Saturn

Developing Solutions for Underwater Radiated Noise

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# SATURN SubTask 2.1.2

## Harmonized test signals to assess harmful underwater noise characteristics

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# Disclaimer

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# Executive Summary

One of the main aims of SATURN is to determine the relevant metrics of ship radiated underwater sounds that can be related to detrimental effects on the physiology and behaviour of aquatic animals. Where possible, these metrics will then be related to the corresponding ship design and operational parameters, to enable the development of mitigation solutions. As part of the approach, controlled exposure experiments will be conducted in the laboratory on representative fish and invertebrate species.

Saturn subtask T2.1.2 has developed a suite of artificially synthesized ship sound signals. These signals are considered suitable for the assessment of harmful underwater noise characteristics in the sense that they are relevant for the impact on marine life as well as subject to technically achievable mitigation measures. Using harmonized test signals for the different bioacoustics playback studies facilitates the comparability of results.

Ideally, these signals could also provide a standard reference for external stakeholders and future projects.

# 1. Introduction

One of the main objectives of SATURN is to *identify the ship radiated underwater sounds that are most harmful to aquatic species and how they are produced and propagated*. The aim is to determine the relevant metrics of sound exposure that can be related to detrimental effects on the physiology and behaviour of aquatic animals. Where possible, these metrics will then be related to the corresponding ship design and operational parameters, to enable the development of mitigation solutions. Not all effects on all species can be studied in the context of a single research programme. SATURN proposes a selection of relevant studies to enhance understanding of shipping sound on aquatic animals.

The assessment of the impact of underwater noise on aquatic animals is especially complex because of the variety of taxa involved, each with their own spectral and temporal sensitivity to sound and their behavioural and physiological sensitivity to acoustic disturbance. The three large taxonomic groups in aquatic ecosystems are invertebrates, fishes and marine mammals. SATURN will focus on three *marine mammal species*: harbour porpoises, pilot whales and harbour seals. *Fishes and invertebrates* are considered to be particularly sensitive to the particle motion components of sound and hear sounds predominantly in the lower frequency ranges, usually below 1000 Hz (Hawkins, Pembroke, & Popper, 2015). Invertebrates' low capacity or inability to escape sound sources makes them potentially more vulnerable to a continuous sound source because they are likely to receive a higher dose of sound compared with species that can escape a noisy area like fish or marine mammals. In addition to marine mammals, SATURN will study the impact of ship sound on a suite of representative species (copepods (plankton), bivalves, crustaceans and cephalopods) and marine and riverine fish (sticklebacks, eels and sturgeons). Because field studies on fish and invertebrates are complex, SATURN proposes to study impacts of sound on these species in the laboratory. We consider laboratory conditions and captive animals critical for progress and essential for revealing fundamental aspects of the processes underlying negative effects of noise pollution. Controlled exposure experiments will be conducted on representative species using harmonized test signals, and state-of-the-art analysis will determine the physiological, pathological and behavioural effects of both particle motion and acoustic pressure on the exposed animals.

Playing back ship sound for controlled exposure experiments is not a trivial task. As argued by (Erbe, et al., 2019): "*once recordings of watercraft have been obtained, they are sometimes played back to animals in different environments for response studies. The recorded sound was affected (in frequency and level) by the environment in which the recordings were made and by the recording system. It will likely be broadcast in yet another, different environment, resulting in further affected received spectrum levels. In addition, the speaker used for playback will have a frequency response, which can distort the signal. Ideally, the speaker's frequency response is measured, and the playback signal is digitally filtered with the inverse of the frequency response before the playback study. Furthermore, the underwater speaker used will have a rather different sound radiation (i.e., directivity) pattern from the recorded vessel. Finally, it is impossible to simulate an approaching vessel with a single, moored speaker, because not only the received level changes as a vessel approaches, but also its spectrum and directionality.*" Moreover, ambient noise will typically be recorded together with the ship noise and if not filtered out before playback, the ambient noise outside the ship noise band may be artificially elevated due to the playback.

# 2. Ship radiated underwater sound

Underwater radiated sound has been used by navies since World War I, as a means for detecting ships (passive sonar), see e.g. (Ainslie, Principles of Sonar Performance Modeling, 2010). Hence, the main sound source mechanisms on ships are generally well-known. The main sound sources are generally the propulsors (propellers, waterjets, or other) and the engines that drive these propulsors, but also other on-board machinery (such as generators, pumps, etc.) and the hydrodynamic flow around the ship hull can contribute, see e.g. (Urick, 1983) and (Ross, 1976).

Propeller sound sources: inhomogeneous wake flow, turbulence at leading edge (inflow turbulence), trailing edge and blade tip, and cavitation on blades (sheet cavitation), blade root cavitation and cavitation in the tip vortex and at the hub. These create tonal sound at harmonics[1] of the propeller 'blade rate' (i.e. the frequency at which the propeller blades pass one by one through the non-uniform wake of the hull, given by the product of the propeller shaft rotation rate and the number of blades), and broadband sound from cavitation and from turbulence. The amplitude of the broadband propeller cavitation sound is typically modulated at the blade rate, because the dominant cavitation dynamics occurs when the propeller blade passes through the wake peak, typically located near the 12 o'clock position. The broadband sound from turbulence can be amplified in some frequency bands by propeller blade resonances. In some cases, interaction between blade resonance and vortex shedding at the trailing edge can cause strong tonal sound known as 'propeller singing'. This can generally be mitigated by small modifications of the shape of the trailing edge, see e.g. (Carlton, 2012)

Machinery sound sources: rotating and reciprocating machinery produce tonal sound at harmonics of the rotation (or oscillation) rate of the machines, including, for example, gear mesh frequencies.

The detailed analysis of the radiated sound of M/V OVERSEAS HARRIETTE in (Arveson & Vendittis, 2000) provides a useful example of the speed-dependent sound of a cargo ship. The radiated noise level (RNL) spectra, see Figure 1, show tonal sound at harmonics of the fixed rotation rate of the ship's service diesel generator, of the firing rate of the main propulsion engine, and of the propeller 'blade rate', in addition to broadband propeller cavitation sound. The broadband sound increases with increasing ship speed (at increasing shaft rotation rate, expressed in revolutions per minute 'rpm') over the full frequency range of the measurements (10 Hz – 40 kHz).

Similar radiated sound characteristics are observed in measurements on most ships, see e.g. (MacGillivray & de Jong, A Reference Spectrum Model for Estimating Source Levels of Marine Shipping Based on Automated Identification System Data, 2021) (MacGillivray, et al., 2020), (Gassmann, Wiggins, & Hildebrand, 2017), (Schael, 2013), (McKenna, Wiggins, & Hildebrand, 2013)

[1] A harmonic is a positive integer multiple of the frequency of the fundamental frequency of the source (e.g. the firing rate of a diesel engine, or the blade passing frequency of a propeller). The fundamental frequency is the first harmonic; subsequent harmonics are known as higher harmonics.

These characteristics are for regular ship transit sounds. Manoeuvring, switching machines on and off, and the operation of thrusters for dynamic positioning can generate additional transient sounds.

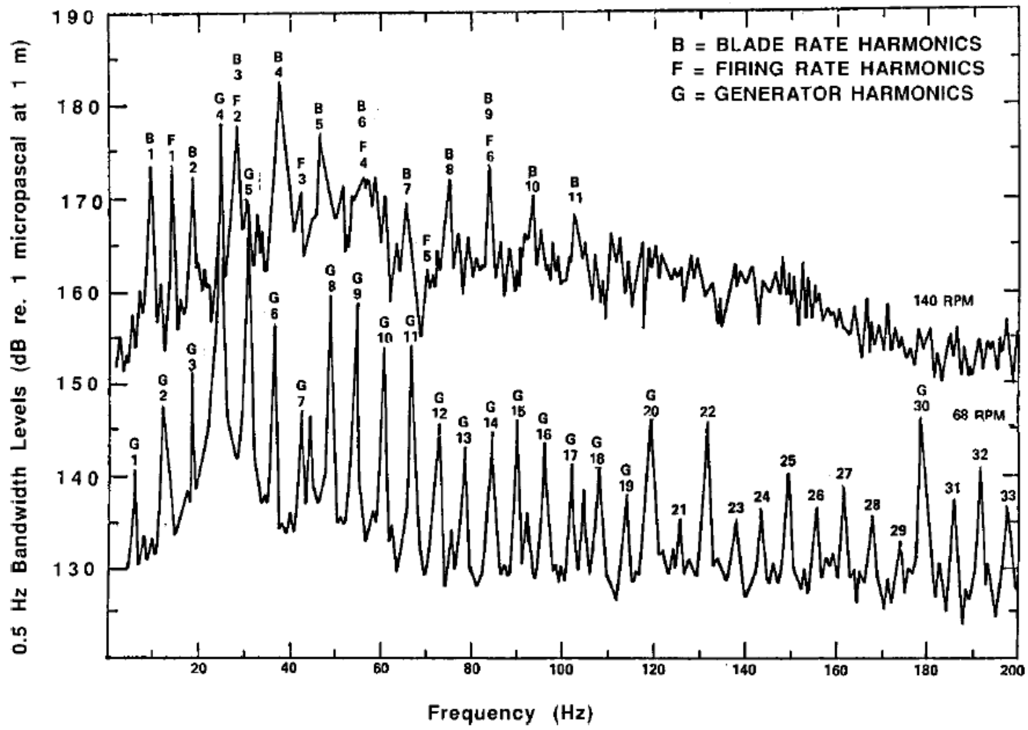


*Figure 1 Keel-aspect narrow-band spectra of M/V OVERSEAS HARRIETTE RNL (re 1 μPa m) in 0.5 Hz bands at low speed (68 rpm)* [2] *and maximum speed (140 rpm). The identification of various tonal harmonics is indicated; the symbols are G (ship's service diesel generator), B (propeller blade rate), and F (diesel firing rate). From (Arveson & Vendittis, 2000).*

[2] rpm = revolutions per minute

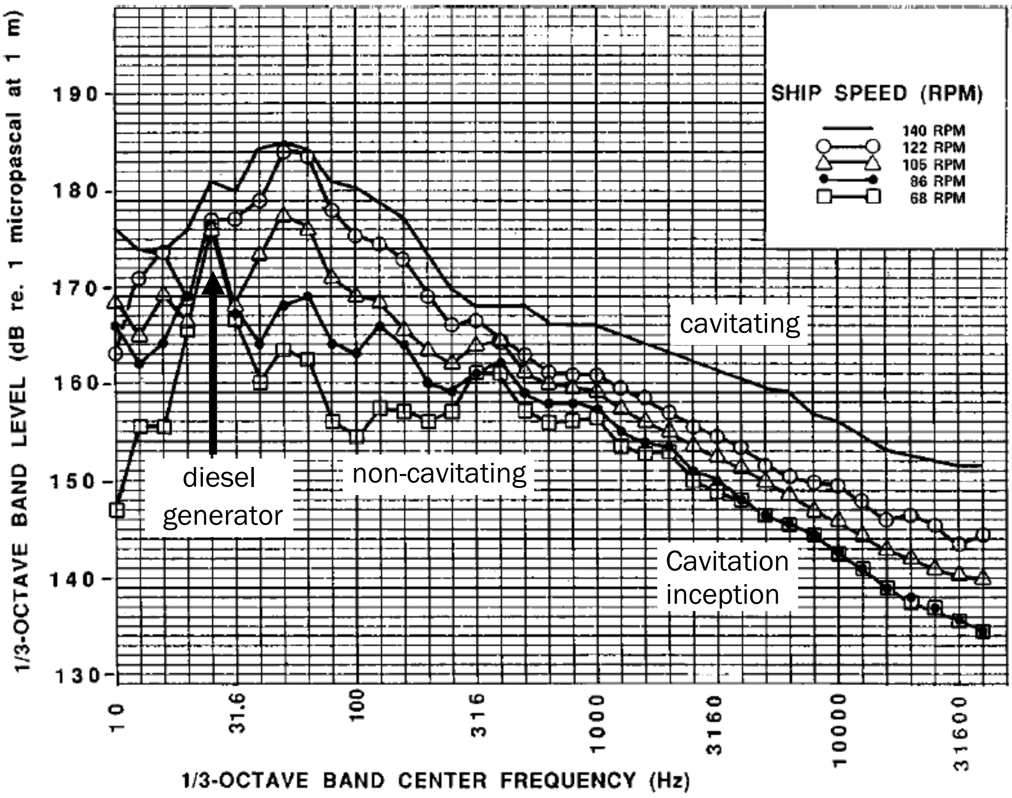


*Figure 2 Keel-aspect "1/3-octave" (decidecade) bandwidth spectra of M/V OVERSEAS HARRIETTE at five speeds. From (Arveson & Vendittis, 2000), with annotation from (Bosschers, et al., June 2021).*

# 3. Sound features

The sound signals used for controlled exposure experiments in the laboratory must represent the relevant temporal and spectral features that can be attributed to specific ship radiated sound characteristics. Spatial features of the playback sound field are relevant as well, but these are mainly related to the geometry of the laboratory test setup and playback devices, outside the scope of this task. This report aims at the design of harmonized digital test signals for playback studies. We focus on the temporal and spectral features of the sound signals. The design of the playback system to convert these (electronic) signals into the appropriate sound pressure and sound particle motion field will be an essential task in the design of the individual controlled exposure studies for the different animal species.

### *Spectral features*

The spectral features of ship sound have already been discussed in the previous chapter. During regular sailing, the ship radiated sound spectrum contains both broadband sounds, typically generated by propeller cavitation, and tonal components, associated with the propeller and with rotating and reciprocating machinery.

- Proportional bandwidth spectra (such as Figure 2), for a relevant auditory bandwidth, provide the relevant information about the spectral distribution of the sound energy in the signal in relation to detection and to possible noise-induced hearing threshold shifts.

- Narrowband spectra (such as Figure 1), provide the relevant information about the presence of dominant tonal sounds in the signal. Humans exposed to sounds with a prominent tonal character experience higher annoyance than when exposed to broadband sounds at the same sound pressure level. Consequently, the airborne environmental noise assessment standard (ISO 1996-1, 2016) suggest adding an adjustment ('penalty factor') of 3 to 6 dB to the measured sound level of sounds with a prominent tonal character. For this purpose, (ISO/PAS 20065, 2016) describes an objective method for assessing the audibility of tones in noise, in relation to human hearing. The tonal character of sound may also be relevant for behavioural response of aquatic animals to sound exposure, but this has not yet been investigated. We recommend investigating the effect of the tonality of ship sound signals in controlled exposure studies. In opportunistic acoustic measurements of ships transiting offshore California (McKenna, Wiggins, & Hildebrand, 2013), dominant narrowband tones were present in 10% of the measured ships.

### *Temporal features*

The following bullets summarize information about the relevant temporal features:

- The audibility of sound signals to animals is affected by signal duration, see e.g. (Kastelein, Hoek, de Jong, & Wensveen, 2010). The integration time of harbour porpoise hearing was found to be similar to that of other mammals, including humans. Because the 'ears' of fishes and invertebrates are different from those of mammals, it is well possible that these have different integration times, but data are largely lacking. One study by Art Popper (Popper, 1972) did not show any dependence on signal duration, but a later study by Dick Fay and Shelley Coombs (Fay & Coombs, 1983) does suggest an integration time of some hundred milliseconds in goldfish.
- The sounds radiated by a ship due to propeller and machinery sound, if the ship is sailing at a constant speed and course, can be considered 'stationary' (meaning that statistical parameters remain constant). at time scales larger than the rotation period (the inverse of the rotation rate) of the main noise sources. Typically, these rotation periods are of the order of 1 s or less.
- The amplitude of broadband propeller cavitation sound is modulated at the blade rate. Defence and security organizations use analysis methods such as DEMON (*Detection of Envelope Modulation on Noise*), to estimate the shaft rotation frequency of detected vessels, as a means for classification, see e.g. (Chung, Sutin, Sedunov, & Bruno, 2011) and (Fillinger, Sutin, & Sedunov, 2011). Animals with a hearing time constant $\tau \approx 125\ \mathrm{ms}$ can likely perceive the amplitude modulation for blade rates up to about $8\ \mathrm{Hz}\ (= 1/\tau)$ as loudness fluctuations. In human psychoacoustics, faster (>12 Hz) amplitude modulations are qualified as 'roughness' of the sound (Daniel, 2008). It is likely that this perception occurs in other species as well, but this has not yet been investigated. Geometric differences between individual blades or shaft eccentricity may also lead to sound modulation at the shaft rotation rate, but this slow modulation is generally
- The sound to which a static animal is exposed when a ship passes varies in time due to the decreasing and increasing distance to the ship, in combination with the interference effects due to reflections of the ship sound at the water surface (the *Lloyd mirror effect* in underwater

acoustics). For typical ship speeds (< 40 knots)[3] and observation distances (> 100 m), these variations occur over time periods of the order of 5 s or more.

- The relative motion between ship and observer will also cause a variation of the observed tonal frequencies due to the *Doppler effect*. Due to the large difference between the ship speed and the sound speed in water, this is a subtle effect which we tentatively ignore in this study.
- In addition, propeller tip-vortex cavitation produces low frequency broadband noise related to variations between blade passages, hence variations in time that have a time scale of the order of blade rate frequency or smaller, see (Bosschers, Propeller tip-vortex cavitation and its broadband noise, 2018). These may have various origins and may include ship motions, variations in rpm, turbulence in the wake, variations in nuclei. These variations in low frequency sound radiations are not yet well-described and hence tentatively ignored in this study.

*Signal representation*

Digital signals representing field quantities such as sound pressure or sound particle displacement, velocity or acceleration, characterize the time-varying amplitude of a sound signal $x(t)$ at discrete, uniformly distributed times $t_n$, with $\delta t$ the time step between the samples, so that $t_n = t_1 + (n-1)\delta t$, with $n = 1,2,\dots,N$, see e.g. (Ainslie, Prior, & de Jong, E&P sound and Marine Life JIP Standard: Underwater Acoustics - Task 2: Processing, 2018). The time step corresponds with a sample rate (or sample frequency) $f_s = 1/\delta t$ . The number of samples $N$ that describe a signal of duration $T$ equals $N = T/\delta t$. The maximum sound frequency that can be represented by a digital signal without distortion (aliasing) is limited by the Nyquist rate $f_s/2$. The statistics of time series $x(t_n)$ characterize the signal.

- The *short-time Fourier transform* (STFT) of the signal quantifies the relevant temporal and spectral features of the sound signal. The frequency resolution $\delta f = 1/\Delta t$ in the STFT is inversely proportional to the duration $\Delta t$ of the subsequently analysed sections of the signal. The STFT reveals the tonal and broadband sound components and how these vary with time.
- Another statistic of the sound signal that may be relevant for predicting the risk of hearing loss or other adverse effects of sound on aquatic animals is *kurtosis* (the moment of order 4 in the standardized probability distribution of a random variable (ISO 3534-1, 2006), see also (Müller, von Benda-Beckmann, Halvorsen, & Ainslie, 2020)). Kurtosis is recommended for quantifying 'impulsiveness', by (Martin, Lucke, & Barclay, 2020). They note: "Sounds from vessels are normally considered non-impulsive; however, 66% of vessels analyzed were impulsive when weighted for very-high frequency mammal hearing … vessel sounds that generate high kurtosis when VHF-C auditory frequency weighted are a mix of rubbing and rasping sounds, cavitation sounds, and mechanical knocking". Although there is no generally accepted definition of 'impulsive' or 'non-impulsive' sounds, it makes sense to include the kurtosis as a feature in studies of the effect of sound on marine animals.

[3] 1 knot = 1852/3600 m/s

# 4. Synthesized ship sound signals

In order to be able to systematically investigate which features of ship sound are the most harmful to aquatic animals, we propose to apply synthesized sound signals with independent variation of the relevant sound features. An earlier example of synthesizing ship sound was presented by (Yağımlı & Sertlek, 2013).

Annex A provides an example of the synthesis of ship sound signals from information about broadband spectrum, blade rate modulation and propeller and machinery tonals. This approach is followed for synthesizing harmonized test signals.
Selection of a harmonized set of representative test signals depends on the intended application of these signals. We have started from the following assumptions:

- The playback signals are mainly required for controlled exposure experiments in the laboratory on fishes and invertebrates (SATURN subtasks 3.1 and 3.2).
- The main frequency range of interest for these experiments is between approximately 10 Hz and 1 kHz.
- The primary interest is in the effects of stationary 'continuous' sound from ships transiting at constant speed and course.
- The main sound feature of interest is the *broadband sound level*. Here 'sound level' can refer to either sound pressure level, or the level of sound particle displacement, velocity or acceleration. The sound level depends on the design of the laboratory setup and the playback system.
- The next feature of interest is the *spectrum* (frequency content) of the signal. This depends on the combination of test signal and playback system. Where appropriate, the test signal can be adapted to correct for the characteristics of the playback system. Design of the appropriate spectrum for the test signals depends on information about the frequency sensitivity of the species that is being investigated as well as on the characteristics of the sound source and environment. The presence of dominant '*tonal sounds*' in the spectrum may be relevant for behavioural response studies.
- Another potentially relevant sound feature for behavioural response studies is the temporal variation of the exposure (*amplitude modulation*), and the corresponding perception of 'fluctuations' and 'roughness' of the sound

The spectrum and the temporal structure have been included in the design of the test signals.

*Ship source level spectra*
Average broadband source level spectra of different classes of ships (transiting at constant speed and course) are predicted by the Jomopans-ECHO ship source level model (MacGillivray & de Jong, A Reference Spectrum Model for Estimating Source Levels of Marine Shipping Based on Automated Identification System Data, 2021). This model calculates the source level spectrum $L_S(f)$ of ship as a function of speed, length and (AIS) ship type. The model is based on the statistics of a large database of ship source level measurements from the Vancouver Fraser Port Authority-led Enhancing Cetacean Habitat and Observation (ECHO) Program.

In a subsequent vessel noise correlation study', again carried out in the ECHO Program, (MacGillivray, et al., 2020) confirmed that "speed through water and actual vessel draft (i.e., the two primary operational parameters) were generally the most influential predictors for underwater noise", while "vessel size (represented via length overall) was ranked as the design parameter with the strongest correlation to underwater radiated noise". An important feature is that "the loud vessels exhibited a distinct cavitation noise hump near 50 Hz (e.g., as discussed by (Wittekind & Schuster, 2016)), whereas the quiet vessels exhibited a flatter spectrum below 100 Hz". Such a 'hump' is tentatively included in the Jomopans-ECHO model for all cargo vessels (container ships, vehicle carriers, bulkers, tankers). The origin of the hump in the radiated noise spectrum is still unexplained. It may be due to propeller vortex cavitation, but the Lloyd mirror effect and cavitation excited hull-plate vibrations also have an effect.

The Jomopans-ECHO ship source level model calculates the ship source level spectrum, for an assumed fixed source depth of 6 m below the water surface. The received sound in a given environment will depend on the propagation conditions. These will affect the shape of the sound spectrum. For the synthesis of ship sound signals, we have incorporated a deep water Lloyd mirror propagation loss correction such as suggested by ISO 17208-2, to avoid overemphasizing the lower frequencies in the playback spectrum[4].

Two widely different source level spectra have been taken to construct the following two synthetic ship signals:

A. Broadband continuous sound (10 Hz – 4 kHz) for a typical fishing boat of 50 m length at a speed of 11 knots.

B. Broadband continuous sound (10 Hz – 4 kHz) of a typical large containership of 300 m length at a speed of 18 knots

The temporal structure ('roughness') associated with blade rate amplitude modulation is added in the next two signals:

C. Fishing boat signal A enhanced with blade rate amplitude modulation, representing a single 4-bladed propeller rotating at 180 rotations per minute (rpm). This corresponds with a blade passing frequency of 12 Hz.

D. Containership signal B enhanced with blade rate amplitude modulation, representing a single 5-bladed propeller rotating at 90 rotations per minute (rpm). This corresponds with a blade passing frequency of 7.5 Hz.

Next, the spectral structure is modified by adding tonals in the following signals:

E. Fishing boat signal A enhanced with tonals at propeller blade rate (12 Hz) harmonics and at harmonics of a ship service diesel generator (30 Hz and harmonics).

F. Containership signal B enhanced with tonals at propeller blade rate (7.5 Hz) harmonics and with two dominant tonals at 350 Hz and 580 Hz, as observed by (McKenna, Wiggins, & Hildebrand, 2013).

[4] The example provided in Annex A does not includes such a correction, because it already represents a measured 'radiated noise level'.

The following signals represent the combination of amplitude modulation and tonal structure:

G. Fishing boat signal C enhanced with tonals at propeller blade rate (12 Hz) harmonics and at harmonics of a ship service diesel generator (30 Hz and harmonics).

H. Containership signal B enhanced with tonals at propeller blade rate (7.5 Hz) harmonics and with two dominant tonals at 350 Hz and 580 Hz.

The statistical properties of the signals are given in Table 1. Figure 3 and Figure 4 show corresponding waveforms and spectra.

*Table 1 Statistical properties of the audio signals for the synthesized ship sound signals. The zero-to-peak levels are equal to 0 dB, indicating that the signals in the wav-files are normalized relative to the maximum amplitude in the 10 s signal. In playback studies, the properties will be modified by the playback system.*

| | signal | $L_{pk}$ [dB re 1] | $L_{rms}$ [dB re 1] | Kurtosis $\beta$ |
|---|---|---|---|---|
| A | FISHINGBOAT_BROADBAND.WAV | 0 | -13.4 | 3.01 |
| B | CONTAINERSHIP_BROADBAND.WAV | 0 | -13.2 | 3.06 |
| C | FISHINGBOAT_BROADBAND_MODULATED.WAV | 0 | -14.1 | 3.34 |
| D | CONTAINERSHIP_BROADBAND_MODULATED.WAV | 0 | -13.2 | 3.42 |
| E | FISHINGBOAT_BROADBAND_TONALS.WAV | 0 | –12.3 | 2.93 |
| F | CONTAINERSHIP_BROADBAND_TONALS.WAV | 0 | -12.3 | 2.89 |
| G | FISHINGBOAT_BROADBAND_MODULATED_TONALS.WAV | 0 | -14.7 | 3.27 |
| H | CONTAINERSHIP_BROADBAND_MODULATED_TONALS.WAV | 0 | -12.0 | 2.96 |

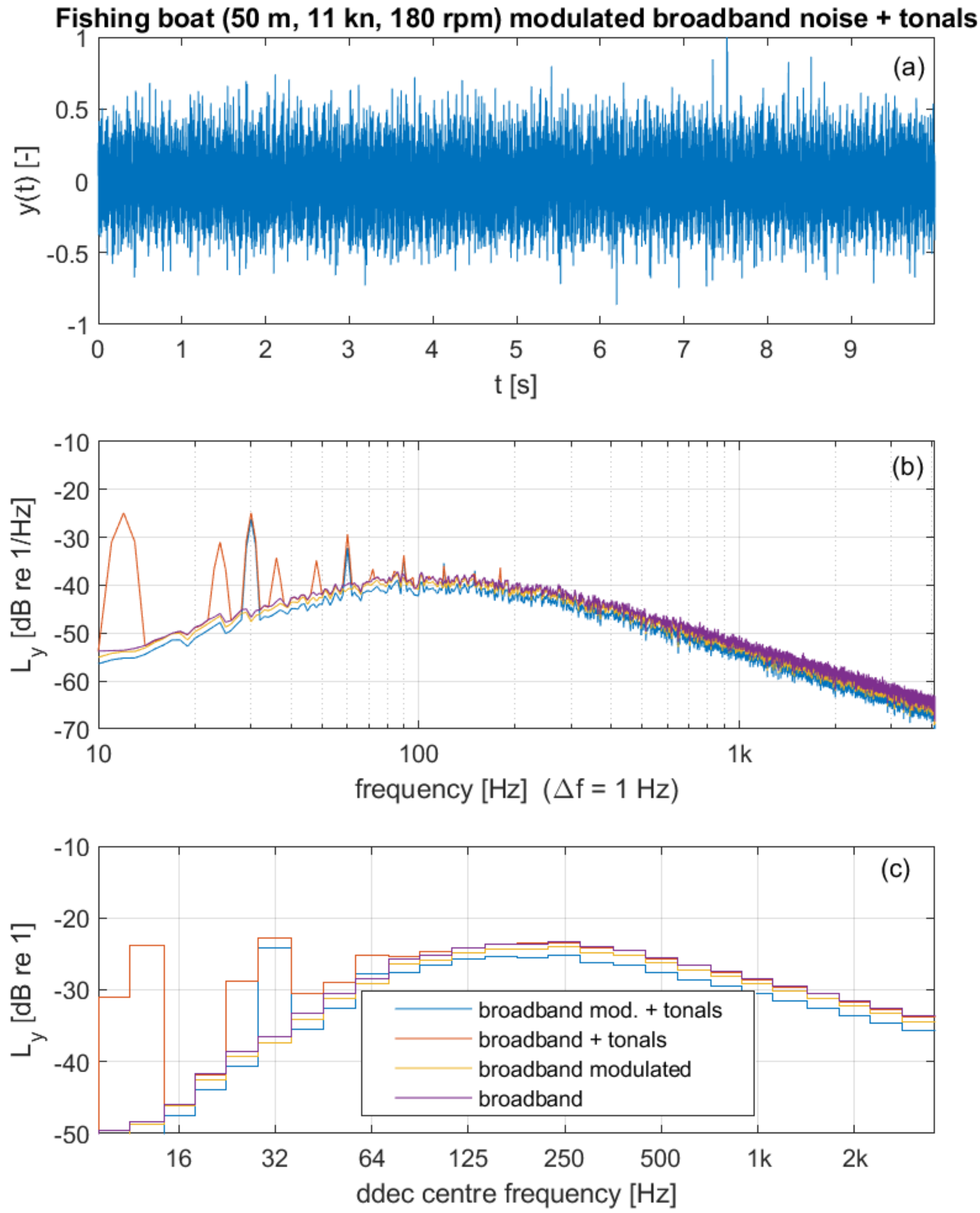


*Figure 3 waveform (a), narrowband spectrum (b) and decidecade spectrum (c) of the fishing boat sound signal G, that represents the blade rate modulated broadband noise plus tonals (in blue). The spectra are compared with those of the sound signals A, C and E, without tonals and without modulation, scaled so that the total power in the spectra is equal for the three signals*

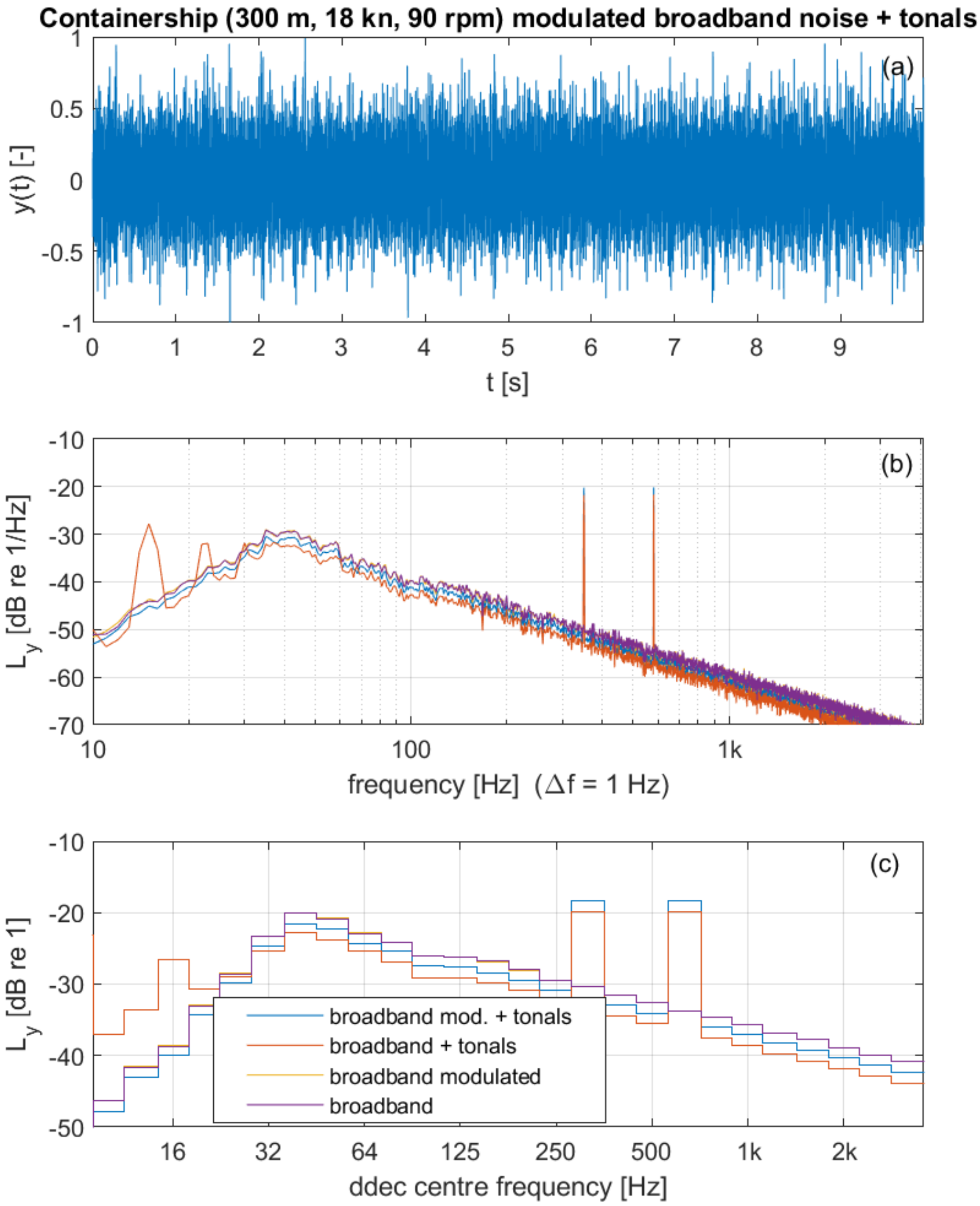


*Figure 4 waveform (a), narrowband spectrum (b) and decidecade spectrum (c) of the containership sound signal H, that represents the blade rate modulated broadband noise plus tonals (in blue). The spectra are compared with those of the sound signals B, D and F, without tonals and without modulation, scaled so that the total power in the spectra is equal for the three signals*

# 5. Concluding remarks

This report describes an approach for selecting and synthesizing ship underwater radiated sound signals for playback studies. This approach has been applied to generate eight test signals for SATURN studies, representing various aspects of the radiated sound of a large containership as well as a typical fishing vessel.

Additionally, test signals can be developed that are independent of the average spectra of ships, but focus on specific sound features, such as band limited noise, transient signals or tonal sounds, if required by the test hypotheses for the controlled exposure studies. These could, for example, represent the transient sound due to switching of engine or gear, or tonal sound from propeller singing. The approach proposed in this report can easily be extended to synthesize such signals.

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# Annex A Example of digital signal synthesis

The test signals for playback studies of ship sound are to be provided as digital audio files, in the uncompressed (linear pulse-code modulation) Waveform Audio File Format (file extension '.wav') developed by IBM and Microsoft.

As an example, we start from the following initial parameters for the audio file:

- Duration of the audio signal: $T = 10\ \text{s}$
- Sample frequency: $f_s = 8192\ \text{Hz}\ \ (2^{13}\ \text{Hz})$

This also determines the following parameters:

- Time resolution of the audio signal: $\delta t = 1/f_s \approx 0.122\ \text{ms}$
- Number of samples: $N = T \cdot f_s = 81920$
- Nyquist frequency $f_{\max} = f_s/2 = 4096\ \text{Hz}$

The synthetic test signal is generated on the basis of a measured or predicted ship sound spectrum. In this example, we start from a rough approximation of the broadband noise component of the radiated noise level decidecade band spectrum of M/V OVERSEAS HARRIETTE (see Figure 1 and Figure 2) at 140 rpm, described by the following equation:

$$L_{\text{RN,ddec}}(f) = \begin{cases} 174\ \text{dB} - 10\log_{10}\left(\dfrac{f}{50\ \text{Hz}}\right)\ \text{dB}\,, & \text{for}\ \ f \geq\ \ 50\ \text{Hz} \\ 174\ \text{dB} + 10\log_{10}\left(\dfrac{f}{50\ \text{Hz}}\right)\ \text{dB}\,, & \text{for}\ \ f <\ \ 50\ \text{Hz} \end{cases}$$

To generate the corresponding time signal, the following steps are taken:

1. Evaluate this field quantity at discrete frequencies $f_k = k \cdot \delta f$, with frequency resolution $\delta f = 1/T = 0.1\ \text{Hz}$, and $k = 1..N/2$.
2. Convert to spectral density:

$$L_{\text{RN},f}(f_k) = L_{\text{RN,ddec}}(f_k) - 10\log_{10}\left(\left(10^{\frac{1}{20}} - 10^{-\frac{1}{20}}\right) \cdot \frac{f_k}{1\ \text{Hz}}\right)\ \text{dB}$$

3. Convert to root-power quantity with amplitude $Y(f_k)$ :

$$Y(f_k) = 10^{\frac{L_{\text{RN},f}(f_k)}{20\ \text{dB}}} \cdot 1\ \mu\text{Pa m}$$

4. Convert this one-sided spectrum to a full double-sided Fourier spectrum:

$$Y(f_k) = \begin{cases} 0, & \text{for}\ \ k = 0 \\ Y(f_k), & \text{for}\ \ k = 1..\left(\dfrac{N}{2} + 1\right) \\ Y(f_{N-k}), & \text{for}\ \ k = \left(\dfrac{N}{2} + 2\right)..(N-1) \end{cases}$$

5. Next, add a random phase $\phi_k$ (uniformly distributed in the range $0..2\pi$, with $\phi_0 = 0$) to each element of the spectrum, to represent random noise:

$$Y_k = Y(f_k) \cdot e^{i\phi_k}$$

6. Apply the inverse Fourier transform and keep the real part:

$$y_n = \mathrm{Re}\left\{\frac{1}{N}\sum_{k=0}^{N-1} Y_k e^{\frac{i2\pi kn}{N}}\right\}$$

7. Normalize to the maximum amplitude in the resulting time series to generate the sound signal for playback: $y(t_n) = y_n / \max(|y_n|)$, so that the amplitude in the wav-file is in the range [-1 .. 1]. The amplitude at which the signal is played back will depend on test configuration, equipment and settings.

Figure A-1 shows the characteristics of the sound signal generated for this example. The sound file is available as 'EXAMPLE_OH_140RPM_BROADBAND.WAV'. The kurtosis of the signal is 3.05.

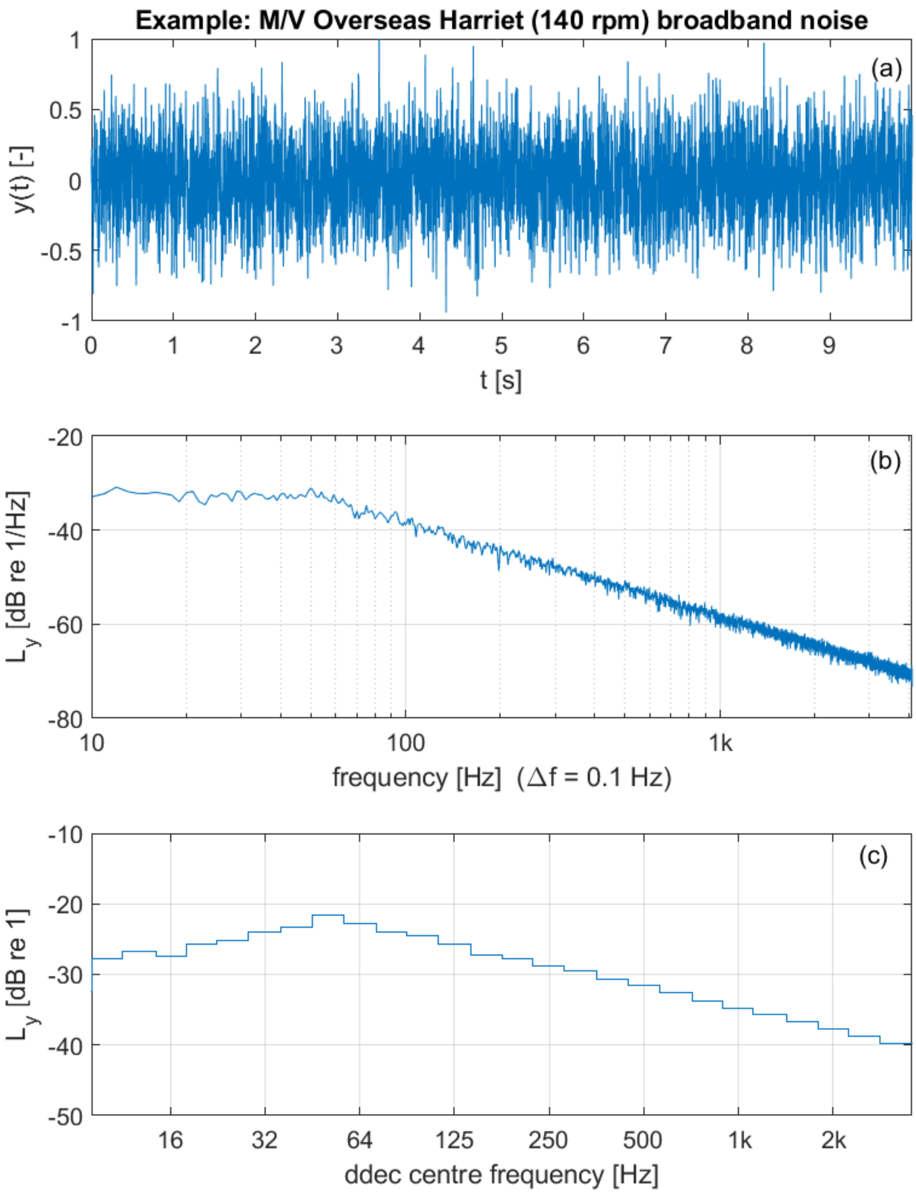


*Figure A-1 waveform (a), narrowband spectrum (b) and decidecade spectrum (c) of the sound signal example, that represents the stationary broadband noise of M/V OVERSEAS HARRIETTE at 140 rpm.*

The temporal and tonal characteristics of the radiated noise of M/V OVERSEAS HARRIETTE are not yet represented in this example. These are added as follows.

The propeller rotation rate (140 rpm), in combination with a 4-bladed propeller, corresponds with a blade rate $f_b = \frac{140\ \mathrm{rpm}}{60\ \mathrm{s/min}} \times 4 = 9.33\ \mathrm{Hz}$.

*Amplitude modulation*
Assuming that the broadband noise in the sound signal is dominated by propeller cavitation noise, it is reasonable to assume that the amplitude of this signal is modulated at the blade rate. This amplitude modulation can be incorporated in the sound signal by multiplying the times series $y(t_n)$ with an amplitude modulation function:

$$y_{\mathrm{am}}(t_n) = y(t_n) \cdot [1 + A_{\mathrm{am}} \sin(2\pi f_b t_n)]$$

The modulation amplitude $A_{\mathrm{am}}$ is not known for M/V OVERSEAS HARRIETTE. For this example, we tentatively assume that $A_{\mathrm{am}} = 0.25$.

The sound file is available as 'EXAMPLE_OH_140RPM_BROADBAND_MODULATED.WAV'. The effect of the amplitude modulation is clearly audible for the human ear. It does not visibly affect the mean spectrum of the sound, but it enhances the kurtosis of the sound signal (over duration $T$) from $\beta = 3.05$ to $\beta = 3.32$.

*Tonal sound*
Based on the narrowband spectrum of M/V OVERSEAS HARRIETTE (Figure 1), we add tonals to the spectrum that represent propeller blade rate harmonics $f_{\mathrm{BR},n} = n \cdot 4 \cdot \left(\frac{140}{60}\right)$ Hz (with $n = 1..10$), diesel firing rate harmonics $f_{\mathrm{FR},n} = n \cdot 6 \cdot \left(\frac{140}{60}\right)$ Hz (with $n = 1..6$), and two harmonics of the main ship service diesel generator $f_{\mathrm{SSDG},n} = n \cdot 6$ Hz (with $n = 4..5$). The relative levels of these tonals are taken from table III in (Arveson & Vendittis, 2000), and then scaled so that the highest tonals exceed the broadband noise spectrum by about 10 to 15 dB. The phase angles $\phi_m$ of the individual tonals are randomly drawn from a uniform distribution between 0 and $2\pi$. The $M$ $(= 18)$ tones are added via:

$$y_{\mathrm{t}}(t_n) = y(t_n) + \sum_{m=1}^{M} A_{\mathrm{t},m} \sin(2\pi f_m + \phi_m)$$

The sound file is available as: 'EXAMPLE_OH_140RPM_BROADBAND_TONALS.WAV'.

In the next example, the tones are added to the amplitude modulated signal:

$$y_{\mathrm{amt}}(t_n) = y_{\mathrm{am}}(t_n) + \sum_{m=1}^{M} A_{\mathrm{t},m} \sin(2\pi f_m + \phi_m)$$

The sound file is available as: 'EXAMPLE_OH_140RPM_BROADBAND_MODULATED_TONALS.WAV'.

Figure A-2 shows the characteristics of the sound signals generated for this example. The kurtosis is 3.26. The tonal noise affects the spectrum below 100 Hz. The level differences between the spectra in this figure are only relevant if all signals are played back at the same total signal power.

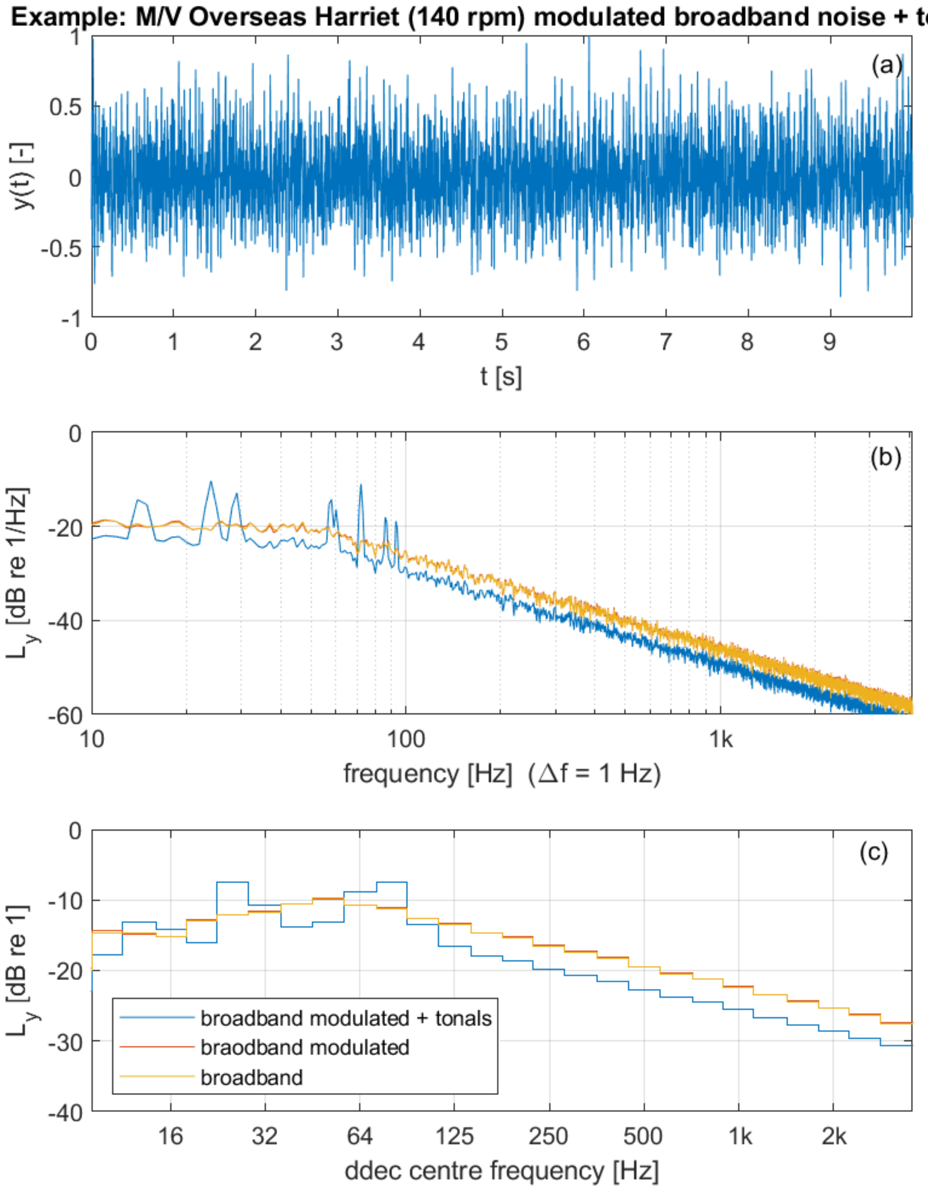


*Figure A-2 waveform (a), narrowband spectrum (b) and decidecade spectrum (c) of the sound signal example, that represents the blade rate modulated broadband noise plus tonals (in blue) of M/V Overseas Harriette at 140 rpm. The spectra are compared with those of the sound signals without tonals and without modulation, scaled so that the total power in the spectra is equal for the three signals.*

*Table A-1 Statistical properties of the audio signals for the M/V OVERSEAS HARRIETTE examples.*

| signal | $L_{pk}$ [dB re 1] | $L_{rms}$ [dB re 1] | Kurtosis $\beta$ |
|---|---|---|---|
| EXAMPLE_OH_140RPM_BROADBAND.WAV | 0 | -13.1 | 3.00 |
| EXAMPLE_OH_140RPM_BROADBAND_MODULATED.WAV | 0 | -13.6 | 3.24 |
| EXAMPLE_OH_140RPM_BROADBAND_TONALS.WAV | 0 | -11.5 | 2.74 |
| EXAMPLE_OH_140RPM_BROADBAND_MODULATED_TONALS.WAV | 0 | -11.8 | 3.03 |