1. INTRODUCTION

The study of underwater vessel noise over the past sixty years has predominantly focused upon the increase in ambient noise caused by the propulsion mechanisms of large, commercial vessels. Studies have identified that the continuous rise of ambient noise levels in open waters is linked to the increase in size and strength of anthropogenic sound sources. Few studies have investigated the noise contribution of smaller vessels or ambient noise levels present in coastal and in-shore waters. This study aimed to identify the level of noise common to non-commercial harbors by studying the noise emissions and behavior of propagation of a diesel generator on board a 70.10m long sailing vessel.

The characteristics of each harbor studied (i.e. water depth, water temperature, structural materials, ground sediment, etc.) were identified to ultimately produce correlations between harbor attributes and apparent sound level. Through the analysis of the sound emanating from various positions of the vessel's hull, the complexity of the acoustic field surrounding the vessel could be portrayed. Near-field sound propagation is highly prone to change, and it was the aim of this study to identify the causes of this variability.

2. BACKGROUND

The evaluation of the underwater noise levels in shipping harbors has been a topic much overlooked in the study of underwater acoustics. Over the past sixty years an interest in the increasing noise levels of the aquatic environment has developed, becoming a descriptor of importance in the European Union's 'Marine Strategy Framework Directive', and a growing point of discussion for the International Marine Organization (IMO) (Abrahamsen, 2014). This analysis of sound level change has been primarily based in off-shore waters and focused on large, commercial shipping vessels, exceeding 100m (OSPAR Commission, 2009). Whilst some work has been carried out providing an insight into the detrimental effects caused by 'pleasure crafts' on in-shore waters (Codarin *et al.*, 2009), few correlations are made to the tendency of level-alteration-dependency upon the exact location (and it's attributes) of the vessel studied. The fundamentals of underwater vessel noise, and an explanation of the potential noise sources, are outlined by Abrahamsen (2014).

2.1 The Study of Small Vessels' Noise

More recent research has begun to delineate not only the artifacts of large, commercial ships (generally classified as being >100m in length), but also the noise characteristics created by "small" (<50m) and "medium" (<100m) vessels. The growing population of such smaller vessels, particularly common in touristic, coastal locations should be noted (Codarin *et al.*, 2009), and recognition given to the presence of on-board machinery on such vessels (e.g. diesel generators, water makers, cooling/ventilation systems, etc.). The average level of noise produced by smaller vessels' method of propulsion and on-board machinery is, of course, not as high in amplitude as that of commercial shipping vessels, with a typical value of approximately 160 – 175dB (re: 1µPa) for small boats, and 165 – 180dB (re: 1µPa) for medium vessels (OSPAR Commission, 2009). However, the magnitude of such vessels and thus accumulation of noise (and hence its effect on coastal areas) should be recognized. It is suggested that such noise has "geographically-limited environmental impacts", and that it is only closed (or partially closed) areas which retrieve the detrimental effects that these vessels protrude upon the underwater environment (OSPAR Commission, 2009). However, many species retain their habitat in such coastal waters, and are thus the victims of such noise pollution.

2.2 Marine Biofouling

Though the studies which concern large-scale data collection focus predominantly upon off-shore waters, it is the noise produced in populated harbors that is of interest here. McDonald *et al.* (2014) argue and present evidence of the negative effects caused by the prolonged exposure of noise upon biofouling organisms when vessels are stationary in harbor. It is, however, not the organisms themselves that suffer (in contrast, they show “100% survival rate” (McDonald *et al.*, 2014)). It is the heightened rate of settlement and reproduction of the biofouling species upon vessel hulls, when stationary in a harbor, which appears to be a growing problem. Once settled, the micro-organisms present the subsequent risk of the “spread of invasive species” across international waters. This cross-contamination of species can lead to significant issues, including the deprivation of less resilient species whilst the newly settled dominant species may thrive in the new habitat.

The incremented settlement cues of biofouling organisms is suggested to be encouraged by the constant operation of machinery on board a vessel in port (Stanley *et al.*, 2014). Whilst vessel owners typically spend a significant amount of money on anti-fouling agents annually, the great expenditure could, seemingly, be avoided through alternative methods.

2.3 Detrimental Effects upon Marine Inhabitants

In addition to the detrimental effects of increased harbor noise upon a vessel’s inclination to hull biofouling, the accumulated noise in enclosed harbors is also thought to be harmful to marine habitants (i.e. fish and mammals). Codarin *et al.* (2009) depict the potential risk created by the increased vessel population (and thus noise produced), affecting the “acoustic communication in fishes”, identifying the heightened use of small (<10m) boats in coastal waters as the cause of several issues. Further studies highlight additional consequences induced by boat noise, such as the trigger of “endocrinological stress” and fishs’ reduced hearing ability (see Scholik *et al.*, 2002, Wysocki *et al.*, 2006, Sara *et al.*, 2007).

2.4 Recognition of Underwater Noise Pollution

The proceedings of Descriptor 11, from the European Union Commission Decision (2010) brought forward the move towards a “good environmental status (GES)” (Van der Graaf *et al.*, 2012) due to the increase of anthropogenic noise and its subsequent effect on the underwater environment. From this Commission Decision, it is now obligatory to hold a license to carry out activities of high energy release, which provides the opportunity to monitor and coordinate the times and duration of such impulsive sounds. Furthermore, the IMO suggests numerous ways in which noise reduction can be obtained, aiming the solutions at specific elements of a vessel’s noise sources (Marine Environment Protection Committee, 2009). The implementation of noise reduction techniques has furthermore been labelled a “high priority item” by the IMO.

2.5 Understanding Vessel Noise

To fully understand the ways in which the underwater environment is being affected by vessel noise, it is important to delineate the propagation characteristics of the noise produced. An on-board generator emits airborne and structure-borne sound. The pressure variations in water can be measured outside of the vessel's hull through the use of a hydrophone. Previous studies have simply assumed typical geometric spreading of the sound, based upon idealized propagation models (Codarin *et al.*, 2009, Abrahamsen, 2014, McDonald *et al.*, 2014). However, the precise location of the on-board sound source (i.e. a generator) is of significance when studying its propagation characteristics, particularly when located in a larger vessel (>50m).

The propagation pattern of sound changes, dependent upon the distance to the source, though not by a standard pattern of intensity declevity. In the "Fresnel field" (close to a sound source), the acoustic impedance varies greatly, giving an irregular pattern of "intensity variations" which contrasts to the assumed immediate spherical spreading (-6dB per doubling of distance) suggested in generic propagation models, as is only attributed in the subsequent "Frauenhofer field" (at a far greater range from the source) (Wahlberg and Westerberg, 2005). Further attributing factors to the way in which sound propagates includes the water depth, ground surface angles, nearby reflective material, "seabed propagation", and "frequency dependent absorption" of the water and surrounding barriers. Such factors, and "additional environmental variables", are however rarely incorporated in the predictions of propagation patterns (Tsoflias *et al.*, 2012, Pine *et al.*, 2014).

2.6 Shallow Water Sound Propagation

Shallow water propagation (where the receiver is further from the source than the ground surface) is studied differently to sound in deep water (Pine *et al*., 2014). Cylindrical spreading is assumed in shallow waters, in which an intensity drop is calculated by $10 \log r$, but is of course also affected by nearby environmental factors. When studying low frequencies, it must be noted that certain frequencies (dependent upon water depth) cannot propagate in shallow water. Wavelengths greater than four times the water depth are unable to propagate as acoustic waveforms, though "sound energy may still appear in terms of local pressure" (Wahlberg and Westerberg, 2005).

2.7 Conclusion

The expanse of research available at present gives an insight to the consequences of noise pollution in harbors, and the past changes in anthropogenic noise in the underwater environment. Few correlations have however yet been drawn between the precise location of the vessel and the way in which sound level and propagation pattern alters, though it is recognized that such environmental attributes should be included in noise analysis.

3. METHODOLOGY

3.1 Underwater Sound Recordings

Underwater recordings were made whilst aboard a 70.10m (LOA) steel-hulled traditional sailing vessel (Figure 3.1). During the recordings one on-board diesel generator, Perkins 4.212

Diesel Engine (Perkins Engines Limited, 1993), was in operation, whilst the main engine and other motorized machinery was inactive. The generator was fixed to a steel frame with minimal acoustic dampening material to isolate vibration. The frame, also only minimally isolated (through aged rubber pads), was bolted to the steel hull. Throughout each recording the vessel was stationary; moored to either a harbor wall, another vessel or at anchor.

Figure 3.1 & 3.2 Tall Ship 'Gulden Leeuw', the vessel under test. Perkins diesel generator, located in the vessel's engine room.

All recordings were made using a HTI-90-U Series hydrophone (Scorpion Oceanics Ltd., 2015) and a handheld H4n Zoom Handy Recorder (Zoom North America, 2015), whilst monitored through headphones. Each recording was stored on the recorder in WAV file format, with a sampling rate of 44.1kHz and bit depth of 16-bit.

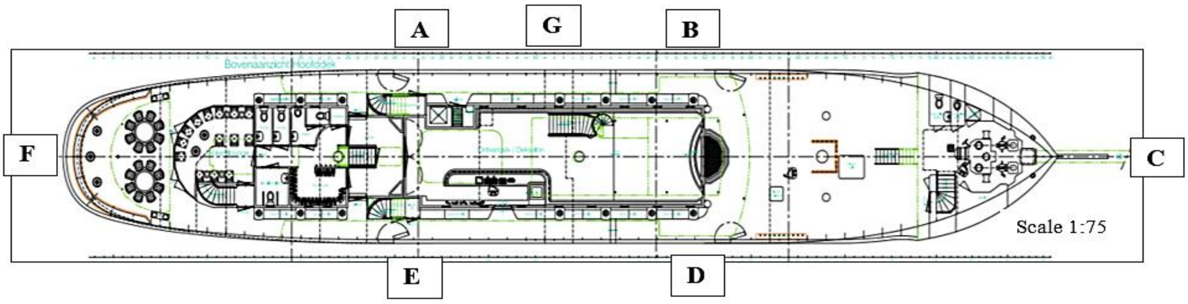


Figure 3.3 Measurement Positions A – G around the vessel, scaled 1:75 (P&T Charters, 2009).

Recordings were taken at seven allocated positions around the vessel (Figure 3.3). This procedure was repeated in eight harbors, in which the vessel remained stationary for several days, around Northern Europe (in Norway, Denmark, Germany, and the Netherlands).

The depth at which recordings were made were based upon the position of the generator (approximately 1.0m below the water surface), and the lowest point of the vessel's hull (excluding the keel, at approximately 3.0m below the water surface). The ambient recordings were taken at 2.0m as a median between the two prior measurement depths, and solely at Position G. In each measurement position three consecutive 1 minute recordings were made, providing a range of material from which the least impaired recording could be selected (though it was often hard to isolate the sound of the generator). The measurement of ambient noise and the general soundscape of each harbor was carried out through one continuous 5 minute recording.

Sets of recordings per location were made on the same day, in a sequential fashion, with breaks in recording only taken if disturbance was caused (i.e. from a passing vessel, noise on deck or heavy rainfall, etc.). All recordings were made between 06:00 and 10:00 (GMT+01.00).

3.2 Supplementary Data Collection

Supplementary data was collected from navigational charts and on-board equipment; Kestral 1000 Wind Meter (Nielsen-Kellerman Co., 2016), Furuno FCV620 echo sounder, Furuno SC-50 Global Positioning System (GPS) (Furuno USA, 2016), Automatic Identification System (AIS), engine cooling-water inlet (as a means of measuring sea water temperature), and 'Reeds Nautical Almanac 2015' (Towler & Fishwick, 2015)).

3.3 Data Analysis

All recordings were calibrated in Matlab R2015b (The MathWorks, Inc., 2016) to obtain the true sound intensity levels. This process accounted for the sensitivity of both the hydrophone and recorder, and the gain level at which recordings were taken. The calibrated sound files were later converted into an appropriate unit (dB re $1\mu Pa^2/Hz$), from which successive analysis could be carried out.

The recordings least impaired by alternative sound sources were noted and used for the analysis. Files were visualized in Matlab to identify typical frequency content and level through the use of a Fast Fourier Transform. Due to the hydrophone sensitivity all analyses were limited to a frequency range of 50Hz to 15kHz, as lower frequency content was assumed to be self-noise of the recording devices.

4. RESULTS & DISCUSSION

Studying the vessel's near field ('Fresnel Zone') accounts for the variance found in the amplitude of noise around the vessel. The intensity of interference (both constructive and destructive) in this zone proves that a geometric spreading model cannot be assumed for all measurement positions.

4.1 Water Surface Reflections

As the generator lies at approximately 1m below the water surface, it is likely that structure-borne sound is stronger at this depth in Positions A, B, D and E (all within 15m of the sound source and directly next to the hull). Positions C and F, however, are areas in which a smaller mass of the vessel's hull is submerged underwater (see Figure 4.11), and lay more than 20m from the sound source.

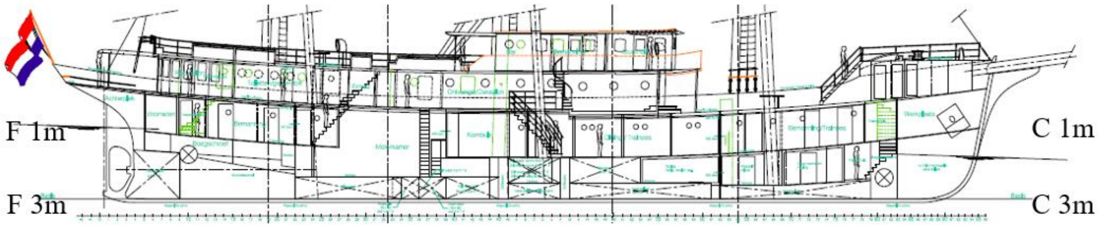
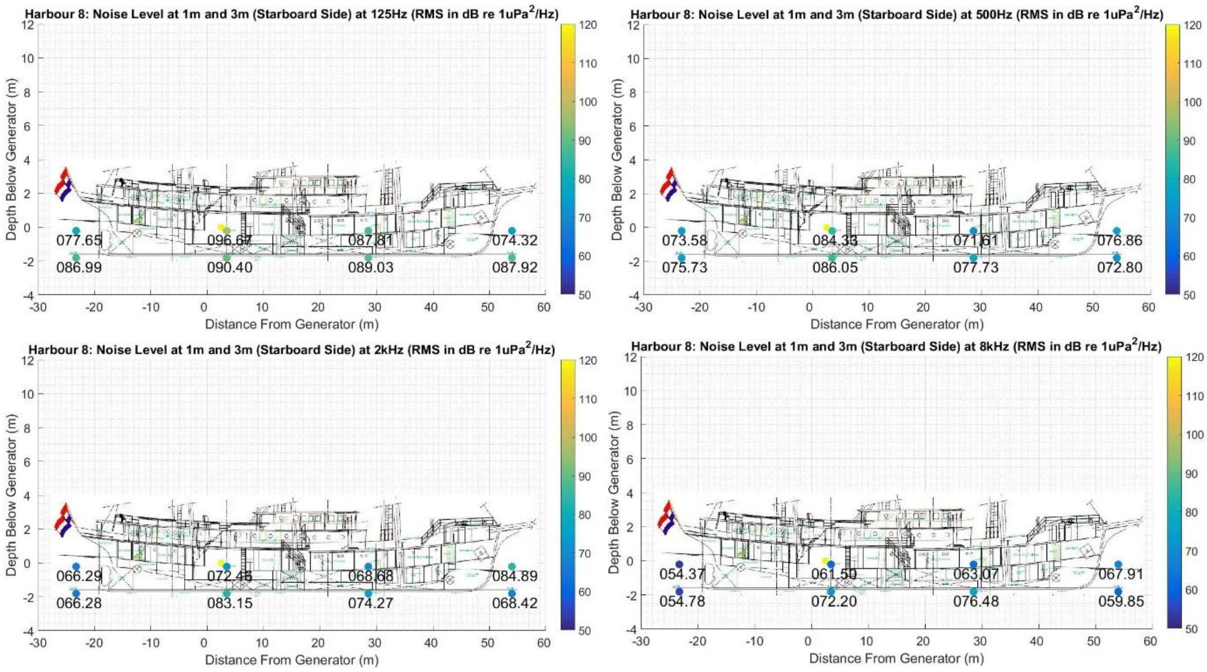


Figure 4.1 Vessel side elevation (not to scale), (P&T Charters, 2009).

It has been seen that the low frequency (structure-borne) sound is received at a lower level at C and F (than A, B, D and E) at 1m, due to the additional distance travelled by the sound to the transducer. However, as frequency is incremented, the pattern between 1m and 3m measurements changes since the sound present is no longer dominated by that emitted from the vessel's steel structure (see Figures 4.2 to 4.5).



Figures 4.2, 4.3, 4.4 & 4.5 Variation in noise level between 1m and 3m recordings, on the vessel's Starboard side through Positions F, E, D, and C (left to right), in Harbor 8.

The distance from the sound source to Positions C and F (32.93m and 23.45m, respectively) suggests that the signal strength consists of little structural sound and of much reflected energy, particularly common at high frequencies (The International Association of Oil & Gas Producers, 2008). The pattern of constructive and destructive interference caused by the Lloyd Mirror Effect (see Figure 4.6) shows that high frequency waveforms are likely to have summed, producing higher levels, whilst low frequencies have been attenuated (due to destructive interference) at this distance from the water's surface (1m).

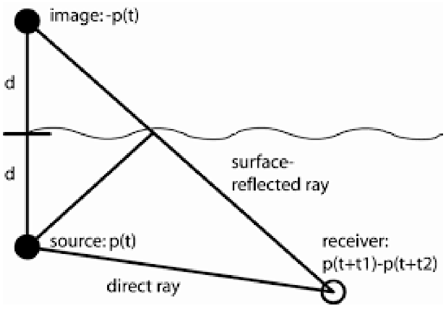


Figure 4.6 Lloyd Mirror Effect (JASCO Applied Sciences, 2011).

4.2 Implications of Harbor Structure

4.2.1 Comb Filtering

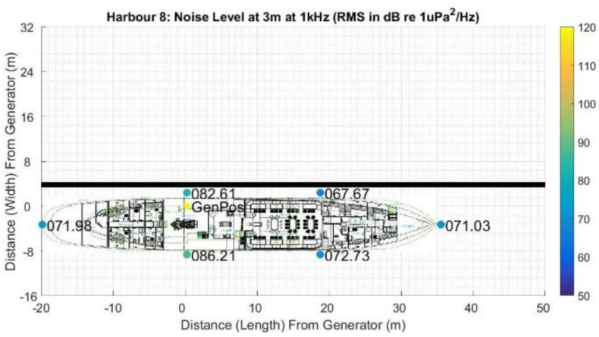
The effect of comb filtering (as that of the Lloyd Mirror Effect) upon the results is apparent throughout, and can be seen in the varying level between recording positions. The secondary arriving wavefront, delayed according to the distance that the sound has travelled, implements successive regions of peaks and nulls. This pattern is however hard to predict, where the length of the sound's travel path must be known to accurately calculate the frequencies at which intensity boosts or attenuations will be seen.

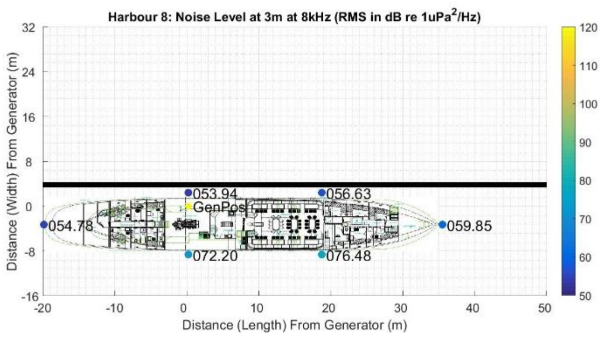
$$first\ peak = f_0 = \frac{1}{(2\times t)} \qquad first\ notch = \ f_n = \frac{f_0}{2}$$

$$\text{Where } t = time\ delay = \frac{distance\ travelled\ (m)}{speed\ of\ sound\ (m/s)}$$

The harbor walls to which the vessel was moored, typically acting as reflective barriers to the sound, cause comb filtering to impair and present unexpected rises and falls of amplitude in the results. Therefore, although Position A was predicted to maintain the highest level throughout, Position E often presented greater signal strength, thus highlighting that constructive addition has taken place at E, deconstructive addition has taken place at A, or a combination of the two.

Harbor 8 (a Port side mooring) presents this effect, in which Positions E and D dominate in level throughout the high frequencies in the 3m measurements (see Figures 4.7 & 4.8). Wooden pillars, acting as diffusion for the sound, were fixed to the harbor wall, but did not reach 3m below the water surface. The comb filtering effect is therefore not pronounced in the 1m measurements. Furthermore, the effect is only eminent in the higher frequency octave bands, in which the separation of notches is far smaller in relation to the bandwidth of the octave band.





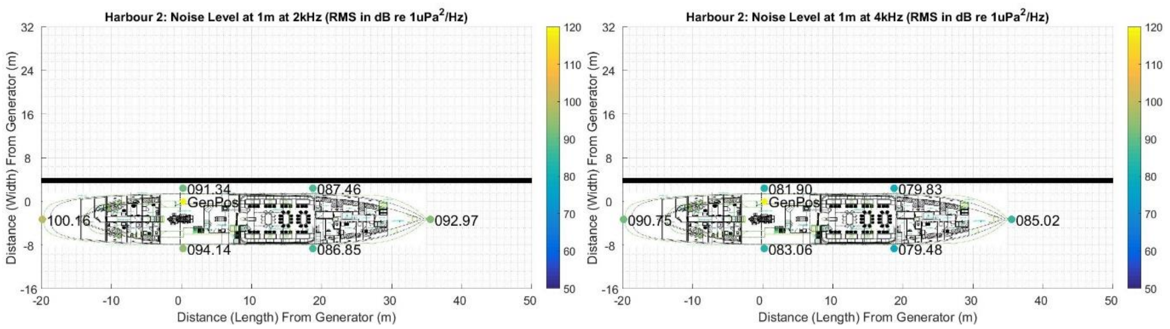
Figures 4.7 & 4.8 Comb filtering in Harbor 8, where destructive interference is seen in Positions A and B.

The complexity of the acoustic field surrounding the stationary vessel is difficult to predict, and ever-changing in accordance to the way in which the vessel is moored (i.e. on which side there is a barrier, the distance from the sound source to barrier, and other surrounding reflective obstructions), as is evident throughout the results. These factors should however be recognized and noted during the prediction of propagation and apparent sound level.

4.2.3 Barrier Absorption

The construction of the walls in the harbors studied consisted predominantly of a concrete structure, often with alternative materials affixed. The use of materials such as wood paneling and rubber tyres was expected to absorb rather than reflect the sound (as the solid concrete structure would have). This effect became apparent at high frequencies, which require porous (‘resistive’) materials to transfer the sound’s energy to friction, in turn absorbing and attenuating the sound (Kuczmarski and Johnston, 2011).

Though comb filtering can be identified in several of the measurements, uncorrelated trends (i.e. attenuation through a wide band of frequencies, rather than at set intervals) could be explained by absorption from a nearby barrier. The presence of softened wood, algae, sea plants and rubber tyres in certain harbors caused drops in the level at positions close to a barrier.



Figures 4.9 & 4.10 Sound absorption on the vessel’s Port side in Harbor 2, where wooden and rubber materials were present.

It can be discerned that the structural material of a nearby barrier accounts for the absorption of alternate frequency ranges. It can be predicted that most harbor barriers will have some effect of attenuation on the sound level, though it is the components that make up that structure that determine the frequency effected and to which extent. Whilst porous materials (such as softened wood and rubber tyres) absorb high frequency content, it is also the placement of these materials that governs their effect.

4.3 Nearby Vessels

4.3.1 Vessel Hull Reflections

The presence of a neighboring vessel has shown to reinforce the sound observed at the recording positions nearest to that vessel. The measurements in Harbor 4 were made whilst a vessel (of similar shape and size to that studied) was moored onto the Port side, adjacent to the generator, of the vessel under test (see Figure 4.11).

Figure 4.11 Mooring in Harbor 4.

The neighboring vessel in Harbor 4 had a mere length of 24m, and thus only covered measurement Position A. The impact of the vessel's presence is seen in the change of amplitude from Positions A to B. Whilst Position A is reinforced throughout the frequency spectrum (see Table 4.1), the level at B is low throughout.

Harbour 4	Starboard Side											
	Recording Position (and Depth (m))											
Octave Band (Hz)	**A1**	**A3**	**B1**	**B3**	**C1**	**C3**	**D1**	**D3**	**E1**	**E3**	**F1**	**F3**
125	105.68	100.20	83.56	81.83	70.79	78.65	85.35	78.82	89.97	86.92	68.00	76.19
250	97.93	88.09	70.21	70.89	59.68	66.82	72.81	71.85	77.52	80.28	67.51	73.14
500	89.66	81.85	64.20	65.26	58.52	62.00	67.77	65.75	69.72	71.94	66.15	70.51
1000	85.21	81.88	64.14	64.72	58.82	62.31	73.34	68.48	66.76	66.03	66.35	67.44
2000	79.67	74.50	56.58	56.89	53.54	58.83	68.06	62.66	63.47	61.59	61.54	63.29
4000	66.90	61.28	49.76	51.08	47.97	55.08	61.25	57.51	54.06	52.27	56.01	59.42
8000	54.06	49.24	45.13	44.71	43.75	52.80	56.48	52.08	48.41	47.90	50.52	57.13

Table 4.1 RMS levels (dB re 1µPa^2/Hz) in octave bands, measured in Harbor 4.

4.3.2 Secondary Noise Sources

The impact of a secondary noise source (i.e. the engine or generator of another, nearby vessel) caused evident peaks in level at the measurement positions closest to the vessel within proximity. Constructive addition of the uncorrelated sound sources was observed in several measurements, as the noise of the secondary source alone would not have reached the apparent levels within the given separation distance of the vessels (and it is furthermore only minimally audible in the sound recordings).

Harbour 2	Port Side											
	Recording Position (and Depth (m))											
Octave Band (Hz)	**A1**	**A3**	**B1**	**B3**	**C1**	**C3**	**D1**	**D3**	**E1**	**E3**	**F1**	**F3**
125	114.71	116.08	115.90	113.25	101.67	106.88	113.08	112.27	117.54	117.48	111.58	112.42
250	109.65	109.12	107.55	105.12	97.13	99.69	105.42	105.34	110.70	110.35	104.80	105.85
500	101.33	101.68	97.39	97.66	93.55	93.80	96.22	96.73	101.91	100.10	99.05	99.68
1000	96.14	98.12	91.60	102.05	97.07	97.64	93.24	97.26	100.14	101.71	105.31	104.95
2000	91.34	94.07	87.46	96.89	92.97	92.57	86.85	90.95	94.14	95.79	100.16	100.08
4000	81.90	85.04	79.83	87.05	85.02	84.16	79.48	82.37	83.06	85.37	90.75	90.80
8000	73.29	76.96	71.96	74.63	73.16	71.21	68.40	69.86	72.21	72.47	78.08	77.85

Table 4.2 RMS levels (dB re 1µPa^2/Hz) in octave bands, measured in Harbor 2.

It is known that the neighboring vessels in Harbor 2 (see Figure 4.12) utilize diesel generators on board. The resultant sound levels in Harbor 2 show high levels in Positions B and F, though Position E is the highest throughout the low frequency bands (see Table 4.2). It can be detected that Position A has experienced some attenuation (through sound cancellation), most likely from the vessel on the opposite side of the quay, whose generator is at a similar position along the length of the vessel (on axis to that studied). The quay structure consisted of vertical concrete pillars, supporting a flat ground structure, therefore, sound could easily travel from one side to the other.

Whilst destructive addition has taken place at Position A, constructive summing is seen in the high frequencies at Position B at 3m. Furthermore, it is the high frequency content (in particular at 1kHz) in Position F that has also been reinforced from the secondary sound source (from the vessel laying astern).

Figures 4.12 & 4.13 Mooring positions of the vessels in Harbor 2, and Harbor 5.

Similarly, Harbor 5 retains Position F as the position with highest sound level (≥500Hz), seen in Figures 4.14 and 4.15. The sound's amplitude is reinforced in this position, due to the close proximity of the secondary vessel (see Figure 4.13).

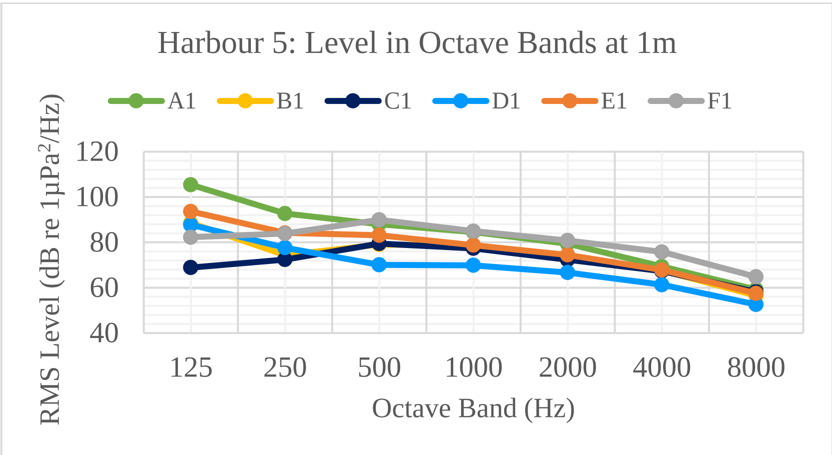


Figure 4.14 Octave band analysis of the sound level in each measurement position, in Harbor 5 at 1m.

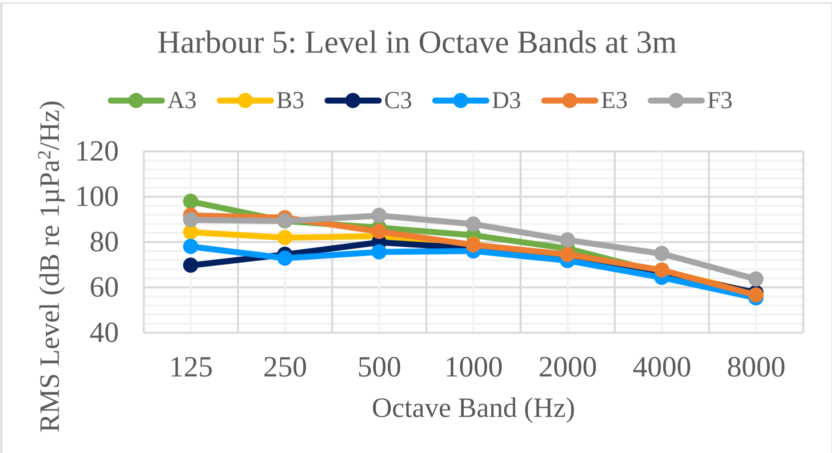


Figure 4.15 Octave band analysis of the sound level in each measurement position, in Harbor 5 at 3m.

The noise emanating from nearby vessels has increased the sound levels measured from the vessel in context, and shows the way in which multiple sources propagate at different frequencies. Though in alternative recordings (example in Figure 4.16, though not used for the analysis of the generator noise) the propulsion mechanism of a passing vessel may be heard, the brief time window in which it is audible does not cause for a significant rise in level over time. Thus it is the stationary vessels, producing a constant level of sound (typically from on-board machinery), that contribute most to the ambient noise level in a harbor. The ambient noise floor of a harbor (similar to those studied, in which vessels arrive and leave, but do not experience a greater extent of traffic) is therefore made of, and increased by, the presence of stationary vessels, using on-board machinery.

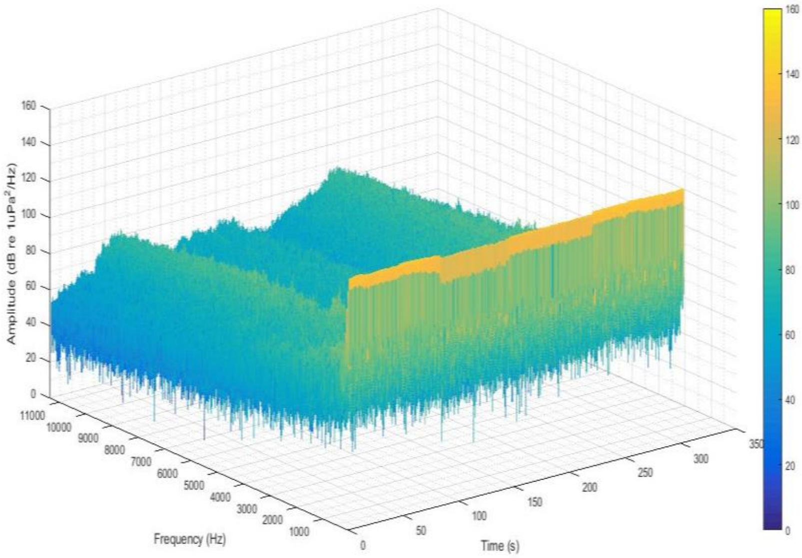


Figure 4.16 Harbor 6 (measurement at center of vessel on Port side at 2m) where three vessels passed on Port side (level in dB re 1µPa^2/Hz).

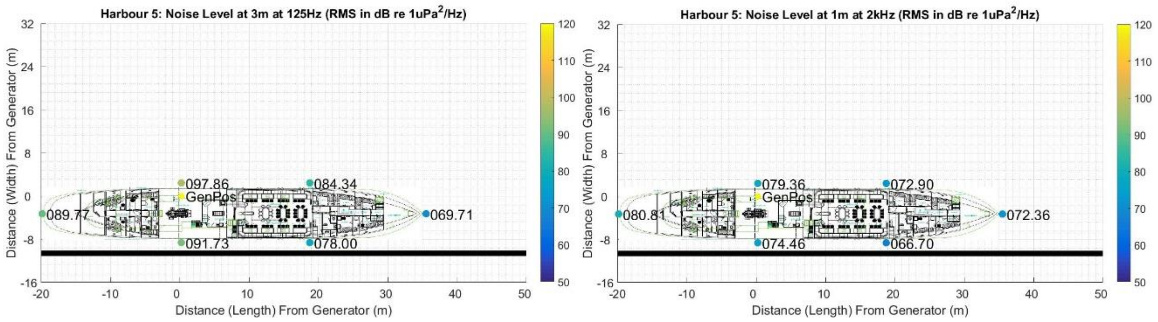
During the measurement of the soundscape in Harbor 6, a high level of noise was produced as the recording was interruption by nearby moving vessels (causing a rise in amplitude throughout the frequency spectrum). Though this is only a temporary contributor to the ambient noise floor, it should not be overlooked in harbors with a higher density of vessel traffic.

4.4 Water Depth

The correlation between water depth and average sound level for each harbor shows (to an extent) a trend of incremented level with increased depth. Though it was expected that shallow depths would produce a higher concentration of noise (reflected between ground and surface), deeper water allows sound waves of a lower frequency, as those produced by the generator studied, to propagate as acoustic waveforms (Wahlberg and Westerberg, 2005). Ground sediment is a major contributing factor to this, as absorption is likely to take place where the sediment is porous. Harbor 5 presents the shallowest water depth recorded, and consists of a sand and stone ground (which upon observation also contained much mud around the bow of the vessel). Positions B, C and D showed much attenuation in level throughout the measurements (in particular at ≤4kHz, see Table 4.3), and were in the shallowest area of the mooring. It is likely, therefore, that the low frequencies in particular could not propagate in the shallow water, and that residual noise was absorbed.

Harbour 5	Starboard Side											
	Recording Position (and Depth (m))											
Octave Band (Hz)	A1	A3	B1	B3	C1	C3	D1	D3	E1	E3	F1	F3
125	105.40	97.86	88.54	84.34	68.88	69.71	87.76	78.00	93.64	91.73	82.26	89.77
250	92.71	89.27	74.41	81.94	72.41	74.51	77.66	72.84	84.19	90.71	83.88	89.27
500	88.02	86.38	79.06	82.60	79.47	79.86	70.09	75.60	83.12	84.60	89.94	91.65
1000	84.58	83.00	78.54	78.88	77.38	77.22	69.87	76.03	78.77	78.71	84.95	87.88
2000	79.36	77.09	72.90	72.78	72.36	71.84	66.70	71.81	74.46	74.49	80.81	80.86
4000	69.34	66.48	67.57	67.24	67.36	66.33	61.30	64.35	67.79	67.59	75.77	74.87
8000	59.21	55.73	56.51	57.50	58.16	57.68	52.62	55.33	57.51	56.63	64.81	63.63

Table 4.3 RMS level (in dB re 1μPa²/Hz) in Harbor 5.



Figures 4.17 & 4.18 Sound levels measured around the vessel in Harbor 5, where Positions B, C and D are lowest in level throughout.

4.5 Atmospheric Conditions

Little correlation was found between the weather and sea state and measured level of ambient noise. The harbors in context (like many others) are protected from prevailing winds, and thus do not suffer from increased levels of wave height or strong winds. It can therefore be suggested that the ambient noise in a harbor is already lower than that of open water (when excluding the noise of vessel traffic), where a rise in wave height or wind strength can increase the level of the underwater soundscape.

5. CONCLUSION

The complexity of the sound field, produced by the noise emitted from on-board machinery, surrounding a stationary vessel proves to be affected by the localized attributes of the vessel's mooring.

Where it is desired that the soundscape of a harbor is limited in level, to reduce the detrimental effects on sea life, and biofouling, factors can be implemented which will reduce the apparent sound level. By limiting the depth of a mooring, low frequency noise cannot propagate as an acoustic waveform, and is thus reduced in audible level. Furthermore, absorptive materials of both harbor structures and ground sediment can also decrease the observed level and spreading distance of noise.

A method of sound attenuation through dampening is also evident to aid the decrease in noise level. Had the generator in context been appropriately isolated from the vessel's steel hull, structural-borne energy would have been less prominent, and thus, noise levels emitted from the vessel would have been lower.

Though comb filtering and surface reflections cannot simply be overcome, they should be noted when predicting the propagation patterns of vessel noise (from stationary vessels). Moreover, when vessels act as multiple (uncorrelated) sound sources, their noise typically sums, further altering the way in which the sound spreads and the apparent level (according to the distance between the sources). Thus, consequently, all localized conditions should be noted to correctly predict a sound's behavior of propagation.

To conclude, it has been identified that the noise of a stationary vessel's generator in confined waters is influenced by the number of nearby boundaries, and their materials, in close surroundings. Furthermore, as change in sea state and wave height is unlikely in such protected areas, it is the multitude of vessels operating on-board machinery that heightens the ambient noise floor of a harbor. This can ultimately lead to the increase of biofouling, and a detrimental change to the underwater environment.

The way in which the sound is seen to spread from a vessel of 'medium' size portrays the falsehood of assuming a geometric propagation model. The noise level around the vessel is dependent on numerous factors, and can therefore not be generalized for every harbor.

6. RECOMMENDATIONS

The work carried out in this project has focused solely on the near field propagation of a lone sound source. To further identify the trends in which sound propagates from a stationary vessel, it would be useful to measure the noise from various positions within the harbor. This process would give an indication to the strength of the noise signal at a distance, and identify if it is problematic to aquatic lifeforms, and if the noise continues to emanate in a similar fashion. Subsequent measurements at alternative depths below the water surface would also aid in classifying the behavior of near field propagation.

Where excessive levels of noise are seen to be produced by the on-board generator, a comparison may be drawn to the use of shore-power. This would allow the generator to be inactive when moored, and may thus decrease the ambient noise level in a harbor (in particular if it were a trend followed by more vessels). To find the efficiency of this alternative, research into the cost and fuel consumption of both diesel generators and land-based power would be required.

7. REFERENCES

Abrahamsen, K. (**2014**). The ship as an underwater noise source. In *Proceedings of Meetings on Acoustics* (Vol. 17, No. 1, p. 070058). Acoustical Society of America.

Codarin, A., Wysocki, L.E., Ladich, F. and Picciulin, M. (**2009**) Effects of ambient and boat noise on hearing and communication in three fish species living in a marine protected area (Miramare, Italy). *Marine pollution bulletin*, *58*(12), pp.1880-1887.

Furuno USA (**2016**) *Furuno U.S.A.* Available at: http://www.furunousa.com/Products/ProductDetail.aspx?product=FCV620 (Accessed: 01.02.2016).

Furuno USA (**2016**) *Furuno U.S.A.* Available at: http://www.furunousa.com/products/ProductDetail.aspx?product=SC50 (Accessed: 01.02.2016).

JASCO Applied Sciences (**2011**) *Noise and the Effects on Marine Mammals, A Pocket Handbook* 3rd Edition,

Australia: JASCO Applied Sciences.
Kuczmarski, M. A. and Johnston, J. C. (**2011**) *Acoustic Absorption in Porous Materials*. NASA/TM-2011-216995 [Online]. Available at: http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20110011143.pdf (Accessed: 01.04.2016).
Marine Environment Protection Committee (**2009**) Noise from Commercial Shipping and its Adverse Impacts on Marine Life USA: *International Marine Organization* (MEPC 60/18).
McDonald, J.I., Wilkens, S.L., Stanley, J.A. and Jeffs, A.G. (**2014**) Vessel generator noise as a settlement cue for marine biofouling species. *Biofouling*, *30*(6), pp.741-749.
Nielsen-Kellerman Co. (**2016**) *KestralMeters.com* Available at: http://kestrelmeters.com/products/kestrel-1000-wind-meter (Accessed: 12.02.2016).
OSPAR Commission (**2009**) Overview of the impacts of anthropogenic underwater sound in the marine environment. *Report*, *441*, p.2009.
P&T Charters (**2009**). *Algemeen Plan 05.* Nordwijk, the Netherlands: KHMB Y&S Design Figure 3.
Perkins Engines Limited (**1993**) *Manual for 4.2482, 4.248, T4.236, 4.236, 4.212 & T4.38 diesel engines* Peterborough, United Kingdom: Technical Publications.
Pine, M.K., Jeffs, A.G. and Radford, C.A. (**2014**) The cumulative effect on sound levels from multiple underwater anthropogenic sound sources in shallow coastal waters. *Journal of applied ecology*, *51*(1), pp.23-30.
Sara, G.I.A.N.L.U.C.A., Dean, J.M., D'Amato, D., Buscaino, G., Oliveri, A., Genovese, S., Ferro, S., Buffa, G., Martire, M. and Mazzola, S. (**2007**) Effect of boat noise on the behaviour of bluefin tuna Thunnus thynnus in the Mediterranean Sea. *Marine Ecology Progress Series*, *331*, pp.243-253.
Scholik, A.R. and Yan, H.Y. (**2002**) Effects of boat engine noise on the auditory sensitivity of the fathead minnow, Pimephales promelas. *Environmental Biology of Fishes*, *63*(2), pp.203-209.
Scorpion Oceanics Ltd. (**2015**) *Scorpion Oceanics* Available at: http://www.scorpionoceanics.co.uk/hydrophones (Accessed: 20.06.2015).
Stanley, J.A., Wilkens, S.L. and Jeffs, A.G. (**2014**). Fouling in your own nest: vessel noise increases biofouling. *Biofouling*, *30*(7), pp.837-844.
The MathWorks, Inc. (**2016**) *Matlab*. Available at: http://uk.mathworks.com/products/matlab/ (Accessed: 12.01.2016).
Towler, P. & Fishwick, M. (**2015**) *Reeds Nautical Almanac* Oxford, United Kingdom: Bloomsbury.
Tsoflias, S.L., Hedgeland, D. and Gill, C. (**2012**) January. Marine Environment Guidance during Geophysical Operations. In *International Conference on Health, Safety and Environment in Oil and Gas Exploration and Production*. Society of Petroleum Engineers.
Van der Graaf, A.J., Ainslie, M.A., André, M., Brensing, K., Dalen, J., Dekeling, R.P.A., Robinson, S., Tasker, M.L., Thomsen, F. and Werner, S. (**2012**) European Marine Strategy Framework Directive-Good Environmental Status (MSFD GES): Report of the Technical Subgroup on Underwater noise and other forms of energy. *Brussels*.
Wahlberg, M. and Westerberg, H. (**2005**) Hearing in fish and their reactions to sounds from offshore wind farms. *Marine Ecology Progress Series*, *288*, pp.295-309.
Wysocki, L.E., Dittami, J.P. and Ladich, F. (**2006**) Ship noise and cortisol secretion in European freshwater fishes. *Biological Conservation*, *128*(4), pp.501-508.
Zoom North America (**2015**) *Zoom*. Available at: https://www.zoom-na.com/products/field-video-recording/field-recording/zoom-h4nsp-handy-recorder (Accessed: 20.06.2015).

ACKNOWLEDGEMENTS

I would like to thank Julius Piercy and Adam Hill for their continuous support over the past year, helping throughout the project. I would also like to send my thanks to P&T Charters for the aid they provided on board of the Gulden Leeuw.

Appreciative thanks also go to David Smith and Russell Smart at the University of Essex, for the supply of the hydrophone used.