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RESEARCH ARTICLE

Spectral analysis using Haar wavelet (original signal, denoised signal, residual signal) and source level (SL) for whistle sound of dolphin (*Tursiops aduncus*) in captivity

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ABSTRACT

This study discussed about Haar wavelet with a view original signal, denoised signal, and residual signal with using fourth whistle sounds of dolphin (*Tursiops aduncus*). The study was conducted in Safari Park, Cisarua, Bogor Indonesia with 2 dolphins. The results showed differences in results Haar wavelet, this study proves that the Haar wavelet is suitable for the analysis of dolphin sounds, and its have frequency ranged 8-22 kHz. The highest value of the noised signal was smaller than residual signal. The highest of residual signal contained in the second whistle, while the lowest was whistle 1, it showed that the larger the signal denoised result residual signal generated using Haar wavelet. The frequency of source level value ranged 8500 Hz to 11800 Hz, with the highest SL value was 43.9 dB (brown cyrcle). The lowest of the frequency of Source Level (SL) value ranged between 15700 Hz to 17990 Hz, with the lowest SL value was 38.5 dB (brown cyrcle). Whistle 1, 2, 3, and 4 have a different value SL and every SL values obtained in 1,2,3, and 4 have differences noise, it shows the same target but SL value and the sound patterns remain distinct by looking at time duration of whistle sound. Beam pattern from an omni directional sound source (DI= 0 dB, cyan trace) and a directional source following the piston model (DI= 18 dB, black trace) and beam pattern with 4 types signal have ranged value 70 º-180°, with highest intensity value was 60º.

Keywords: Haar wavelet, whistle sounds, dolphins (*Tursiops aduncus*), source level (SL), beam pattern

INTRODUCTION

Passive acoustic science is very important to know the range of the sound spectrum of fish and others biota. Passive acoustic monitoring has proven to be a successful tool in identifying the presence of baleen whales (*Megaptera novaeangliae*), and combined with other datasets for example, genetics and stable isotope ratios, it can be used to infer distribution and migration patterns of the whales (*Megaptera novaeangliae*) (Clark *et al.,* 2004, and Stimpert *et al.,* 2011). Passive acoustic instrumental is hydrophone, and the hydrophone can "listen" to sound in air but will be less sensitive due to its design as having a good acoustic impedance match to water, which is a denser fluid than air. Likewise, a microphone can be buried in the ground, or immersed in water if it is put in a waterproof container, but will give similarly poor performance due to the similarly bad acoustic impedance match (Miller and Dawson, 2009). The Studies made both in captivity and in the field are therefore important for our understanding of animal echolocation and how it evolved (Wulandari *et al.*, 2016; Lubis *et al.*, 2016a; Lubis *et al.*, 2016b; Moron and Andriolo, 2015; Wulandari, 2016; Lubis, 2016). The vocalizations with the underwater behavior of dolphins has proved difficult due to the lack of underwater access to animals and life history, sex, and relationship information.

Male dolphins bottle nose have small groups of dolphins frequently approached the recording platform. Data acquisition was manually initiated when dolphins were observed surfacing within 100 m of and toward the array. The acquisition lasted until the dolphins had passed the recording platform, interrupted 5 second every minute for data storage. The noise level, measured with SQ 03 hydrophone (receiving sensitivity 184 dB re 1 µPa/V) was high, up to 60 dB re 1µPa in the measured frequency range 200–40000 Hz, probably below this level in the whole frequency range of interest for *Tursiops* echolocation (up to some 120000 Hz). Ambient noise was broad spectral noise from snapping shrimps (for details on noise measurements, see (Jensen *et al.*, 2009). The recordings were made with a linear four-hydrophone array (Figure 1). The hydrophones have spaced 1 m apart and aligned by mounting them with an interconnected set of PVC pipes. Hydrophone array was suspended vertically between a surface buoy and a 0.5 kg lead weight, the top hydrophone held at a depth of a few meters. The hydrophones SQ 03 can be connected to a four-channel custom-built amplifier, containing noise rejecting and antialiasing filters (40 dB amplification, one-pole high pass filter with 3 dB cutoff frequency at 1000 Hz, and a four-pole low pass filter with 3 dB cutoff frequency of 2000 Hz). The objectives of this study were to analysis the spectral using Haar wavelet and source level for whistle sound of dolphins. Setup for recordings of *Tursiops aduncus* in Jensen *et al*., (2009) as showed in (Figure 1).

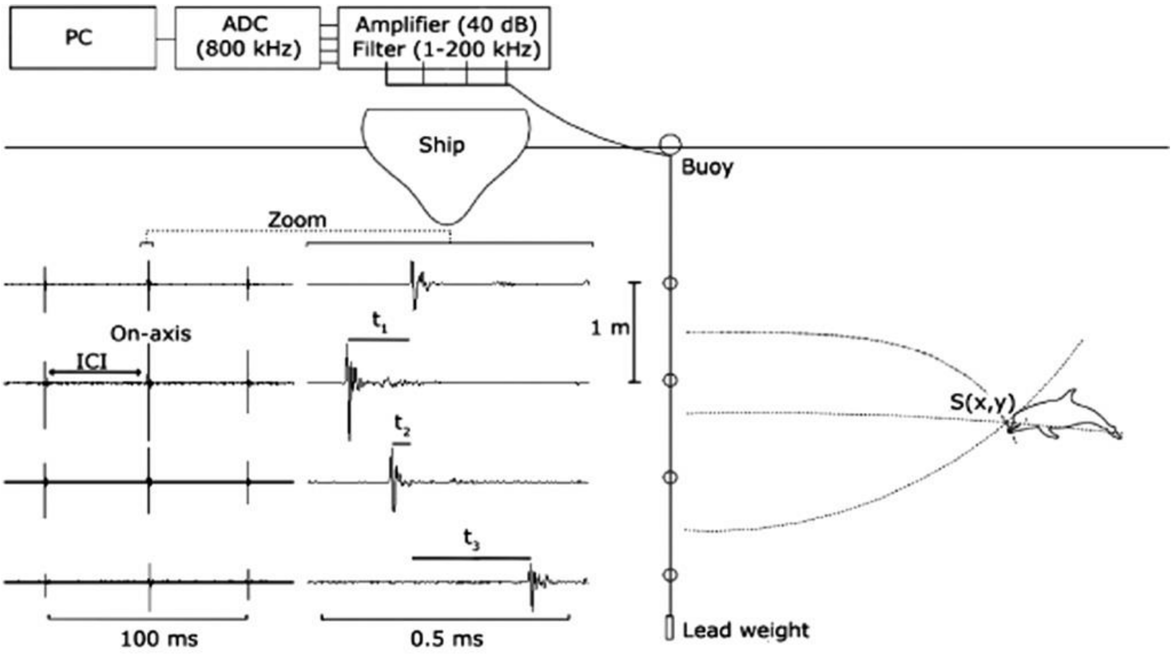


Figure 1. Setup for recordings of *Tursiops aduncus*. The recording setup t1, t2, and t3 are the time-of-arrival differences between the same click arriving on the four different hydrophones.

MATERIALS AND METHODS

Whistle source parameters were calculated using equations. The apparent source level (ASLpp) is defined as the backcalculated sound pressure level 1 m from the source at an unknown angle from the acoustic axis (Møhl *et al*., 2000). It was calculated using the following equation:

$$ASL = RL + TL = RL + 20 \log R + \alpha R \quad (1)$$

Power Spectral Density (PSD) function to equalize the number of rows and columns of data matrix m-file of the results of the voice recording process. Power spectral density is a useful concept to determine the optimum frequency band of the signal transmission system. PSD is a variation of power (energy) as a function of frequency spectrum in the form of density estimated using FFT, PSD method is one of the modern spectral estimation technique proposed during this decade (Stoica and Moses, 1997) Power Spectral value can be obtained equation (2,3 and 4):

$$\lambda = \frac{v}{f} \quad (2)$$

$$\lambda = \frac{C}{f} \quad (3)$$

$$PSD = \frac{|Xn|^2}{f} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \left(\frac{(Amplitudo)^2}{Hz}\right) \quad (4)$$

Whistles were narrowband, frequency-modulated sounds (Herzing, 2000). There were at least five different whistle types, categorized according to their spectral contours (Figure 2). Whistle type 5 was the only whistle that exhibited harmonics and was therefore placed in a category on its own termed harmonic whistles.

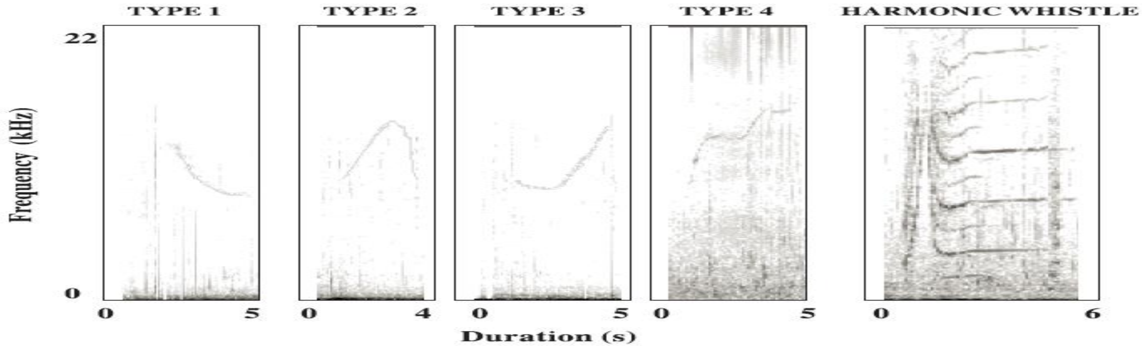


Figure 2. Spectrograms of the five sound whistle types (type 1, type 2, type 3, type 4, and harmonic) of Risso's dolphins (with sampling rate: 44100 Hz, –10 db, FFT 512).

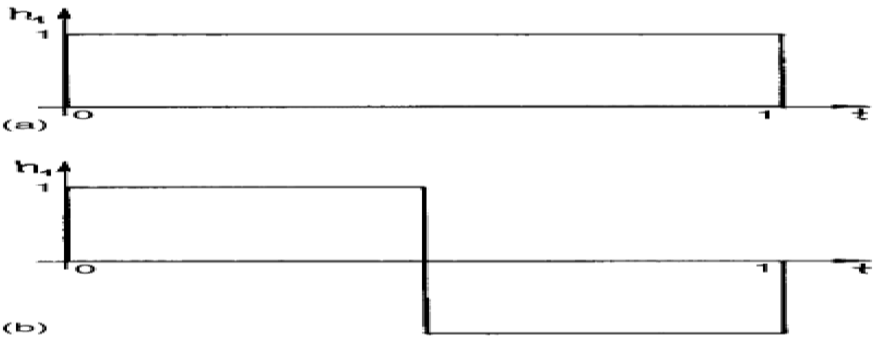


Figure 3. Haar wavelet: (a) scaling function, (b) mother wavelet.

Recording and Sound Analysis

Sounds were recorded with a High Tech SQ 03 hydrophone (sensitivity -162dB re 1VμPa^{-1} @20ºC, frequency response within ±1 dB from 7 Hz to 22 kHz) placed just above the rim of a territorial in aquaria with connected to Sea Phone Sensor (Dolphin Ear), with recording software is Wavelab 6. Sounds were digitized at a rate of 22 kHz (16 bit resolution) and analyzed with Raven Pro 1.5 with sound duration at rate of 500 ms (Cornell Lab of Ornithology).

Haar Wavelet Basis

Further simplification of the solution can be obtained if in each segment only one collocation point is taken. It is assumed that the highest derivative is constant in each segment, therefore this method is called "piecewise constant approximation (PCA)". This method is very convenient in the case of nonlinear differential equations, since for each segment only one nonlinear equation should be solved. This method has been applied by (Hsiao and Wang, 1999).

In 1910 Alfred Haar introduced a function which presents a rectangular pulse pair (Figure 3b). After that various generalizations and definitions were proposed (state-of-the art about Haar transforms can be found in (Stankovic and Falkowski, 2003). In 1980s it turned out that the Haar function is in fact the Daubechies wavelet of order 1. This enabled to introduce the Haar wavelet, which is the simplest orthonormal wavelet with compact support. It should be mentioned that the Haar wavelet has an essential shortcoming: it is not continuous. In the points of discontinuity the derivatives do not exist, therefore it is not possible to apply the Haar wavelet directly for solving differential equations. The Haar wavelet family for $t \in [0, 1]$ is defined as follows:

$$h_i(t) = \begin{cases} 1 \quad For & t \in \left[\frac{k}{m}, \frac{k+0.5}{m}\right) \\ 1 \quad For & \\ 0 \; elsewhere & t \in \left[\frac{k}{m}, \frac{k+0.5}{m}\right), \frac{k+1}{m} \end{cases} \tag{5}$$

Haar wavelet family for $t \in [0, 1]$ have Integer $m = 2^j$ ($j = 0, 1, \ldots, J$) indicates the level of the wavelet; $k = 0, 1, \ldots, m - 1$ is the translation parameter. Maximal level of resolution is J. The index i in (1) is calculated according the formula $i = m + k + 1$; in the case of minimal values $m = 1$, $k = 0$ we have $i = 2$, maximal value of i is $i = 2M = 2^{j+1}$. It is assumed that the value $i = 1$ corresponds to the scaling function for which $h_l \equiv 1$ in [0, 1] and vanishes elsewhere (Figure 3a). The collocation points $tl = (l - 0.5)/(2M)$, ($l = 1, 2, \ldots, 2M$) and discretize the Haar function $hi(t)$; in this way we get the coefficient matrix $H(i, l) = (h_i(t_l))$, which has the dimension $2M \times 2M$. Next the operational matrix of integration P, which is a $2M$ square matrix, is defined by the equation:

$$(PH) \int_0^{t_l} hi(t)dt. \tag{6}$$

The elements of the matrices H and P can be evaluated according to (1) and (2). For instance, if $M = 2$, the result as follow:

$$P_4 = H_4 = \begin{pmatrix} 1 & 1 & 1 & 1 \\ 1 & 1 & -1 & -1 \\ 1 & -1 & 0 & 0 \\ 1 & 0 & 1 & -1 \end{pmatrix} \frac{1}{16} \begin{pmatrix} 8 & -4 & -2 & -2 \\ 4 & 0 & -2 & 2 \\ 1 & 1 & 0 & 0 \\ 1 & -1 & 0 & 0 \end{pmatrix} \tag{7}$$

Source Level (SL)

Before we delve further in active sonar equation though, let's start with a revisit and redefinition of the source level term, SL. In the active sonar equation, the source level is no longer the level of the contact or target, but rather the source level of the projector from the active sonar system. This source level is the level (in dB re 1µPa) of the projector, 1 yard from the object source. To solve for the source level, we can start with the definition of passive source level by Urick (1983) as follow:

$$SL = 10 \log \frac{I_{1yd}}{I_{ref}} \tag{8}$$

Directivity Index (DI)

The directionality and intensity of sound signals are not independentfeatures.Intensity changes with directionality,such that an increase in directionality will lead to a corresponding increase in intensity a long the acoustic axis. The directivity index (DI) of the source reflects this relationship. A DI of e.g. 18 dB implies that sound intensity along the acoustic axis is 18 dB higher than it would be for an omnidirectional sound source radiating sound with the same acoustic power (Figure10). For the piston model, the DI simply follows from the relation between size and wavelength:

$$DI = 20 \log_{10}(k \times a) \tag{9}$$

where $k = 2\pi/\lambda$, λ is the wavelength, and a is the radius of the piston. Using measured data,the calculation of DI is slightly less simple. It requires an estimation of thesound field behind the dolphin and assumes that the beam is rotationally symmetric (Møhl *et al.,* 2003).

The increase in on-axis intensity with increasing directionality also means that increasing thesignal frequency does not necessarily lead to a reduction in detection distance, in spite of the increased atmospheric attenuation at higher frequencies. This is because an increase in frequency increases the signal directionality and there by the on axissound level. Again the situation is simple for the piston model, where a change in frequency from $f1$ to $f2$ leads to a change in DI of:

$$\Delta DI = 20 \log_{10} \left(\frac{f2}{f1}\right) \tag{10}$$

Illustration of experimental research conducted in Safari Park, Cisarua, Bogor Indonesia, with two dolphins showed in (Figure 4).

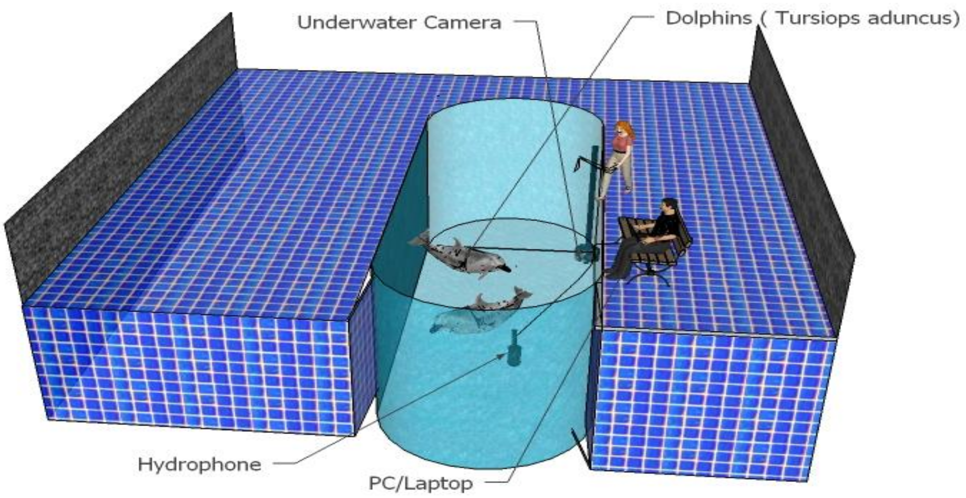


Figure 4. Illustration of experimental research

RESULTS AND DISCUSSION

Data recording performed 4 times peremanan which produces whistle 1, 2,3 and 4. Total duration of each whistle is 0-700 ms on any sound produced. This research of whistle sound from underwater video and sound recordings made between May and June 2015 with video cameras (Gopro Hero 3+) and a SQR 3 hydrophone, flat to 22 kHz with a –192 dB re 1 μPa. Whistles were assigned to specific individuals when a dolphin was alone in the camera/hydrophone vicinity, in sole proximity (<1m) of the camera/hydrophone, or showed simultaneous bubble emissions correlated with a whistle. Whistles were digitized from audio recordings using *Raven Pro 1.5* software (Cornell University, Ithaca, NY, USA) at 44.1 kHz sampling rate (whistle 1, 2, 3, and 4). Analysis of wavelets and Source Level (SL) were run with Matlab R2008b. Result analysis of wavelets using Haar wavelet showed in (Figure 5, 6, 7 and 8).

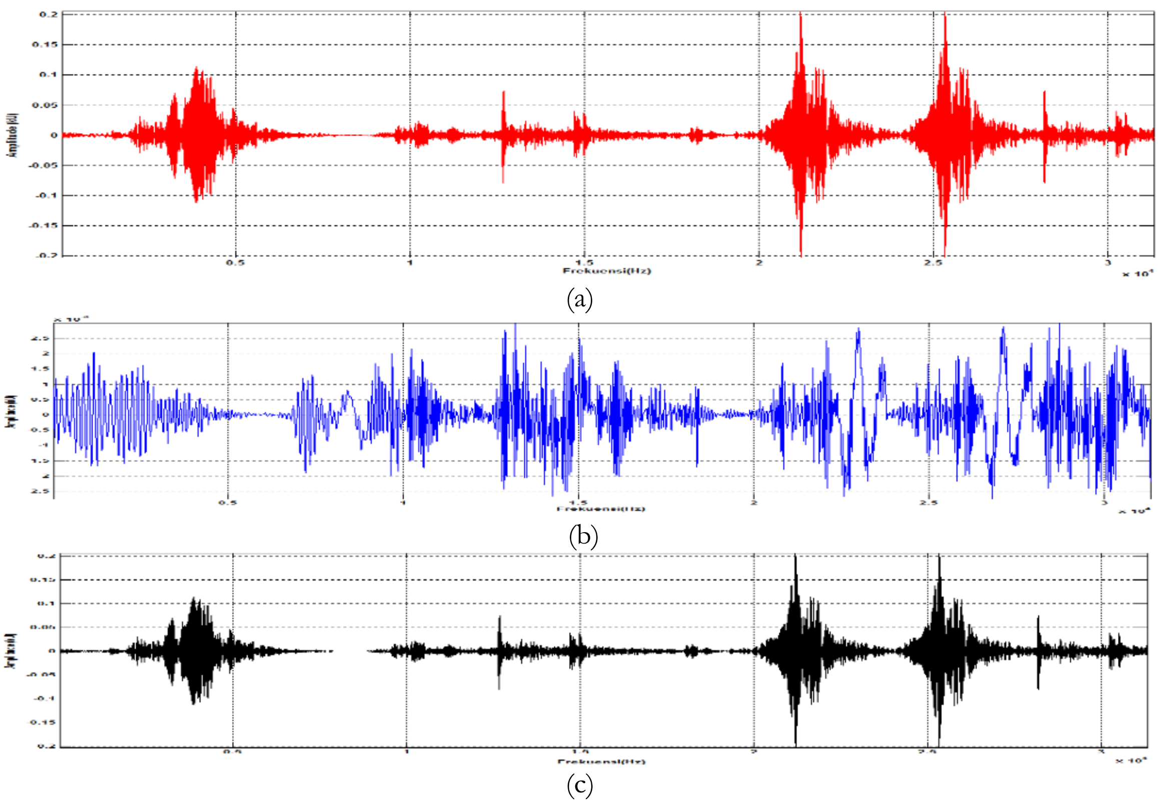
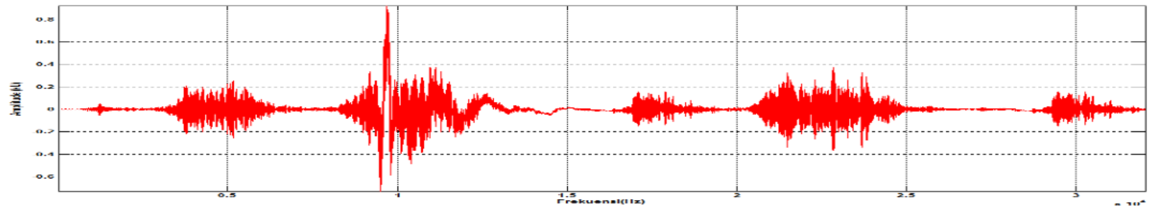
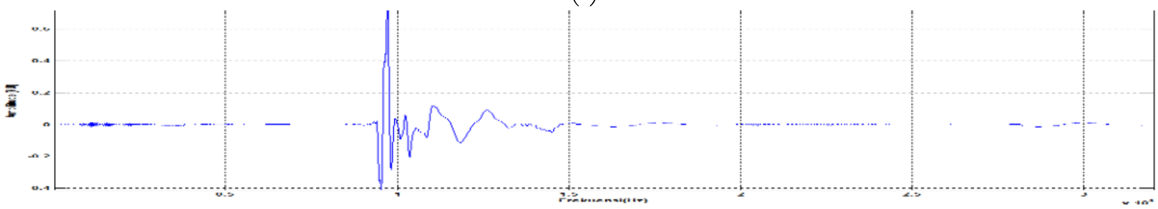


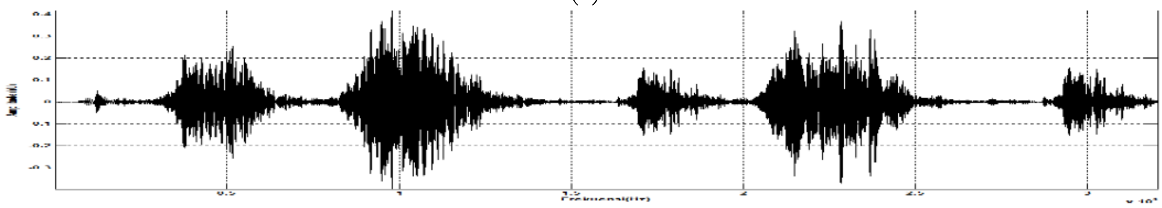
Figure 5. Signal of whistle 1 (a) original signal, (b) denoised signal, (c) residual signal using Haar wavelet



(a)

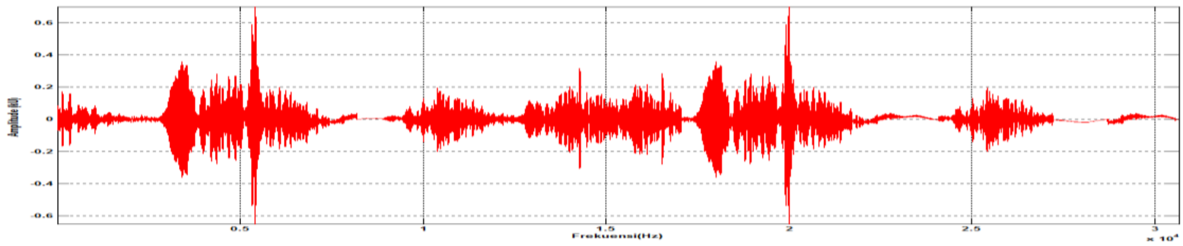


(b)

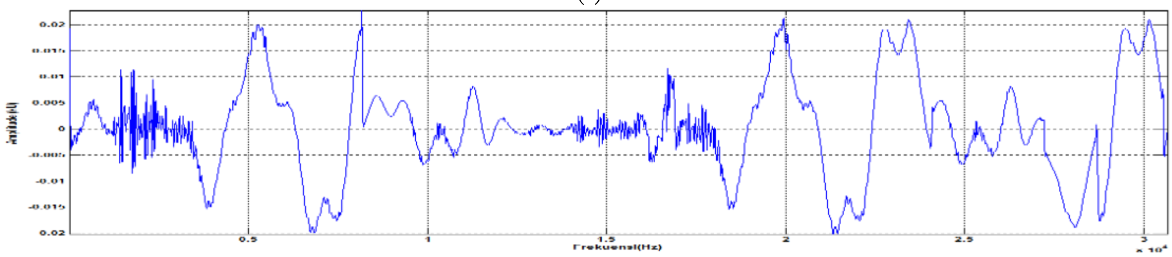


(c)

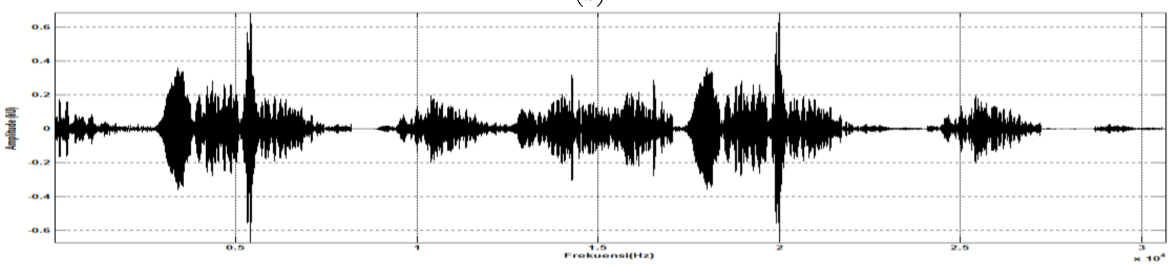
Figure 6. Signal of whistle 2 (a) original signal, (b) denoised signal, (c) residual signal using Haar wavelet



(a)



(b)



(c)

Figure 7. Signal of whistle 3 (a) original signal, (b) denoised signal, (c) residual signal using Haar wavelet

The results showed in (Figure 5,6,7, and 8) is the signal processing using the Haar wavelet. Noised highest in first whistle, while the lowest is on a whistle-noised 2. Rated highest of residual signal contained in the second whistle, whistle while the lowest is 1, it shows that the larger the signal denoised result residual signal generated using Haar wavelet, and noised signal will be significantly affect residual values as well as the pattern and duration of the equation mathematics (Cattani, 2001). Source Level (SL) showed in (Figure 9).

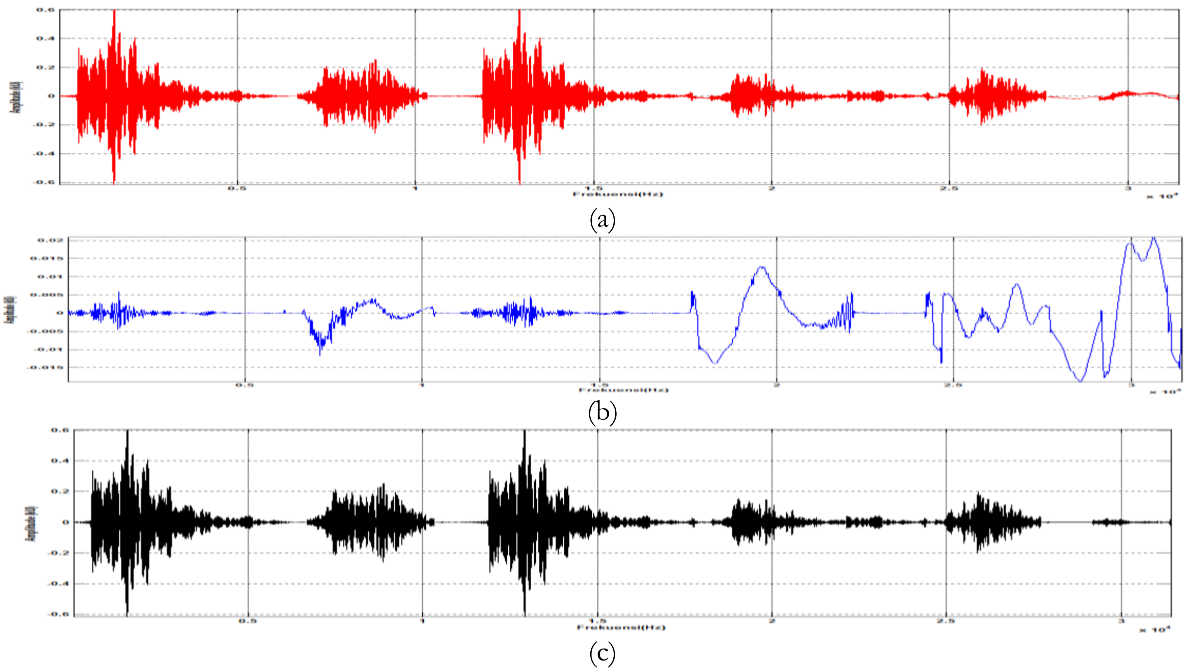


Figure 8. Signal of whistle 4 (a) original signal, (b) denoised signal, (c) residual signal using Haar wavelet

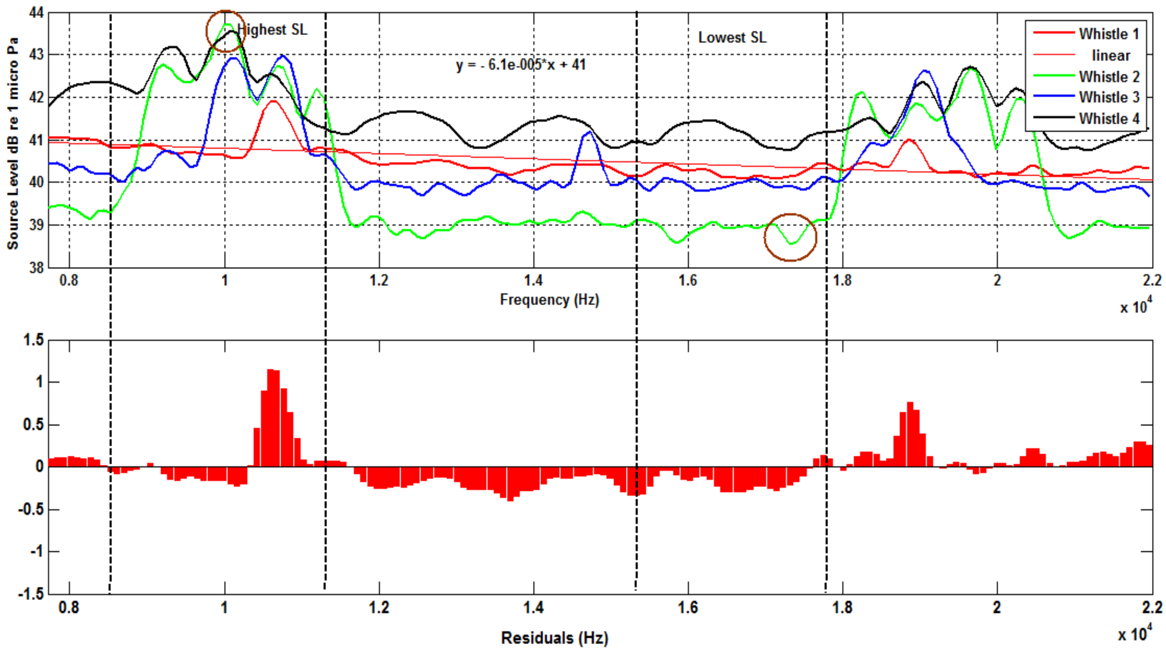


Figure 9. Source Level (SL) of whistle 1, 2,3, and 4.

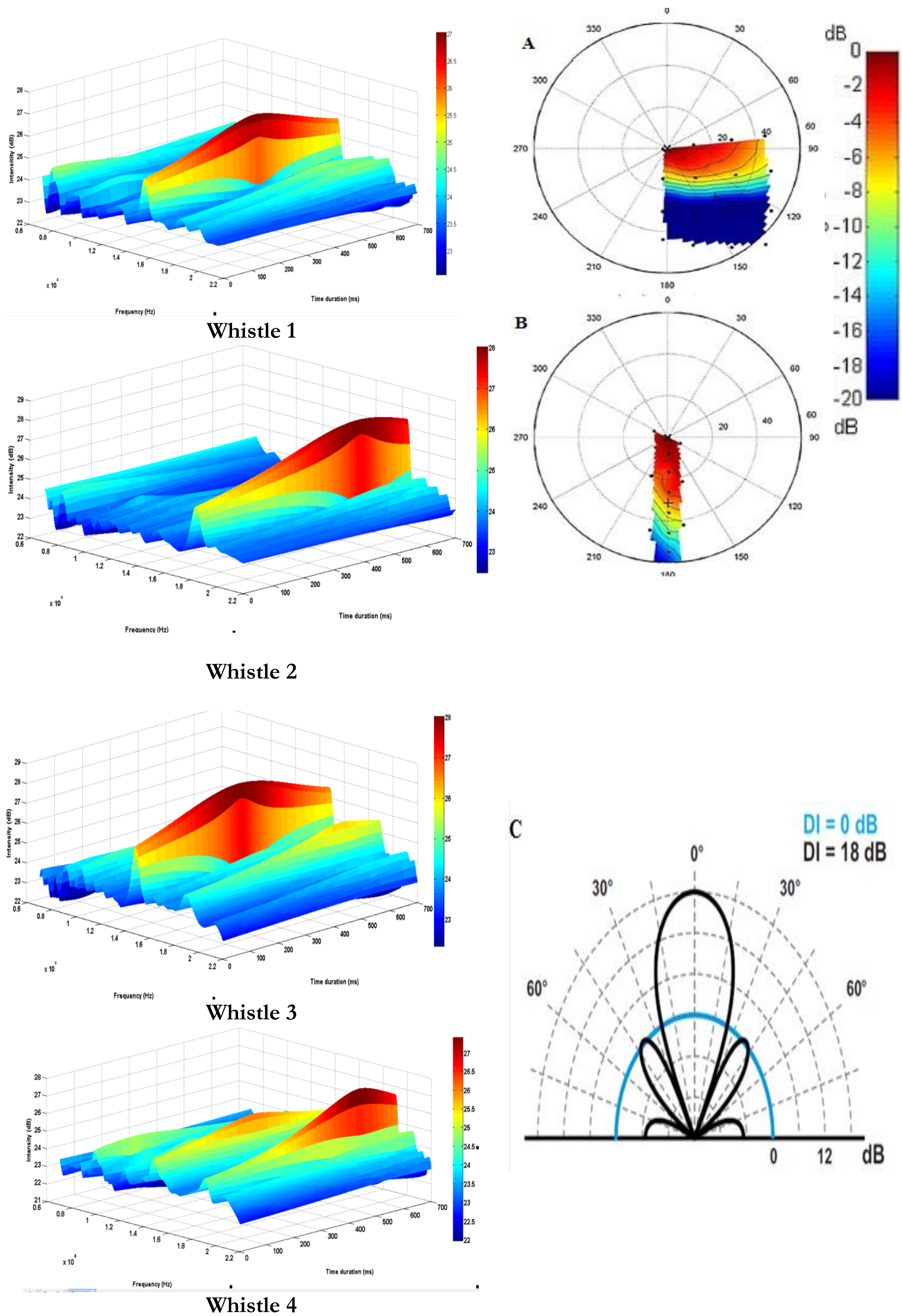


Figure 10. 3D figure (Intensity, Frequency, and Time duration) whistle 1,2,3,and 4 with approach 4 type signal in beam pattern (A, B), beampattern from an omni directional sound source (C).

Source Level (SL) produced by dolphins in quarantine pool with two dolphins. Whistle 1 was showed with red line, Whistle 2 was showed with green line, Whistle 3 was showed with blue line, and Whistle 4 was showed with black line. The highest of Source level value is with frequency range value of 8500 Hz- 11800 Hz, with the highest SL value was 43.9 dB (brown cyrcle). The lowest of Source level with frequency range value is 15700 Hz- 17990 Hz, with a lowest SL value was 38.5 dB (brown cyrcle). The frequency ranged 11800 Hz – 15700 Hz is the mean value from Source Level (SL). Whistle 1, 2, 3, and 4 have a different value SL. SL value was lowest for the second whistle, this is because dolphins are far away from the hydrophones. Distance and volume will affect the value of the resulting frequency (Wulandari *et al.*, 2016; Lubis *et al.*, 2016b), it can be stated with a different frequency. Source Level (SL) value will be also different from each and other. Physical parameters will affect the value of the frequency and magnitude of the object recorded (Lubis and Pujiyati, 2014; Lubis, 2014).

According in Bebus and Herzing (2015) average minimum frequency sound of the whistle is 8090 Hz, the average maximum frequency sound whistle 21030 Hz, it indicates the difference between the minimum frequency of the sound of the whistle to the research conducted is 10 Hz, and the difference between the maximum frequency of the sound of the whistle is 100 Hz. In the study conducted by Janik (2000) obtained maximum value Source Level (SL) of the common bottlenose dolphin is 40 dB with a frequency is 12 kHz, this indicates that there are differences in values Source Level (SL) obtained from this study, in this study derive maximum value SL is 29 dB with a frequency is 16 kHz. Value Source Level (SL) conducted in an captivity, Safari Park, Indonesia have smaller value than studies (Rasmussen *et al.,* 2006, Jakobsen *et al.,* 2013; Wahlberg *et al .,* 2011), earning the Source Level (SL) is 43.9 dB with a frequency of 10 kHz, this shows the frequency value with the same, but the value Source Level (SL) is different. 3D figure (Intensity, Frequency, and Time duration), approach signal in beam pattern, and Beampattern from an omni directional sound source (DI = 0 dB, cyan trace)and a directional source following the piston model (DI = 18 dB, black trace). The source sradiate sound of equal acoustic power showed in (Figure 10).

CONCLUSIONS

Signal of dolphin sound (*Tursiops aduncus*) recording in Safari Park, Cisarua, Bogor Indonesia have frequency ranged between 8 kHz to 22 kHz and residual signal contained in the second whistle, whistle while the lowest is 1, it shows that the larger the signal denoised result residual signal generated using Haar wavelet. Each source level values obtained in noise 1,2,3, and 4 have differences with each other, it shows the same target but SL value and the sound patterns remain distinct by looking at time duration of whistle sound. Implementation of the results of this study can be used as a reference as the caller dolphin with active acoustic way in the sea.

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