CLICK DISCRIMINATION IN THE DOLPHIN

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1. ABSTRACT

A bottlenose dolphin was able to discriminate between a square pulse and its replica filtered through a second-order all-pass circuit. The signals had identical and flat energy spectra but different phase spectra. However, the dolphin could not distinguish a double-pulse from the single pulse passed through the all-pass circuit at a certain pole quality factor of the circuit despite considerable differences in the signal energy spectra.

KEY WORDS: discrimination; click; waveform; phase spectrum

2. INTRODUCTION

Dubrovskiy et al. [1] found that the dolphin was able to discriminate the double-click comprised of a small and a large click from its time reversed counterpart. The mirror image double-clicks had identical energy spectra, but theoretically they could be identified by their phase spectra. The dolphin discriminated between the double-clicks at an interclick interval as small as 5 µs.

A short-time spectral analysis in the dolphin was suggested as an alternative to the phase analysis of the double-clicks with identical energy spectra. Johnson et al. [2] used windowed FFT analysis to demonstrate differences in the short-time spectrum of a "direct" and a "time-reversed" double-click for a 200-µs interclick interval. A flat energy spectrum of the first smaller click turned into a highly rippled spectrum of the double-click as the second larger click entered a 300-µs chi-square window. Very little rippling occurred for the reverse double-click. However, with the auditory time resolution as high as around 25 µs, Zaslavskiy [4], the dolphin could discriminate the double-clicks by a difference in the temporal order of a small and a large click Zaslavskiy [5]. Results of our experiments suggested that the dolphin might discriminate the mirror image double-clicks in the time domain for interclick intervals even smaller than the auditory time resolution.

In the present paper, we examined the chances of the single click discrimination by the dolphin in the time domain. First, the dolphin's discrimination between the single clicks with identical energy spectra was investigated. Second, the dolphin was presented with clicks, which had different energy and phase spectra but were similar in waveforms. Clearly, there are no two signals with the same waveform and different frequency spectra. However, we found a couple of signals, which could be considered, within the frequency range of the dolphin hearing, similar in waveforms in spite of differences in the frequency spectra.

3. MATERIALS AND METHODS

In order to produce the clicks with identical energy spectra, we used a second order all-pass circuit, Sedra and Smith [3]. The all-pass circuit is characterized by the *pole frequency* (ω_0) and the *pole quality factor* (Q). The magnitude response of the all-pass function was constant over all frequencies (figure 1). The frequency selectivity of the all-pass function was in its phase response. The phase shift reaches 180 degrees at the *pole frequency*. By changing a Q factor, the phase gradient around the *pole frequency* could be varied (figure 1). The transient response of the all-pass filter to a square pulse could also be controlled by the same circuit parameters ω_0 and Q.

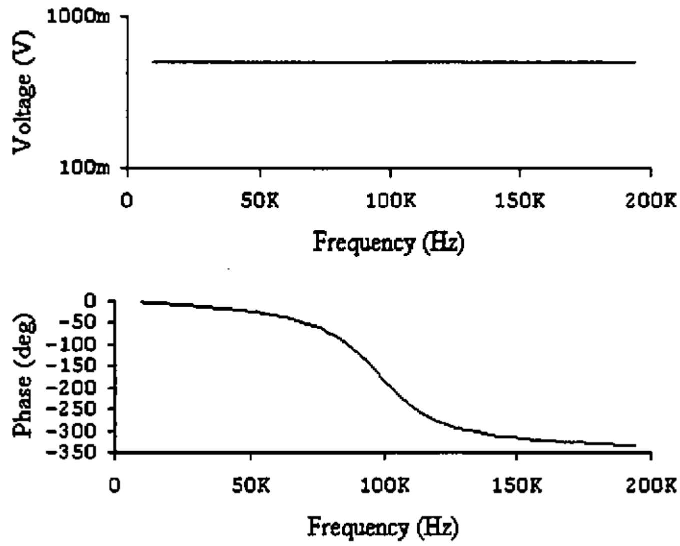

Figure 1. Magnitude and phase response of the second order all-pass circuit for the *pole frequency* of 100 kHz and *pole quality factor* of 3.

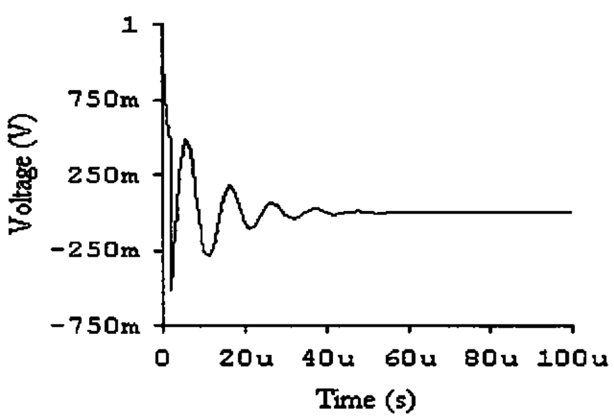

Figure 2. Transient response of the second order all-pass circuit to a 2-µs square pulse for the *pole frequency* of 100 kHz and *pole quality factor* of 3. Time scale is in microseconds.

The subject was a bottlenose dolphin (*Tursiops truncatus*). Experiments were conducted in a 28 × 13 × 4 m concrete pool. A two-response forced-choice procedure was used. A vertical net partition between two transducers (1.2 cm in diameter) set a minimum distance of 5 m, from which the dolphin made his choice. Signals were presented simultaneously through transducers situated on either side of the partition at 1m depth and 3 m from each other. Prior to stimuli presentation, the dolphin positioned itself at the far (from the transducers) end of the partition. Having made its choice the dolphin swam to the chosen transducer. The stimuli repetition rate was 3 - 5 per second. Transducer reaction to a 2-µs electrical square pulse was a 25-µs acoustic click with a peak frequency at 110-120 kHz. Sensation level of the stimuli was around 40 dB. Stimuli parameters were monitored on the electrical side of the transducers and in water, using a B&K 8103 hydrophone. The signal discrimination thresholds were measured with the method of constant stimuli. The animal performed around 300 trials per session. Experimental results from the last 3 – 4 sessions were averaged for each threshold estimate at the 75% correct response level. Computer simulation of a pass band filter was used to evaluate a suggested discrimination model.

In the first series of experiments, the dolphin was required to discriminate between a 2-µs square pulse and its replica filtered through the second order all-pass circuit (we named this filtered pulse the "all-pass pulse"). The energy spectra of the signals were identical and flat within the dolphin hearing range but their phase spectra were different. The phase spectrum of the square pulse was practically flat within the frequency range of the dolphin hearing, whereas the phase spectrum of the all-pass pulse abruptly changed near 100 kHz (figure 1). The experiments started with $Q = 5$. The dolphin was trained to approach the transducer of the all-pass pulse. It took the dolphin only several trials to learn the difference in the signals. The minimum value of a Q factor, at which the dolphin still was able to discriminate between the stimuli, was measured.

In the second series of experiments, the dolphin discriminated between the all-pass pulse (figure 2) and the double-pulse (figure 3). The interval between the pulses in the double-pulse was 10 µs.

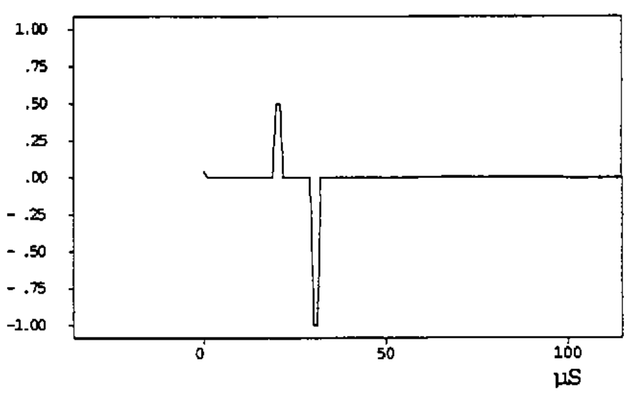

Figure 3. The double-pulse with 10-µs interval and 6-dB difference in the pulse amplitudes.

The amplitude spectrum of the double-pulse had only one minimum within the frequency range of the dolphin hearing at 100 kHz (figure 4), the same frequency as the pole frequency of the all-pass circuit (figure 1). In contrast to the flat amplitude spectrum of the all-pass pulse, the amplitude spectrum of the double-pulse has a deep trough at 100 kHz. It appeared that the dolphin could discriminate the signals by differences in energy spectra or simply in intensities. However, there was a chance that the dolphin would fail to discriminate the signals at some Q factor. The idea to examine whether the dolphin would be able to discriminate between the signals with very different energy spectra was brought about by the results of the dolphin's discrimination the mirror image double-clicks, Zaslavskiy [5]. We found that in order to discriminate the double-clicks, the dolphin analyzed frequency band around the minimum in the amplitude spectra where a rapid change in the phase spectra occurred. Namely, to discriminate the double-pulse shown in figure 3 from its time-reversed replica, the dolphin used the auditory filter centered at 100 kHz. It seemed very likely that the dolphin would also extract needed information from the frequency area covering an abrupt jump in the phase spectrum of the all-pass pulse at 100 kHz (figure 1).

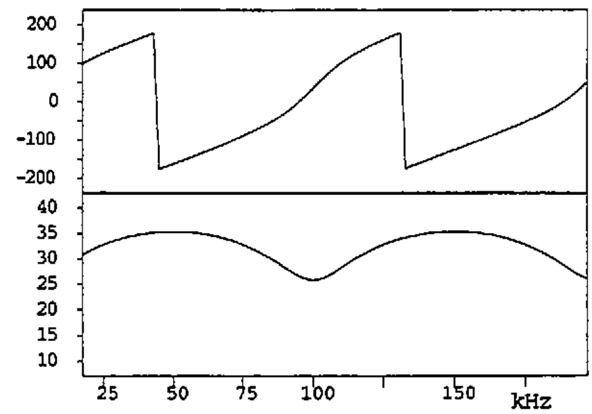

Figure 4. The phase (top block) and amplitude (bottom block) spectra of the double-pulse shown in figure 3. Y-scale is in degrees and dB, respectively.

The reactions of the pass band filter centered at 100 kHz to the double-click (figure 5) and to the all-pass pulse (figure 6) could be described as consisting of a small pulse followed by a large pulse. A gap between the pulses depends on the filter order and bandwidth.

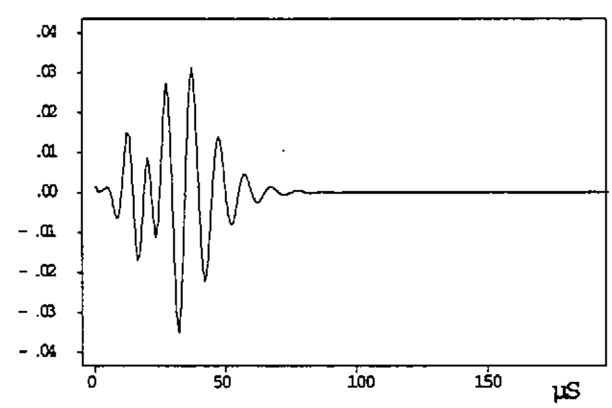

Figure 5. The reaction of the pass band filter (90-110 kHz, 6-order, Butterworth) to the double-pulse shown in figure 3.

The smaller the Q factor, the smaller the amplitude of the first pulse in the reaction of the pass band filter to the all-pass pulse (figure 6 and 7). By changing the Q factor of the all-pass circuit, the filter reaction to the all-pass pulse and the double-pulse could be made similar. The similarity here means that the both signals could be described as consisting of a small pulse followed by a large pulse with approximately the same difference in the pulse amplitude. At any other position of the pass band filter aside from the 100 kHz, its reactions to the all-pass pulse and to the double pulse were smooth and similar to the filter reaction to a single square pulse.

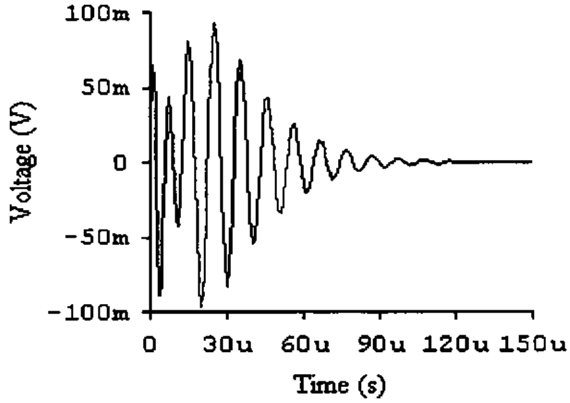

Figure 6. The reaction of the pass band filter (90-110 kHz, 6-order, Butterworth) to the all-pass pulse shown in figure 2. Time scale is in microseconds..

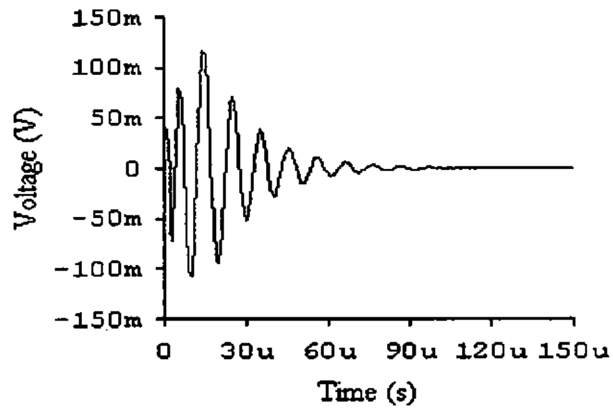

Figure 7. The reaction of the pass band filter (90-110 kHz, 6-order, Butterworth) to the all-pass pulse for the *pole quality factor* of 1. Time scale is in microseconds.

Should the dolphin analyze the reactions of the auditory filter centered at 100 kHz, it might fail to discriminate between the all-pass band and the double-click despite the differences in their frequency spectra. The experiments started with discrimination between the double-pulse and the all-pass pulse for Q = 1. The amplitude of the single pulse was equal to the amplitude of the larger pulse of the double-pulse. The dolphin was trained to approach the transducer of the double-pulse, which was an easy task for him. A Q factor was gradually increased, in order to make the waveforms of the all-pass pulse and the double-pulse identical for the dolphin. The dolphin's performance as a function of a Q factor was measured.

4. RESULTS AND DISCUSSION

The dolphin was able to discriminate a 2-µs square pulse from its replica passed through the all-pass circuit for Q factors larger than 3 (figure 8).

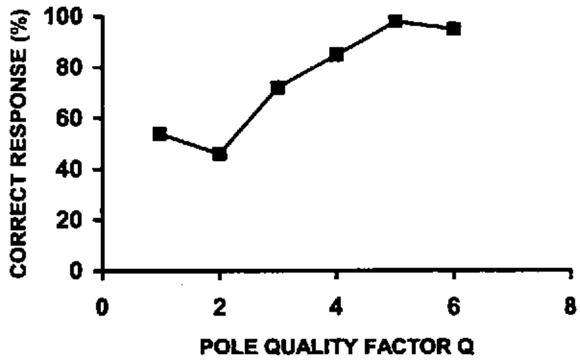

Figure 8. The dolphin's discrimination between a 2-μs square pulse and the all-pass pulse as a function of the *pole quality factor*.

The dolphin distinguished between the clicks of identical and flat energy spectra when the phase spectra were different enough. It might have signified that the dolphin analyzed the phase spectra of the signals, if the signals have had the same waveform. Should the dolphin used the auditory pass band filter at 100 kHz, the waveform of the filter reaction to the all-pass pulse (figure 6) would differ significantly from that to a 2-μs square pulse.

The results of the dolphin's discrimination between the double-pulse and the all-pass pulse certainly suggest the time domain auditory analysis of the signals. Despite the considerable differences in the phase and amplitude spectra, the dolphin could not discriminate the signals for Q = 4 (figure 9).

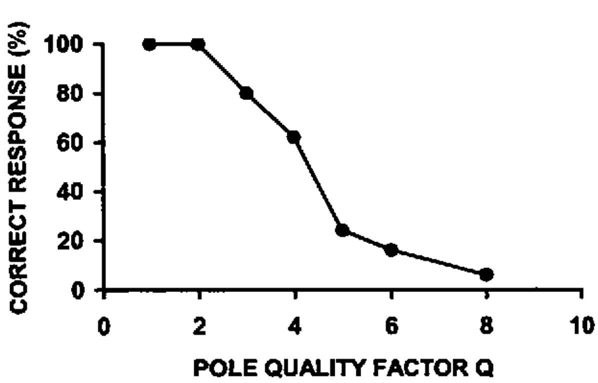

Figure 9. The dolphin's discrimination between the double-pulse and all-pass pulse as a function of the *pole quality factor* Q. Amplitude difference between the first and the second pulses of the double-pulse was 6 dB.

For a Q factor of 4, the waveforms of the double-pulse and the all-pass pulse were similar when compared at the output of the pass band filter centered at the abrupt change in the phase spectra (figure 5 and 6). Our suggestion that the dolphin might discriminate between the all-pass pulse and the double-pulse by differences in the waveform of the auditory filter reactions appeared to be correct. A specific combination of the amplitude and phase spectra caused the time domain waveforms of the all-pass pulse and the double-pulse to be indistinguishable for the dolphin. The dolphin appeared not to be concerned about the small details of the waveform, but rather judged the signals by distinctive differences in the waveform. In fact, the waveforms were different at any Q factor because the frequency spectra of the signals were different.

The decrease in the correct response below 50 % in figure 9 means that the dolphin changed a positive stimulus from the double-pulse to the all-pass pulse. For a Q factor larger than 4 the dolphin persistently approached the transducer transmitting the all-pass pulse. Computer simulation showed that as a Q factor was increased the smaller first part of the filter reaction in figure 6 to grow until it reached the amplitude of the second part, with a gap between the two more distinctive than that in the filter reaction to the double-click (figure 5). The criterion of a positive stimulus for the dolphin appeared to be a degree of separation between the two parts of the filter reaction.

When compared at the output of the pass band filter centered at the pole frequency, the differences in waveform between the all-pass pulse and 2-μs square pulse are similar to that between the double-pulse (figure 5) and its time-reversed image, Zaslavskiy [5]. This suggests that the dolphin might discriminate between the double-clicks with identical energy spectra in the time domain at interclick intervals as small as at least 10 μs.

Surprisingly, the dolphin could not discriminate the all-pass pulse from the double-pulse by differences in the energy spectra. By all accounts, the dolphin appeared to be able to discriminate between the signals with considerable differences in the frequency spectra. The critical bands of the dolphin auditory system are narrow enough to unveil a wide and deep trough at 100 kHz in the energy spectrum of the double-pulse. On the other hand, there is no direct evidence of dolphin's ability to analyze frequency spectrum of short pulses.

5. CONCLUSIONS

The dolphin was capable of discriminating between the clicks of identical and flat (without ripples) energy spectra when their phase spectra were sufficiently different. However, the dolphin could not distinguish between the clicks with considerable differences in the energy and phase spectra if their waveforms were similar when compared at the output of the pass band filter centered at the pole frequency. The results suggest that the dolphin discriminated between the clicks in the time domain. The time domain analysis of the clicks appears to be even finer than the dolphin's auditory time resolution of 20-30 μs, Zaslavskiy [4].

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