis of error between calculated and known source levels.

	2kHz	2.5kHz	3.15kHz	4kHz
	(dB)	(dB)	(dB)	(dB)
Mean Difference	0.4	1.5	0.6	0.6
Standard Deviation	0.5	0.4	0.4	0.3

5 CONCLUSIONS

By employing the energy balance between the direct field and the reverberant field in a highly reflective enclosure, the critical radius can be obtained from the known reverberation time and then used to calculate the source level from SPL measurements made in the reverberant field. As shown in our experimental validation, the source level obtained in this method has a good level of accuracy. This method is also much easier to perform in comparison to the direct method which requires a direct or free field condition, particularly if the acoustic medium is water. Moreover, as the reverberation time is indeed a function of frequency, the T60 in one-third octave bands is used for the calculation of the critical radius and provides more detail as well as improving the accuracy of the evaluation of the source level under consideration. It has been demonstrated that the method presented in this paper allows one to obtain an equivalent free-field source level in water tanks with satisfactory accuracy.

REFERENCES

Beranek, L.L., Ver I.L., (2006*).* Noise and Vibration Control Engineering. 2ed., John Wiley & Sons, Inc

Bies, D. and Hansen, C.H. (2003). Engineering Noise Control – Theory and Practice. 3rd ed. Spon Press.

Cochard, N., Lacoume, J.L., Arzelies, P. and Gabillet, Y., (2000). Underwater Acoustics Noise Measurement in Test Tanks. *IEEE Journal of Oceanic Engineering*, Vol. 25, No. 4, pp. 516-522.

Fahy, F.(2001). Foundations of Engineering Acoustics. Academic Press.

Hopkins, Carl (2007). Sound Insulation. Butter-Heinemann Publications.

Jones, A.D. and Hoefs, S.A. (1996). Acoustical properties of the MOD Salisbury test tank and techniques for measurements. *DSTO-RR-0068*, Melbourne, Vic., Defence Science and Technology Organisation (Australia)

Kinsler, L. E., Frey, A.R., Coppens A.B., and Sanders, J.V., (2000). Fundamentals of Acoustics. 4th ed. John Wiley & Sons.

Kuttruff H. (2009), Room acoustics. 5th ed. Spon Press.

Milošević, M. A., Milošević, N.D., and Milošević, M.S., (1997). Criterion of Diffuseness of Sound Field in Rectangular Room. Faculty of Electronic Engineering, *Working and Living Environmental Protection* Vol. 1, No 2, pp. 33-44.

Schroeder, M. R., (1965), New method of measuring reverberation time, *Journal of the Acoustical Society of America*, Vol. 38, pp. 329–361.

Rossing T. D. (2007), Handbook of Acoustics. Springer.