

Modeling of the Dolphin's Clicking Sound Source: The Influence of the Critical Parameters¹

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Abstract—A physical and a mathematical models of the dolphin's source of echolocation clicks have been recently proposed. The physical model includes a bottle of pressurized air connected to the atmosphere with an underwater rubber tube. A compressing rubber ring is placed on the underwater portion of the tube. The ring blocks the air jet passing through the tube from the bottle. This ring can be brought into self-oscillation by the air jet. In the simplest case, the ring displacement follows a repeated triangular waveform. Because the acoustic pressure gradient is proportional to the second time derivative of the displacement, clicks arise at the bends of the displacement waveform. The mathematical model describes the dipole oscillations of a sphere “frozen” in the ring and calculates the waveform and the sound pressure of the generated clicks. The critical parameters of the mathematical model are the radius of the sphere and the peak value and duration of the triangular displacement curve. This model allows one to solve both the forward (deriving the properties of acoustic clicks from the known source parameters) and the inverse (calculating the source parameters from the acoustic data) problems. Data from click records of Odontocetes were used to derive both the displacement waveforms and the size of the “frozen sphere” or a structure functionally similar to it. The mathematical model predicts a maximum source level of up to 235 dB re 1 μ Pa at 1-m range when using a 5-cm radius of the “frozen” sphere and a 4-mm maximal displacement. The predicted sound pressure level is similar to that of the clicks produced by Odontocet. © 2004 MAIK “Nauka/Interperiodica”.

1. INTRODUCTION

In our previous publications, we have suggested that the clicking source of dolphins is driven by the air pressure created in the upper respiratory tract either by lungs or by air sac muscles [1–3]. The essential feature of this suggestion is the formation of an air jet through the nasal passage that is blocked by a sphincter (a muscle plug, a lip). A physical model of the nasal passage was implemented (Fig. 1). The model consists of (1) a displacement sensor attached to (2) a rubber ring, which is put on (3) a rubber tube opened at one end and attached to a high-pressure gas bottle at the other end [1–3]. The rubber ring blocks the air passage through the tube. When the air pressure in the tube increases, the rubber ring begins to perform typical self-oscillations during which the tube is periodically opened for short periods of time (Fig. 1). The displacement sensor (see Fig. 1) measures the movements of the ring whose surface shows different displacement waveforms. In the simplest case, the displacement waveform is triangular. The oscillating ring is the source of acoustic clicks, which are time-locked to the bends of the displacement curve. This observation is in accord with the acoustic Euler equation stating that the pressure gradient is proportional to the second time derivative of the displacement [4].

A simple mathematical model (MM) based on this physical model has been developed [1–3]. The model is based on the assumption that the ring does not move except for a small spherical portion that performs the above-mentioned self-oscillations. It is also assumed

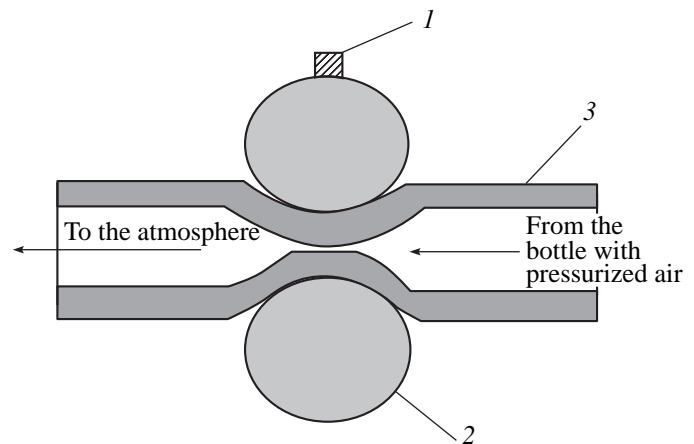


Fig. 1. Schematic view of the underwater part of the physical model: (1) a displacement sensor, (2) a rubber ring, and (3) a rubber tube. The excess air pressure is delivered to the right end of the tube. The left end is connected to the atmosphere. In the state of the model shown in the figure, the expanding forces inside the tube prevail over the compressing forces of the ring.

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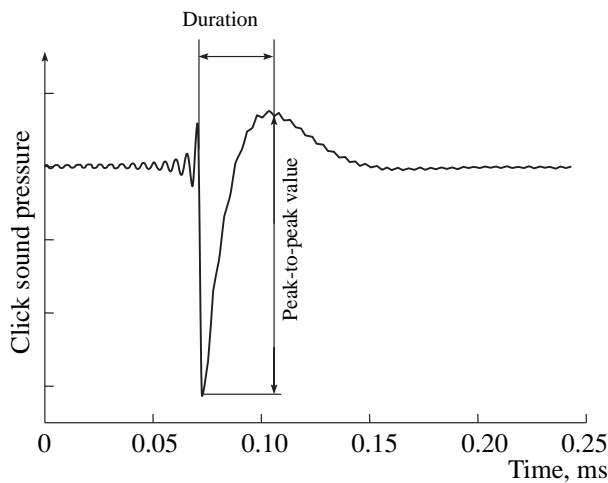


Fig. 2. Calculated click waveform and the definition of the peak-to-peak value and duration of the click in the mathematical model. The duration of the triangular displacement is 1 ms and the maximum of sphere displacement is 2 mm.

that the sphere has no mass. Under these assumptions, the sphere (thereafter called the “frozen sphere”) moves in accord with the observed displacement waveform of the ring. The acoustic pressure caused by the sphere displacement (which represents an acoustic dipole) at an angular frequency $\omega = 2\pi f$ can be expressed by the formula [4]

$$p(r, t) = i\rho\omega^2 a^3 \xi(\omega) \times \frac{(ikr - 1) \cos \alpha \exp(-ika) \exp(ikr - i\omega t)}{(2 - 2ika - (ka)^2) r^2}. \quad (1)$$

Here, a is the radius of the “frozen sphere,” r is the distance from the center of the sphere to the observation point, $k = \omega/c$ is the wave number, c and ρ are the speed of sound and the density of tissue around the source, α is the angle between the dipole axis and the direction to the observation point, and $\xi(\omega)$ is the Fourier transform of the sphere displacement waveform. At this stage of analysis, we assume that the density and the speed of sound propagation in the biological tissue around the delphinid sound source are equal to the corresponding parameters of water, which is at least approximately true [5]. In addition, we disregard the possible distortion of the acoustic click due to the diffraction by the complex structures of the air sacs and passages and the melon [10]. Some comments on these assumptions is given below.

The pressure waveform of the radiated acoustic click is computed by means of the inverse Fourier transform of the click amplitude spectrum density taken from Eq. (1). The computed acoustic clicks are indeed time-locked to the bends of the displacement curve, which agrees well with the physical model [3].

In this paper we further explore the influence of the critical parameters of the mathematical model on the peak-to-peak value of sound pressure, the duration of the simulated clicks, and the maximum (peak) of their amplitude spectral density (SDP). The critical parameters of the MM are the radius of the “frozen sphere” and the duration and maximum (height) of the displacement triangle (MSD). The results of simulation are compared with experimental data for different species of Odontocetes. Here, we consider only the forward problem (deriving the properties of acoustic clicks from the known source parameters). The inverse problem (calculating the source parameters from acoustic data) will be the subject of another paper.

2. RESULTS OF THE SIMULATION STUDY

Let us first examine the waveform of the acoustic click. Figure 2 depicts the calculated click waveform and the definition of the peak-to-peak value and duration of the click for the case when the displacement waveform of the frozen sphere is a triangle. The click has a short positive peak (phase of compression) and a large short negative peak (phase of rarefaction) followed by a prolonged positive peak (the second phase of compression). This click resembles the simplest click waveform (the “typical,” “standard” or “direct” click) observed in different species of Odontocetes [6–10] mostly in tanks. However, recently, an observation of the “standard” waveform from killer whales (*Orcinus orca*) in open water has been reported [11].

The “standard” dolphin’s click also comprises two compression half-waves separated by a rarefaction half-wave with a higher peak value. Clicks recorded in water contain several oscillations at a frequency roughly corresponding to the frequency of the spectral density peak. The missing first compression half-wave in our mathematical model is due to the ideal triangular displacement waveform.

From Fig. 3, the sound pressure level at 1-m range and re 1 μPa (the source level) of the acoustic click can be assessed for different radii of the “frozen sphere” and different maxima of sphere displacement (MSD). For example, the source level (SL) can be as small as 150 dB at a radius of $a = 0.5$ cm and MSD = 0.1 mm. When the radius of the “frozen sphere” is as big as $a = 5.0$ cm and the MSD runs up to 2 mm, the SL can reach almost 230 dB.

We note that Eq. (1) is valid provided that the displacement maximum h is much less than the radius of the “frozen sphere” a ($h \ll a$) and the wavelength λ ($h \ll \lambda$) [4]. In our case, the maximal value of the MSD is $h = 2$ mm and the minimal value of the radius a is 3 mm. Hence, the maximal value of h at $a = 3$ mm should not exceed 1 mm. In the assessment of the second condition, the wavelength should be the minimal one, which corresponds to the high-frequency boundary of the click spectrum. It implies that, when $h \ll 2$

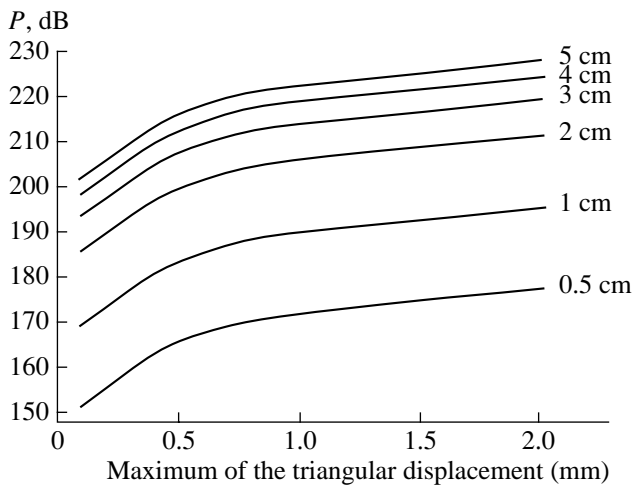


Fig. 3. Source level (SL) of the calculated clicks as a function of the maximum displacement (MSD) and the radius of the frozen sphere (shown as a parameter of the set of curves). The duration of the triangular displacement of the sphere is 1000 μ s.

mm, the condition $h \ll \lambda$ will be fulfilled in the entire frequency range.

The influence of the sphere radius on the click sound pressure level or source level is much more pronounced than the influence of the MSD, which is easily seen from Eq. (1). A tenfold MSD change (from 0.2 mm to 2.0 mm) results in an approximately 25-dB increase in the SL, while a tenfold increase in the sphere radius causes an approximately 50-dB growth of the SL.

Figure 4 depicts how the peak spectral density of the click (SDP) depends on the frozen sphere radius. The SDP shifts to the low frequency range when the sphere radius increases. The most pronounced change in the SDP is observed for $0.3 \text{ cm} < a < 1.5 \text{ cm}$. The SDP is decreased from 120 kHz down to 30 kHz within this range of radii. The graph in Fig. 4 allows an assessment of the radius of the “frozen sphere” (or sizes of equivalent biological structures presumably responsible for the click radiation) on the basis of the observed SDP for different Odontocetes species. The results of such an assessment are shown in Fig. 4 by the numbered circles, and these results are also presented in the table.

We selected the data for eight species to span the whole range in size and weight of the toothed whales: from one of the smallest toothed whale with the highest SDP (Harbor porpoise [12]) to the biggest one with the lowest SDP (Sperm whale [18]). Our MM predicts that the radius of the frozen sphere (or its biological correlate) varies from 0.25 to 3.5 cm, i.e., by about a factor of 13.

We assume that the assessment of the SDP based on averaging the spectral density is trustworthy, because a superposition of many standard clicks with different

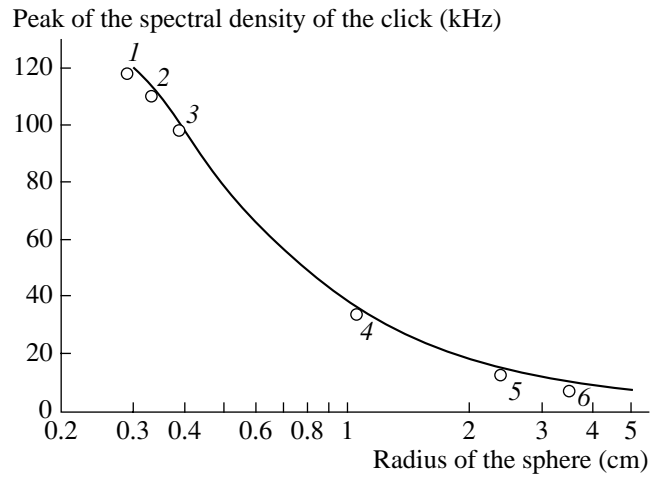


Fig. 4. Peak of the spectral density (SDP) for the calculated click versus the frozen sphere radius. The sphere displacement waveform is a triangle at a fixed MSD = 2.0 mm and duration of 1000 μ s. The circles indicate the spectral peak measurements of the Odontocetes clicks fitted to the model: (1) Harbor porpoise [12], (2) Atlantic bottlenose dolphin [10], (3) Beluga whale [15, 16], (4) Narwhal [17], (5) Killer whale [11], and (6) Sperm whale [18].

delays and peak values results in a rippled SDP but not in a shift of the bandwidth and the SDP itself.

The duration of the simulated click (Fig. 5) varies almost proportionally to the “frozen sphere” radius: from 5 μ s at $a = 0.3 \text{ cm}$ to 53 μ s at $a = 5.0 \text{ cm}$. The estimates of the standard click duration for six species of Odontocetes (measured from recorded signals) and different sphere radii (from the table) are indicated by circles in Fig. 5. The experimental data for comparison were chosen among the clicks radiated in the frontal direction (zero azimuth and elevation angles).

3. DISCUSSION

Let us first compare the waveform of a simulated click and the actual acoustic clicks of Odontocetes.

The “standard” or “direct” click of dolphins consists of two half-waves of compression separated by a half-wave of rarefaction whose peak value is higher than that of compression half-waves. The first positive half-wave of the modeling click is very small due to the use of the ideal triangular displacement of the “frozen” sphere. Besides, the actual clicks of Odontocetes (contrary to the modeling click) have no such abrupt front with which the rarefaction phase of the modeling click begins. An abrupt front in the actual dolphin clicks would imply a large acceleration of the biological correlate of the “frozen” sphere that would require high air pressure in the nasal passages. Actually, this pressure is rather small, and a smoothing of the click waveform should occur if the sphere under consideration has a mass not equal to zero.

Assessment of the radii of the frozen sphere from the peaks of the spectral density of clicks (SDP) for different toothed whales

Species	Limits of the SDP (kHz)	Radius of the equivalent sphere (cm)	Ref.
Harbor porpoise	120–140	0.25 (extrapolation)	[12]
Atlantic bottlenose dolphin	110–130	0.30	[13]
Risso's dolphin	47.9	0.77	[14]
Beluga whale	100–115	0.35	[15, 16]
Narwhal	40	1.00	[17]
Killer whale	20–30, 40–60	1.3, 0.75	[7]
Killer whale in a tank	14–20	2.35	[11]
Male Sperm whale	10–12	3.50	[18]

Most of the clicks recorded in water deviate from the standard waveform, because they are formed “by a large number of internally reflected pulses that arrive very close together soon after the arrival of the direct pulse, since the melon region is close to the air sacs and the areas of the skull that could reflect acoustic energy into the melon region” [10]. Acoustic clicks recorded in directions that deviate from the longitudinal axis of the dolphin body also contain some oscillations with frequencies roughly corresponding to the peak of click's spectral density [10].

The analysis of Fig. 3 shows that the range of the peak values of clicks in our model varies from 150 dB to 230 dB as the radius of the “frozen” sphere increases from 0.5 cm to 5.0 cm and the maximum of the triangular displacement of the sphere varies from 0.2 mm to

2 mm. At the comparison of these simulation data with actual ones, it is necessary to take into account that the concept of the source level of dolphins [10] includes both the source of clicks and the biological structures (skull bones, melon, air bags, etc.) participating in the formation of the time and spatial structure (directivity) of the click in water. Au [10] has summarized the data on the source level for clicks recorded in tanks and in open water for various species of sea and freshwater dolphins. According to these data, the source level varies from 151 dB for the Hector dolphin to 228 dB for the false killer whale and the Atlantic and Pacific bottlenosed dolphins. This is in a very close agreement with the simulated data shown in Fig. 3 for the sound sources of sizes typical of Odontocetes.

The maximal value of the SL among Odontocetes (235 dB) is also observed for the Sperm whale [18]. The values of the radius of the sphere and the maximum of the sphere displacement (MSD) corresponding to this SL are not depicted in Fig. 3. However, by the assessment based on the peak of the spectral density (10–12 kHz), the radius of the equivalent sphere for the Sperm whale is close to 3.5 cm (Fig. 4). To fit this radius estimate with the estimate of the sphere radius based on the SL, it is necessary that the maximum of the triangular sphere displacement be approximately equal to 4 mm.

It is important to take into account that the SL of Odontocetes may considerably vary depending on the echolocation conditions. Babkin and Dubrovsky [19] reported on a gradual increase in the SL by 27 dB at the detection of a target by the Black Sea Tursiops on the background of random noise with an evenly growing level. It also has been shown that, when the target range increased up to 600 m, the level of the click radiation increased on the average by 52 dB: from 170 up to 222 dB [20]. Au and Pawloski [21] have found a change in the source levels by up to 12 dB for a Tursiops truncatus discriminating targets against the background of a masking noise.

As it was already mentioned, the source level in our model grows by no more than 25 dB when the maximum of the triangular displacement of the sphere

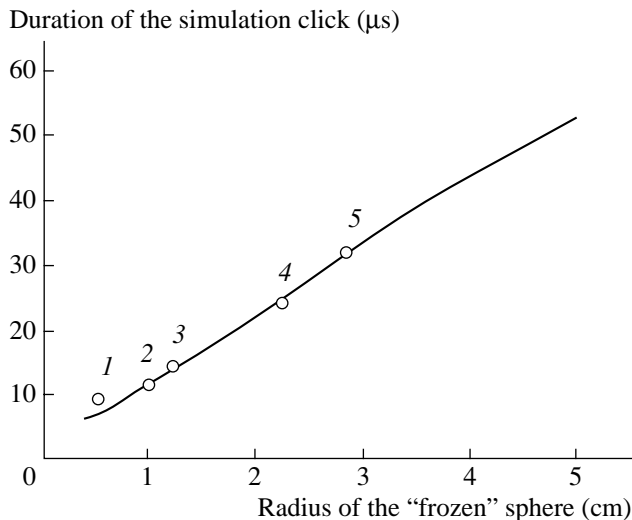


Fig. 5. Duration of the simulated click in microseconds as a function of the radius of the frozen sphere in centimeters. The duration of the triangular displacement is 1000 μ s, and the maximum displacement of the frozen sphere is 2 mm. The circles indicate the durations of the dolphin's standard clicks: (1) Atlantic bottlenose dolphin [10, 13], (2, 3) Risso's dolphin [14], and (4, 5) Killer whale [11].

increases from 0.2 to 2 mm. Meanwhile, the Black Sea bottlenose dolphin increased the SL of clicks up to 52 dB with an increase in the target range to 600 m [20]. To explain this increase within the framework of the proposed model, it is necessary to admit an opportunity for the Odontocetes to change somehow the radius of the equivalent sphere, i.e., the size of the muscular plug or "lip" performing the dipole oscillation at radiation of a click. According to Fig. 3, such a change allows a variation of the SL by 50 dB. It is possible that the Odontocetes use both possibilities, namely, change both the maximum of the displacement and the size of the equivalent sphere.

Au *et al.* [11] reported on the radiation of acoustic clicks by the Killer whale with a click spectrum containing two pronounced peaks: a low-frequency one with a maximum between 20 and 30 kHz and a high-frequency one with a maximum located between 40 and 60 kHz. The simultaneous emission of low- and high-frequency clicks may testify in favor of the assumption that Odontocetes, either simultaneously or with a delay about the duration of a click, "use" two different equivalent spheres: a larger one for the radiation of low-frequency clicks and a smaller one for the radiation of high-frequency clicks. A possible mechanism for this could be to switch the sound production between the two nasal plugs, which in most delphinids have very different sizes [22]. This assumption, however, needs an additional analysis.

4. CONCLUSIONS

The development of a simulation model of the acoustic click radiation by Odontocetes is presented in this paper. The simulation model is based on the mathematical model of the source of acoustic clicks that was developed and described earlier [1–3]. A software in MathCAD was created to study influence of the critical parameters of the mathematical model (the radius of the "frozen" sphere and the maximum of its triangular displacement) on the sound pressure reduced to 1 m (the source level) and the position of the spectral density peak of the click and its duration.

A comparison of the model predictions with experimental data for various species of Odontocetes is carried out.

It is shown that the waveform of the simulated click generally meets the waveform of the "direct" or "standard" click of the Odontocetes. It consists of the first peak of compression, the peak of rarefaction, and the second peak of compression. Such clicks are observed in directions close to the longitudinal axis of the animal body (at zero azimuth and elevation angles). For a closer agreement of the simulation model with its biological prototype, it is necessary to take into account the mass of the oscillating ("frozen") sphere and to compare the pressure of the air necessary for creating the required displacement of the sphere with the mea-

sured values of air pressure in the nasal passages of Odontocetes.

Although the range of the radii of the "frozen" spheres (0.25–5.00 cm) and the maxima (MSD) of the sphere displacement (0.2–2.0 mm) were chosen arbitrarily, i.e., proceeding from the feasible sizes of the biological structures responsible for the generation of the clicks, the range of source levels predicted by our model (150–230 dB) satisfactorily agrees with those observed for various species of Odontocetes.

The maximal changes in the SL (up to 52 dB) observed with an increase in the range of a target to 600 m [20] cannot be explained by a change in sphere displacement alone. It is necessary to assume that, in addition, the animals are able somehow to change the size of the biological equivalent of the "frozen" sphere.

The model of the click generation predicts the size of the sound generating structures throughout a broad size range of Odontocete species. These predictions should be compared with anatomical data of the structures inferred to be involved in the click generation.

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REFERENCES

1. L. R. Giro and N. A. Dubrovskiy, in *Proceedings of XXIII International Physiological Congress* (St. Petersburg, 1997).
2. L. R. Giro and N. A. Dubrovskiy, *J. Acoust. Soc. Am.* **105**, 1263 (1999).
3. L. R. Giro and N. A. Dubrovskiy, in *Echolocation in Bats and Dolphins*, Ed. by J. Thomas, C. Moss, and M. Vater (Chicago Univ. Press, Chicago, 2003), Chap. 10, pp. 59–65.
4. M. A. Isakovich, *General Acoustics* (Nauka, Moscow, 1973), p. 495.
5. K. S. Norris and G. W. Harvey, *J. Acoust. Soc. Am.* **56**, 659 (1974).
6. K. T. Diercks, R. T. Trochta, C. F. Greenlaw, and W. E. Evans, *J. Acoust. Soc. Am.* **49**, 1729 (1971).
7. W. E. Evans, *J. Acoust. Soc. Am.* **54**, 191 (1973).
8. N. A. Dubrovskii and G. L. Zaslavskii, in *Proceedings of VIII All-Union Acoustic Conference* (1973), Section Ts, p. 56.
9. V. M. Bel'kovich and N. A. Dubrovskii, *Sensory Basis of Cetacean Orientation* (Nauka, Leningrad, 1976; Joint Publ. Research Service L/7157, Arlington, VA, 1977).
10. W. W. L. Au, *The Sonar of Dolphins* (Springer, New York, 1993).
11. W. W. L. Au, J. K. B. Ford, J. K. Horne, and K. A. Newman Allman, *J. Acoust. Soc. Am.* **115**, 901 (2004).
12. B. Möhl and S. Andersen, *J. Acoust. Soc. Am.* **54**, 1368 (1973).

13. W. W. L. Au, in *Animal Sonar Systems*, Ed. by R. G. Busnel and J. F. Fish (Plenum, New York, 1980), pp. 251–282.
14. J. D. Philips, P. E. Nachtigall, W. W. L. Au, *et al.*, *J. Acoust. Soc. Am.* **113**, 605 (2003).
15. W. W. L. Au, D. A. Carder, R. H. Penner, and B. L. Scronce, *J. Acoust. Soc. Am.* **77**, 726 (1985).
16. W. W. L. Au, R. H. Penner, and C. W. Turl, *J. Acoust. Soc. Am.* **82**, 79 (1985).
17. B. Möhl, A. Surlykke, and L. A. Miller, in *Sensory Abilities of Cetaceans*, Ed. by J. A. Thomas and R. A. Kastelein (Plenum, New York, 1990), pp. 295–303.
18. B. Möhl, M. Wahlberg, P. T. Madsen, *et al.*, *J. Acoust. Soc. Am.* **114**, 1143 (2003).
19. V. P. Babkin and N. A. Dubrovskii, *Tr. Akust. Inst. Akad. Nauk SSSR*, No. 17, 29 (1971).
20. M. P. Ivanov, Candidate's Dissertation (St. Petersburg State Univ., St. Petersburg, 1999).
21. W. W. L. Au and D. A. Pawloski, *J. Acoust. Soc. Am.* **70**, 662 (1988).
22. T. W. Cranford, M. Amundin, and K. S. Norris, *J. Morphol.* **228**, 223 (1996).