研 究 解 説

Towards Identification of Sperm Whales from Their Vocalizations

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I. INTRODUCTION

Sperm whales (*Physeter macrocephalus*) (see Fig. 1) are known to produce loud impulsive broadband sounds called "clicks" at various repetition rates. Apart from the usual clicks, they also produce "creaks" that are very rapid clicks emitted for limited durations. Each click also has a multi-pulse structure. Various studies have been conducted[1-3] regarding the time and frequency characteristics of sperm whale clicks and creaks. Some insight has also been provided into the bio-sonar and inter-whale communication aspects of sperm whale clicks. However, conclusive evidence of the purpose of the clicks (and creaks) vis-à-vis the dive cycle has not been forthcoming so far[3].

The purpose of our study is a systematic attempt to fill this gap in the knowledge. Our attempt is to study a group of vocalizing sperm whales that would necessarily be in different modes of their individual dive cycle or any other routine. Such a study would require adequate isolation of individual sperm whale vocalizations in time and space so that each animal's behavior is properly studied. This paper demonstrates the feasibility of isolating individual animal's clicks based on signal processing techniques.

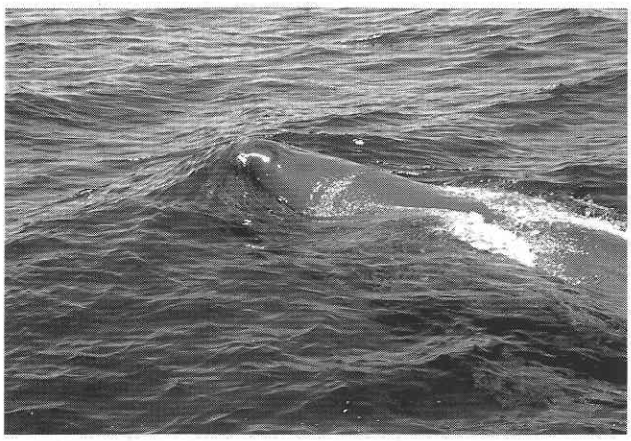

Fig. 1　Sperm whale seen off Ogasawara islands

II. DATA COLLECTION

The major known features of sperm whale clicks are:

- ◆ Click duration is 10–20 milliseconds
- ◆ Click rate is usually between 0.5 to 2 clicks per second
- ◆ Creaks can have a rate as high as 200 clicks per second
- ◆ Each click may have several pulses of decaying amplitude
- ◆ Bandwidth is very wide with significant energy up to 15 kHz.

The recordings of sperm whale vocalizations were made in early August 2002 during an expedition to Ogasawara islands. Figure 2

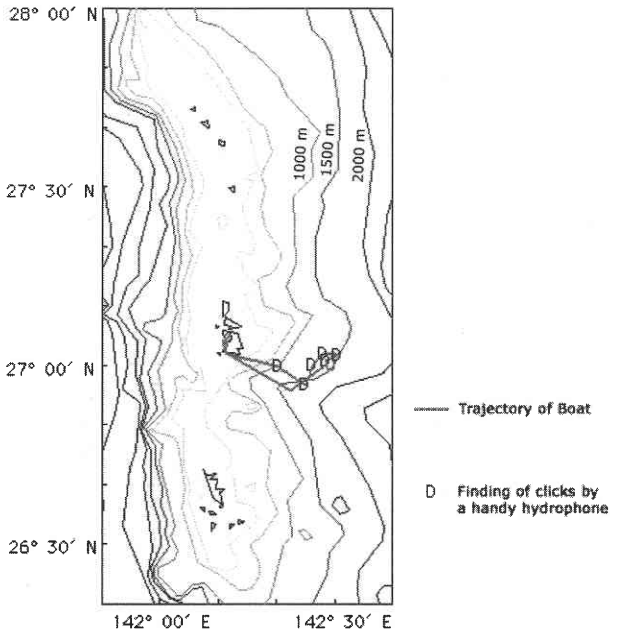

Fig. 2 Map showing the search trajectory and finding of sperm whale clicks

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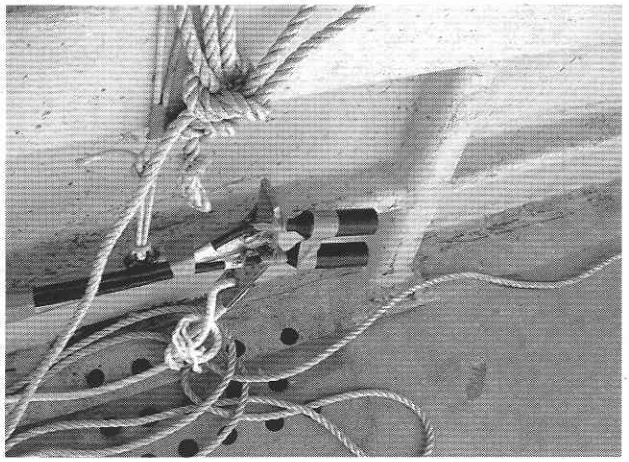

Fig. 3　Hydrophone pair used for recording

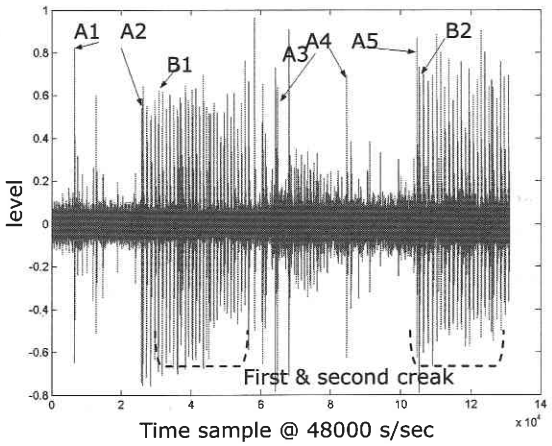

Fig. 5　High pass filtered signal

shows the search trajectory and the locations (mainly at ocean depths between 1000–1500 meters) where sperm whale clicks were picked up.

The sperm whale signals were picked up by a pair of hydrophones with sensitivity better than −200 dB re 1V/μPa (10 Hz to 30 kHz) separated by 75 mm (see Fig. 3). The hydrophone signals were passed through amplifiers with a gain of 40 dB ± 0.1 dB between 1 kHz to 100 kHz, and recorded in 2-ch Sony TCD D10 DAT recorder at a sampling rate of 48 kHz.

Recordings have been stored on CDROM in 16-bit stereo 'wav-file' format for further analysis. The major analysis platform is the MATLAB. The following sections describe the step-by-step signal processing tasks for extraction and parameterization of the clicks.

III. SIGNAL CONDITIONING

The sperm whale sounds were recorded with hydrophones just below the sea surface. The recorded signals, therefore, have significant low frequency ambient noise (Fig. 4). This made it difficult to acquire the short clicks with reasonable S/N ratio. It was decided to filter the recorded signals through a 5 kHz high pass linear phase FIR filter (31-sample Least Squares). Figure 5 shows improvement in S/N offered by the filter since it rejects most of the low frequency interference.

Subsequent signal processing has been performed using the filtered signals of both hydrophones.

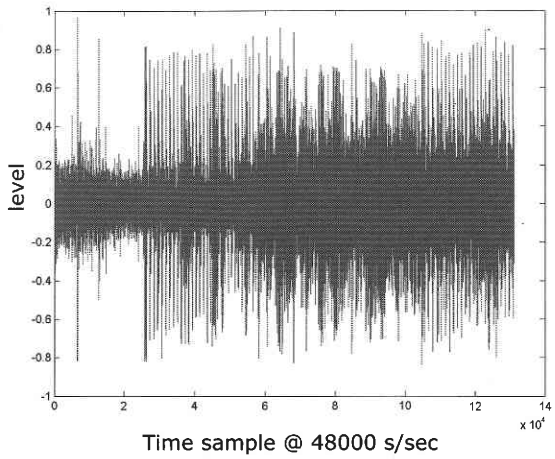

Fig. 4　Raw hydrophone signal

IV. CLICK CORRELATION

A first step towards identification of sperm whales is to cross-correlate an isolated click with a signal segment. In the event that the reference click is similar to the signal at a particular time a large correlation peak would result, else the correlation will be small or poor. The signal in Fig. 5 was cross-correlated by using certain clicks from the same sequence as references.

Figures 6 and 7 show the result of correlation of the test signal with the non-creak click A1 and the creak click B1, respectively. The correlation of click A1 with most of the creak clicks is very

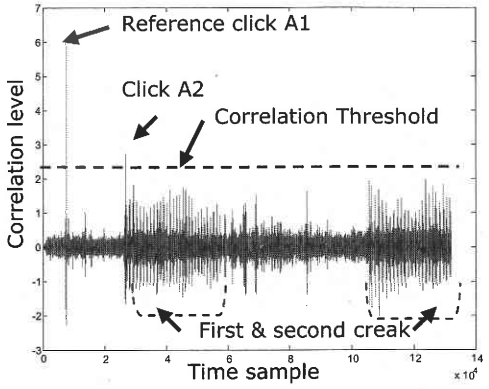

Fig. 6　Correlation with click A1

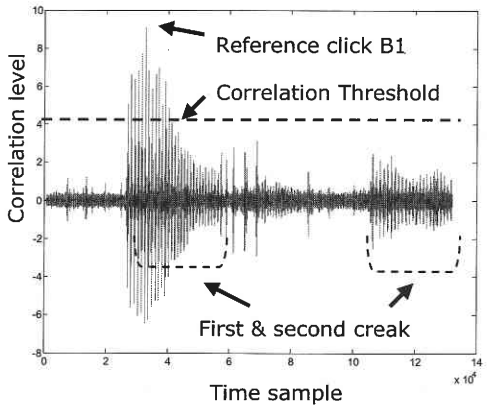

Fig. 7　Correlation with click B1

small (below the dotted line) except with itself and with one click A2 just before the onset of the first creak.

The correlation of click B1 (Fig. 7) is very high (several clicks above the dotted line) with the neighboring clicks within the creak, while it is very low with click A1 and click A2.

The above results demonstrate that clicks within and outside the creak belong to different animals. However, it is to be noted that the correlation falls with increasing distance from the reference click even for the same animal. We, therefore, need more convincing analysis to associate clicks with specific individuals.

V. INTER-PULSE INTERVAL

The second characteristic that provides good clues about the identity of the clicking individual is the phenomenon of multiple pulses within each click. The multiple pulses are thought to arise due to repeated reflections between the frontal and distal air sacs in the sperm whale's head (Fig. 8).

Since the distance between the two air sacs separated by the spermaceti oil sac depends on the size of the animal, it is expected that the time gap between multiple pulses would depend on the size of the animal. The "inter-pulse interval" (IPI) may thus, be regarded as a distinguishing feature between individual animals. Figure 9 shows a typical click with the multiple pulse structure clearly visible.

Signals consisting of multiple delayed replicas can be considered to arise by a process of convolution with the "channel" impulse response. Cepstrum is an important tool used in homomorphic filtering (or deconvolution) that reveals the multiple-pulse structure of such signals. It is convenient to extract the IPI by simple thresholding of the cepstrum beyond the initial click duration. Figures 10 and 11 show cepstrum and the IPI for two different clicks.

It is evident from the cepstrum results that the two clicks arise

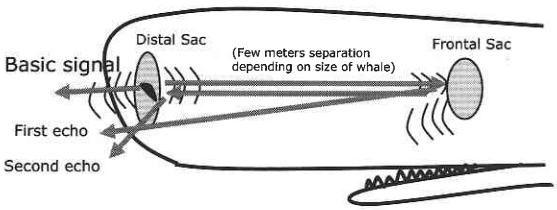

Fig. 8　Multiple pulse generation in the sperm whale

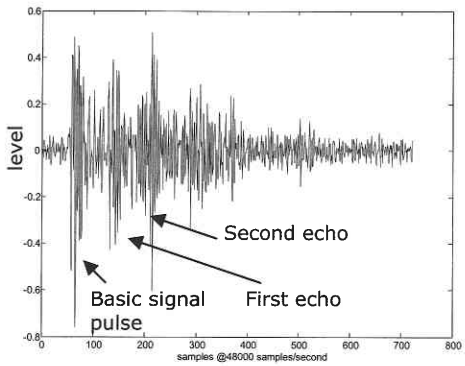

Fig. 9　Typical click showing multiple pulse structure

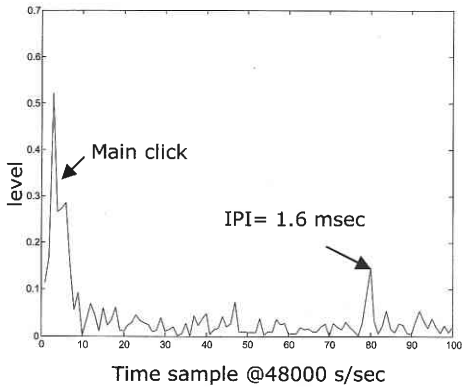

Fig. 10　Cepstrum of non-creak click A1

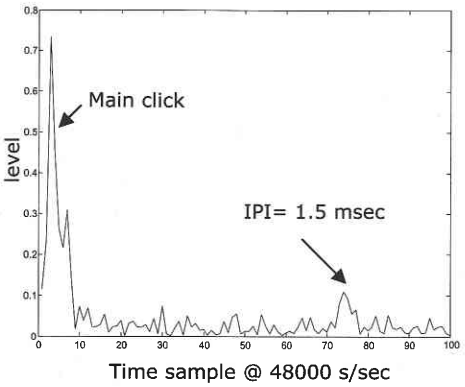

Fig. 11　Cepstrum of creak click B1

from animals of different size as indicated by the difference in the IPI (1.6 msec and 1.5 msec): click B1 is perhaps generated by a smaller animal than that of click A1.

We can, therefore, reinforce the results of correlation with cepstrum analysis to further discriminate the clicks and to distinguish the particular vocalizing animals.

VI. TIME DELAY ESTIMATION

The results of the previous two sections have suggested a reasonable method to discriminate between clicks from the recording of a single hydrophone. There could, however, be ambiguities in associating the clicks with individual animals, unless spatial localization is carried out. One simple method to spatially segregate the sounds is by time-delay estimation (TDE) between two or more hydrophones. The angle of arrival of a wavefront determines the inter-hydrophone time delay which, in turn depends on the spatial orientation of the hydrophones. We carried out TDE of isolated clicks between the two hydrophones (Figs. 12 and 13) used in our data collection exercise.

Since we need very high time resolution to find the time delay between the two hydrophone signals, we performed interpolation

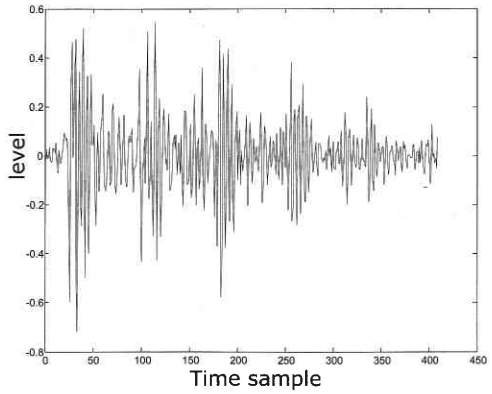

Fig. 12　Isolated click on left hydrophone

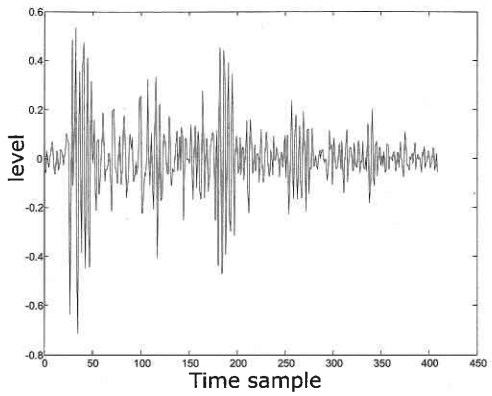

Fig. 13　Isolated click on right hydrophone

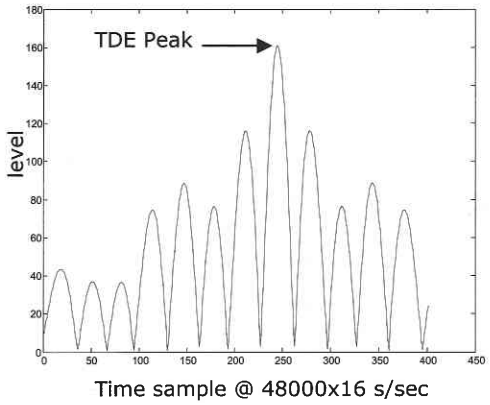

Fig. 14　Expanded view of auto-correlation peak of left hydrophone

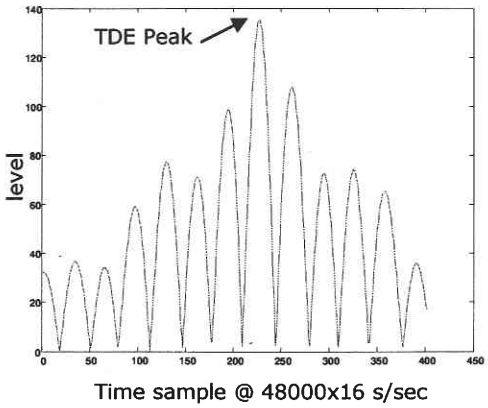

Fig. 15　Expanded view of the cross-correlation

by a factor of 16 to get a data rate of 48000x16 samples/sec.

Figure 14 shows the autocorrelation peak occurring at time sample #245, while Fig. 15 shows the cross-correlation peak between the two hydrophones at sample #225. The time difference of 20 samples is an indicator of the angle of arrival of the wavefront at the hydrophones.

VII. IDENTIFICATION RESULTS

We applied the above TDE technique on various clicks indicated in Fig. 5. It was confirmed that the set of clicks A1, A2, A3, A4 and A5 have similar time delay and so they arrive from one location. Clicks B1 and B2 from the two creaks have similar time delay but are different from the previous set, hence they come from another location. In view of the correlation results, IPI values and TDE estimates obtained from the recorded data, it can now be broadly said that clicks A1-A5 come from one animal (whale A), while clicks B1 and B2 (in the two creaks) belong to another animal (whale B). The identification results for the two specific whales are indicated in Fig. 16.

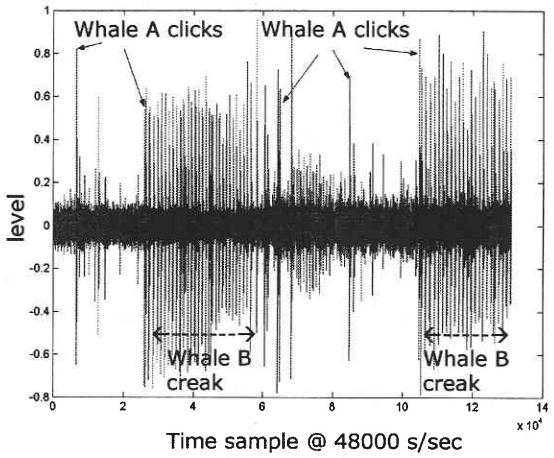

Fig. 16　Identification results

A more comprehensive analysis based on the above techniques would reveal the identity of several other clicks that are present in the data.

VIII. CONCLUSIONS

The above analyses on sperm whale clicks provide us characterization of the individual animals. Correlation is useful in segregating adjacent clicks, but it is not a strong enough indicator beyond a few clicks even for the same animal. IPI analysis helps in determining animal size and can be used in association with the correlation level for identifying the concerned animal. Finally, TDE between two hydrophones provides us with spatial evidence for segregating animals. The three techniques when used together are seen to help in identifying the individual sperm whales.

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