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ZOOLOGY

The Influence of Amplitude Modulation on the Structure of Call Spectrum in Marmots (*Marmota*, Rodentia, Sciuridae)

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Abstract—A relationship was established between the amplitude modulation and the structure of call spectrum in animals by the example of alarm call in three marmots (*Marmota sibirica, M. menzbieri*, and *M. caudata*). In the case of amplitude modulation, side frequencies are produced higher and lower than the carrier frequencies. In the absence of amplitude modulation, no side frequencies are produced.

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Amplitude modulation, i.e., time-related change of signal amplitude, is widespread among sound signals of mammals (Tembrock, 1963). The amplitude modulation is characterized by that the modulating oscillation changes the structure of communication spectrum. This property of amplitude modulation is daily used in radio communication for decades. The diversity of amplitude modulation of the sound signals in mammals suggests that it enhances the solution by animals of many tasks related to the transmission of information over the acoustic communication channel. However, the mechanism of control of the sound signal spectrum by means of amplitude modulation has not been sufficiently reflected in biological literature.

As a result of amplitude modulation higher and lower than the carrier frequency (F_0), which is subject to amplitude modulation, side frequencies (Ω) are formed (Baskakov, 2003). In the simplest case, when the modulating oscillation is harmonic, two side frequencies are added higher and lower than the carrier frequencies: $F_0 + \Omega$, upper side frequency, and $F_0 - \Omega$, lower side frequency. However, such monotone modulating oscillations either do not occur among sound signals of animals or are extremely rare. The modulating oscillation is usually characterized by complex spectral composition. In addition to the main oscillation, the spectrum of such signal contains groups of upper and lower side frequencies. Side frequencies Ω_i form an ascending sequence: $\Omega_1 < \Omega_2 < \ldots < \Omega_N$ (Baskakov, 2003). The upper and lower side frequencies are related to the carrier frequency by equation: $F_0 \pm \Omega_i$ (i = 1, 2, …).

Unlike the Fourier series, frequencies Ω_i should not be multiple to each other and the spectrum of upper side frequencies is a scale copy of the modulating oscillation spectrum shifted to the area of high frequencies by the carrier frequency value F_0, while the spectrum of lower frequencies is located mirror-like relative to the carrier frequency F_0 (Baskakov, 2003). These properties of amplitude modulating signals are essential, since they should be taken into account when diagnosing the mechanisms of formation of the sound signal spectrum in animals, when there are grounds to believe that the spectrum structure is controlled by amplitude modulation.

The aim of this work was to show the influence of amplitude modulation on the spectrum of acoustic signals in mammals on the example of alarm call in three *Marmota* species (*M. sibirica, M. menzbieri*, and *M. caudata*) (Nikol'skii, 1984, 1992). The signals consist of individual sounds organized in series.

MATERIALS AND METHODS

Studies were carried on samples of the signal with distinct amplitude modulation characteristic for each *Marmota* species as compared to samples of the same signal without or with weakly expressed modulation.

The signal was tape recorded in the field. Tape recorders and microphones allowed registration of the signal within the range of 60 to 12000–16000 Hz. The records stored on magnetic tape were digitized and stored on a compact disc (CD). The signal on CD was analyzed on a computer using SpectraLab v.4.32.11 software for Win.

The signal of the studied marmots is characterized by amplitude modulation accompanied by frequencies located upper and lower than the carrier frequency. The signal of *M. sibirica* consists of two components: high- and low-frequency components. The spectrum of high-frequency component is usually complicated by side frequencies, which are expressed to different degrees in different individuals and sometimes are absent

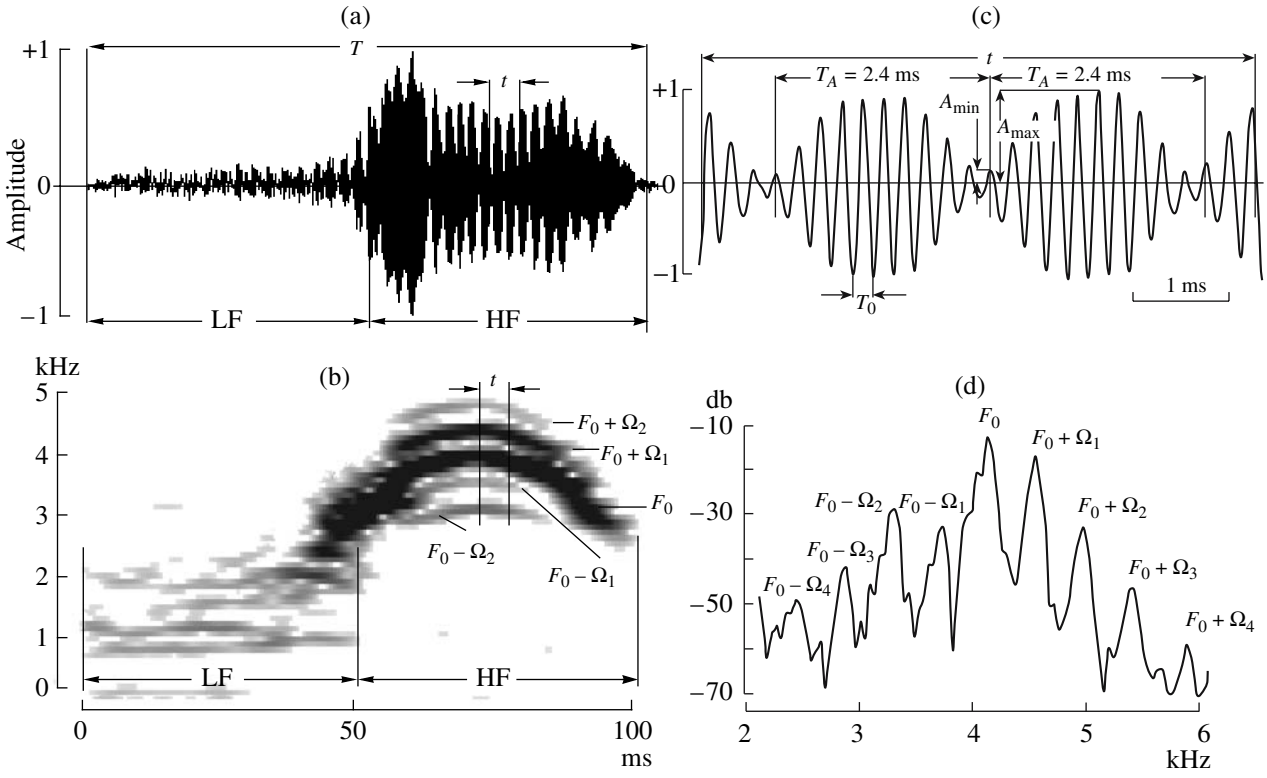

Fig. 1. Amplitude-modulating signal of *M. sibirica*: (a) amplitude-temporal characteristic (oscillogram); (b) sonogram; (c) two periods of amplitude modulation; (d) capacity spectrum of two periods of amplitude modulation.

In Figs. 1, 3, and 4: *T*, total signal duration; *t*, duration of two periods of amplitude modulation; T_0, period of carrier frequency; T_A, period of amplitude modulation; LF, low-frequency component; HF, high-frequency component; F_0, carrier frequency; Ω, amplitude modulation frequency; ($F_0 + \Omega_1 \ldots, \Omega_5$) 1st–4th upper side frequencies; ($F_0 - \Omega_1 \ldots, \Omega_5$) 1st–4th lower side frequencies; A_{max}, maximum amplitude of modulated oscillation; A_{min}, minimal amplitude of modulated oscillation.

(Nikol'skii, 1976; Figs. 1 and 2). Therefore, two signal samples were used: (1) with distinct amplitude modulation and, correspondingly, with side frequencies in the spectrum, and (2) practically without amplitude modulation and, correspondingly, without distinct side frequencies. In both cases, the signals were emitted by adult marmots and recorded in the Central aimak (region) of Mongolia by the author in June 1975.

The beginning of signal of *M. menzbieri* is characterized by a weakly expressed low-frequency component, which usually passes into a short region complicated by side frequencies (Nikol'skii, 1976; Nikol'skii and Pereladova, 1994) (Fig. 3). The signal presented in this work was emitted by an adult marmot and recorded in the Chatkalsky State Reserve (Uzbekistan) by O.B. Pereladova in July 1974.

Deep amplitude modulation is the most characteristic feature of the signal of *M. caudata* (Nikol'skii, 1976; Nikol'skii et al., 1999), which is less expressed in young animals than in adults. Two signal samples were used: (1) signal of adult marmot with amplitude modulation and, correspondingly, multiple side frequencies in the spectrum, which was recorded in the Osh district (Kirghizstan) by T.Yu. Lisitsyna and A.A. Nikol'skii in August 1966, and (2) signal of a young marmot practically without amplitude modulation and, correspondingly, without distinct side frequencies (Fig. 5), which was recorded in the western part of the Zaalaiskii mountain ridge (Tadzhikistan) by N.L. Nesterova in July 1988.

The influence of amplitude modulation of the signal spectral structure was studied using four characteristics:

(1) Amplitude-temporal characteristic (oscillogram) with relatively low time resolution, sufficient to identify modulating oscillation. This first, preliminary, stage of diagnostics made it possible to reveal the presence (absence) of amplitude modulation.

(2) Sonogram. The signal spectrum in the form of sonogram exposes side frequencies and their distribution near the carrier frequency.

(3) Oscillogram with high time resolution. High time resolution of the signal amplitude–temporal characteristics allows, first, revealing of the ratio between the periods of the carrier and modulating oscillations and, second, direct measurement of the amplitude modulation period.

(4) Capacity spectra. Being integral spectrograms, they provide for (a) additional information about the

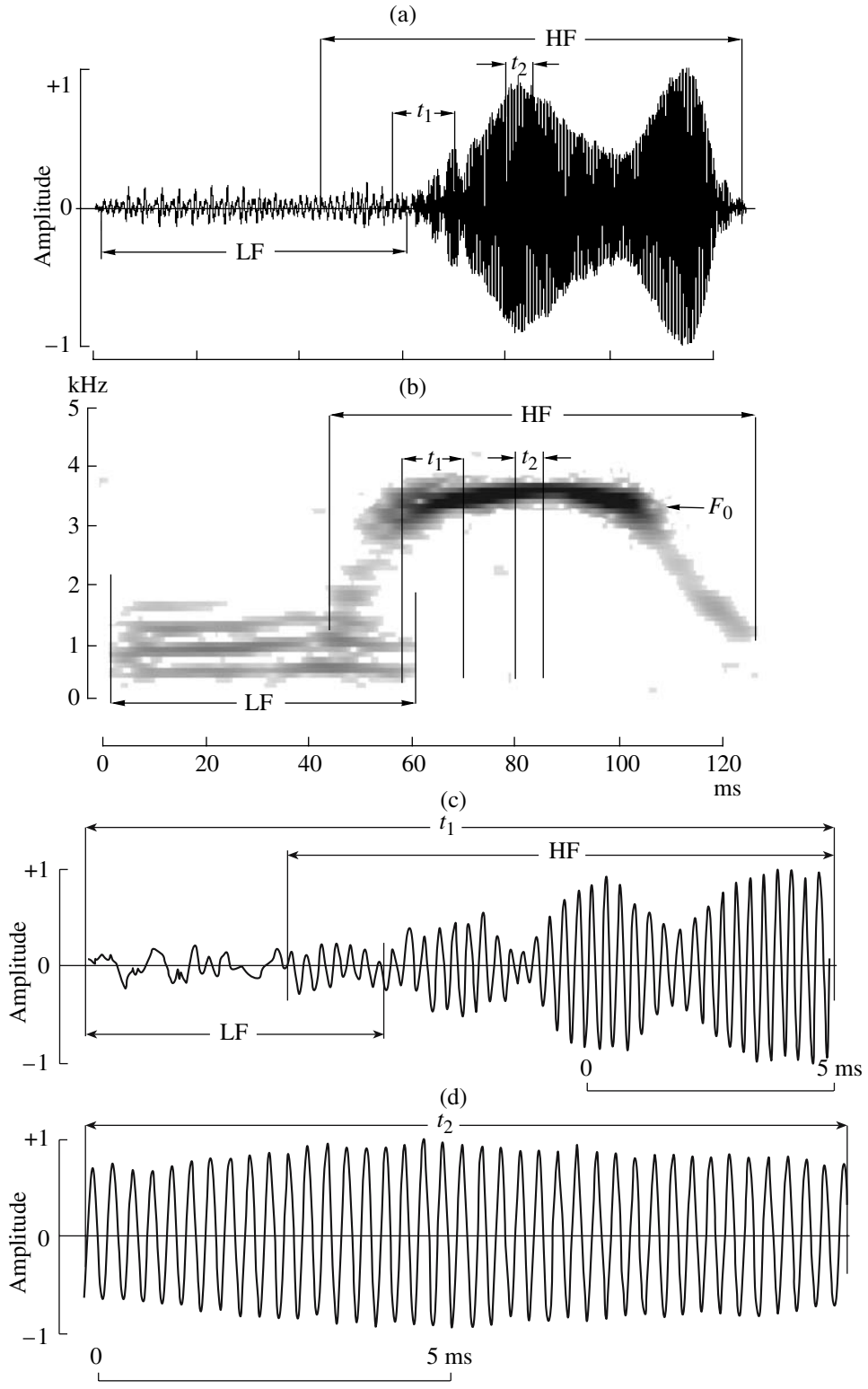

Fig. 2. Signal of *M. sibirica* with weakly expressed amplitude modulation: (a) oscillogram; (b) sonogram; (c) a fragment of signal including low- and high-frequency components with amplitude modulation; (d) a fragment of signal without amplitude modulation. t_1, length of a signal fragment including low- and high-frequency components with amplitude modulation; t_2, length of a signal fragment without amplitude modulation.

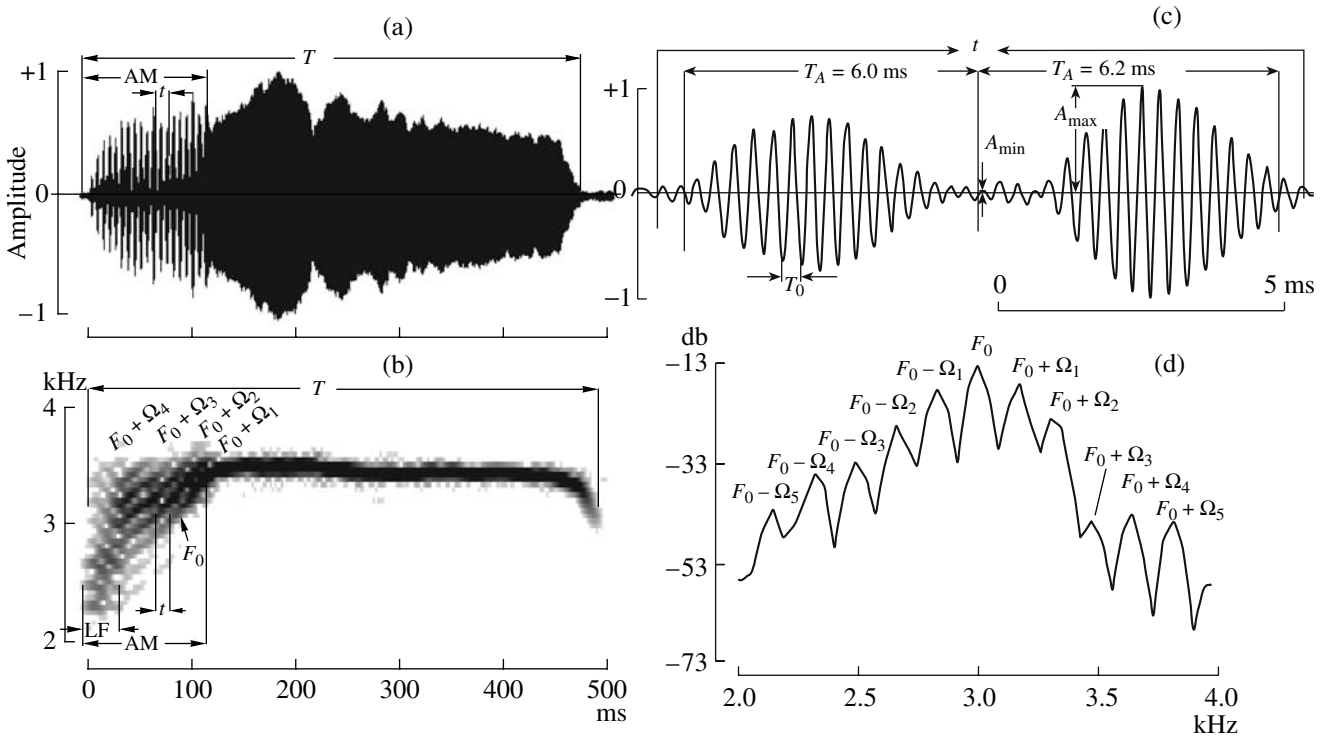

Fig. 3. Signal of *M. menzbieri*. AM, amplitude modulated part of the signal.

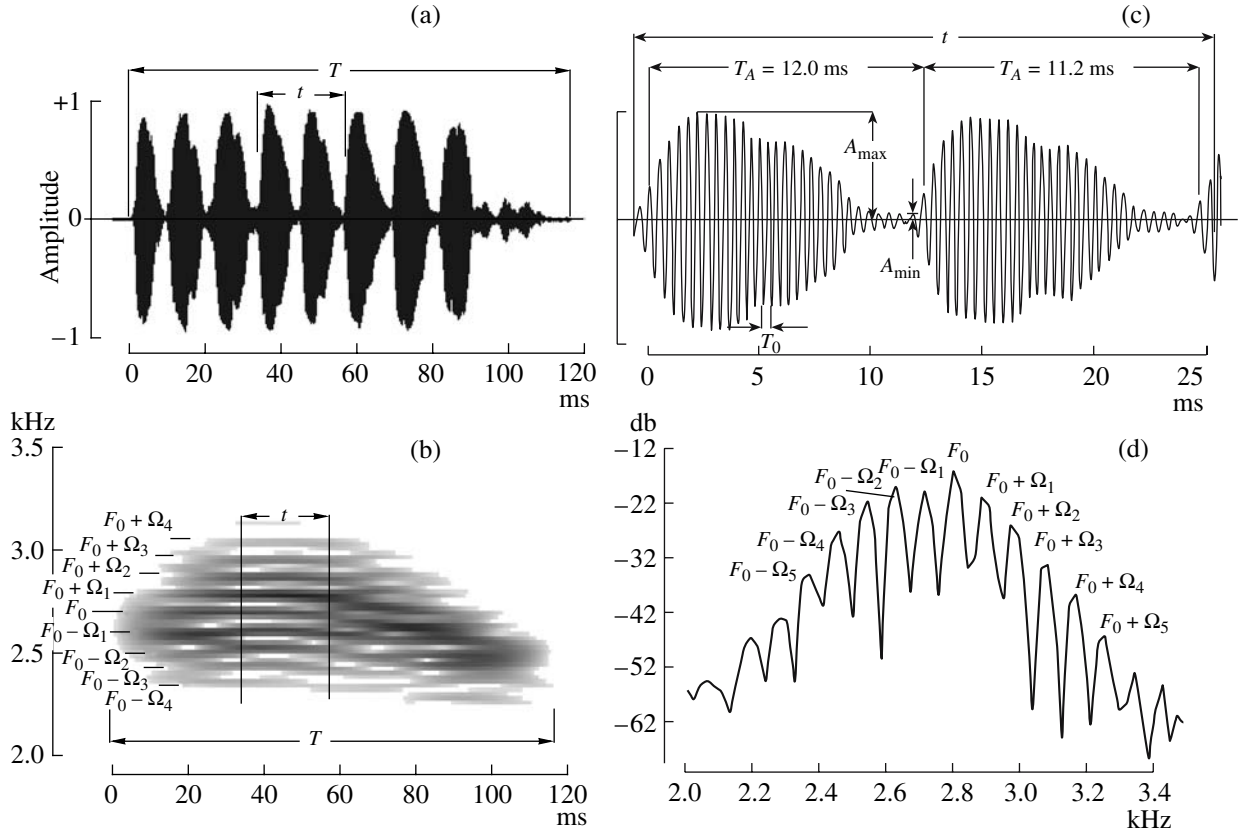

Fig. 4. Amplitude-modulated signal of adult *M. caudata*.

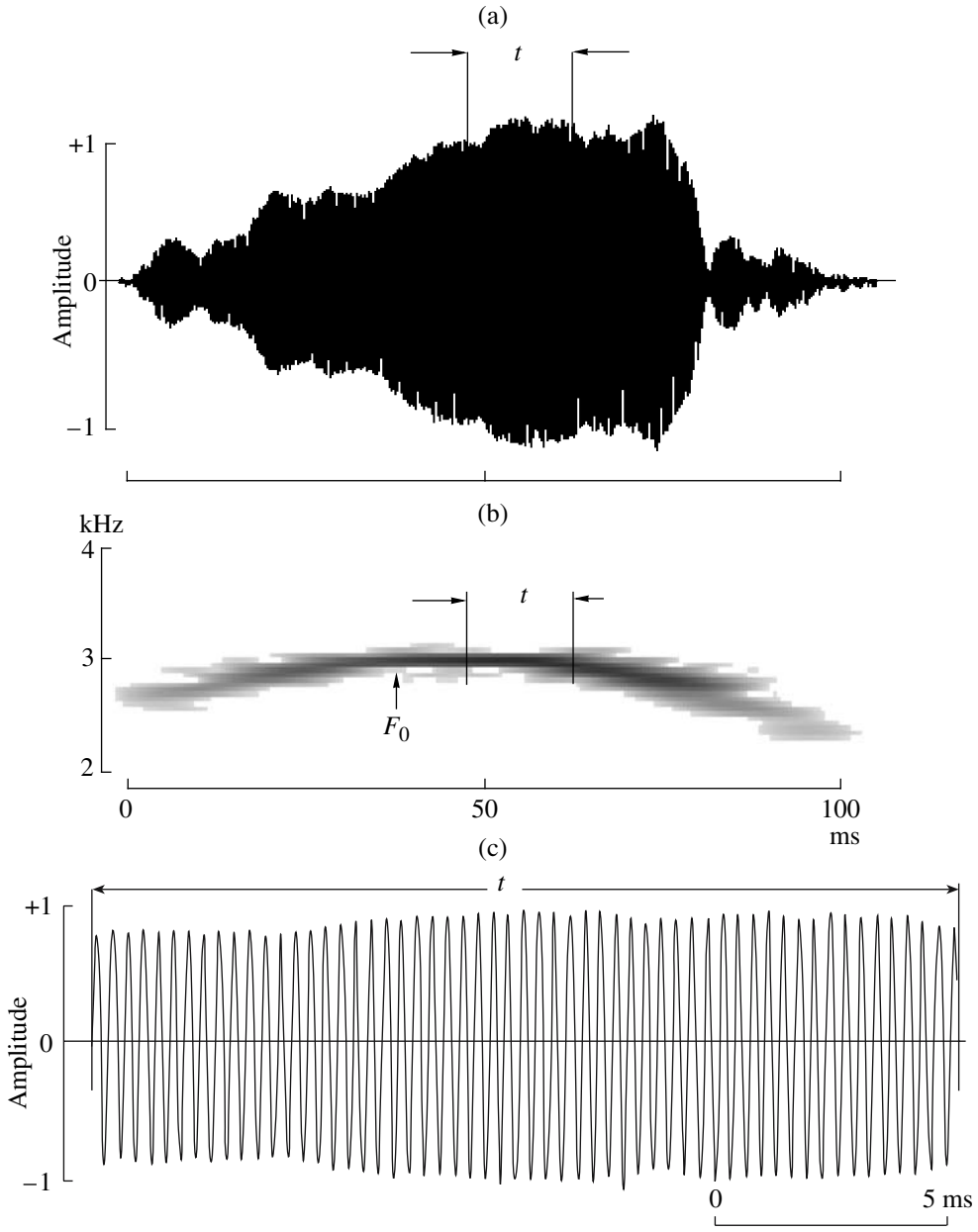

Fig. 5. Signal of young *M. caudata* without regular amplitude modulation: (a) oscillogram; (b) sonogram; (c) amplitude-temporal characteristic of a short (*t*-long) signal fragment. F_0, carrier frequency.

presence (absence) of side frequencies, (b) measurement of carrier and side frequencies, and (c) calculation of the modulating oscillation frequency (Ω_i). The latter takes into account that amplitude-modulating signals have the upper and lower side frequencies shifted up- and downwards by the carrier frequency value (F_0). For example, the signal carrier frequency (F_0) and third lower side frequency of *M. sibirica* amount to 4136 and 2845 Hz, respectively, according to the capacity spectrum. Correspondingly, the modulating oscillation frequency Ω_3 equals 1291 Hz (4136 – 2845) (table).

The capacity spectrum is excluded from analysis of signal samples without amplitude modulation (Figs. 2 and 5), since side frequencies are absent in such cases.

Carrier and side frequencies were measured according to the capacity spectra using Cursor measurement to a precision of 1 Hz. Note that although the spectrum analyzers possess discrete resolving capacity limited by FFT size, dedicated software, including SpectraLab, perform interpolation between two neighboring points and calculate frequency to a precision of 1 Hz.

Spectrum of amplitude-modulating signal of marmots, Hz

Ordinal number of side frequency band	*M. sibirica*		*M. menzbieri*		*M. caudata*	
	$F_0 \pm \Omega_i$	Ω_i	$F_0 \pm \Omega_i$	Ω_i	$F_0 \pm \Omega_i$	Ω_i
5	–	–	2153	860	2367	435
4	2747	1729	2328	685	2453	349
3	2845	1291	2497	516	2541	261
2	3273	863	2669	344	2627	175
1	3698	438	2841	172	2713	86
0	4136	0	3013	0	2802	0
1	4564	428	3185	172	2887	89
2	4000	864	3318	305	2973	171
3	5427	1291	3487	474	3060	258
4	5856	1720	3659	646	3147	345
5	–	–	3831	818	3233	431

Note: F_0 is carrier frequency, $F_0 \pm \Omega_i$ are side frequencies, and Ω_i are modulating oscillation frequencies.

In this work, the following SpectraLab setups were common for all cases of spectrum analysis: window of smoothening Hamming and overlapping by frequency axis of 75%. In order to obtain the optimal resolving ability by frequency, the FFT size was selected individually for each sample*: M. sibirica,* 512 points for both cases; *M. menzbieri*, 1024 points; and *M. caudata*, 2048 points for the sample with amplitude modulation (Fig. 4) and 1024 points for the sample without amplitude modulation (Fig. 5). The substantiation of FFT size selection is discussed in detail by Darden et al. (2003).

RESULTS

Formation of side frequencies is induced by superposition of the signal carrier frequency with the amplitude modulation frequency (Magnus, 1982). Indeed, as will be shown below, if the signal is modulated, side frequencies are always present in its spectrum and, on the contrary, the absence of regular periodic amplitude modulation is accompanied by the absence of side frequencies.

M. sibirica. The signal consists of two components: low- and high-frequency components (Fig. 1). The high-frequency component is usually characterized by deep amplitude modulation.

The low-frequency component is inherent, above all, in the signal of bobak marmots (Nikol'skii, 1976, 1984; Nikol'skii and Formozov, 2005). Its description is complicated by some specific features. Specifically, it has a relatively low amplitude and complex form of oscillation forming its spectrum (Figs. 2a and 2c).

A sample of the signal is modulated over the entire length of the high-frequency component (Fig. 1a). Amplitude modulation is accompanied by side frequencies. In the sonogram (Fig. 1b), they look like lines located above and below the carrier frequency.

In order to demonstrate the details of amplitude modulation, two periods were isolated from signal, equal to 2.4 ms each (Fig. 1c). Correspondingly, the amplitude modulation frequency equals 417 Hz (1000 ms/2.4 ms = 416.6 Hz).

The signal capacity spectrum, like the sonogram, confirms the presence of side frequencies. Four upper and four lower side frequencies can be distinctly seen on the spectrum envelope (Fig. 1d).

The values of carrier (F_0) and side frequencies ($F_0 \pm \Omega_i$), as well as modulating oscillation frequencies (Ω_i) are presented in table. The absolute values of the corresponding bands of the upper and lower modulating oscillation frequencies little differed from each other, i.e., the bands of side frequencies were practically symmetrical.

The spectrum of the signal with weakly expressed modulation looks differently (Fig. 2).

The signal sample used in this work includes a small, less than 10 ms long, fragment of shallow regular amplitude modulation t_1 (Figs. 2a and 2c), which consists only of three periods. Amplitude modulation of the remaining part of the high-frequency component represents a slow irregular process, during which (t_2) the carrier frequency amplitude changes by no more than 50% (Figs. 2a and 2d). Correspondingly, side frequencies could not be found in the signal spectrum. The upper side frequency tended to be formed only at the boundary between the low- and high-frequency components (Fig. 2b).

M. menzbieri. A relatively long duration is the most characteristic feature of the signal (Nikol'skii, 1976). Previously (Nikol'skii and Pereladova, 1994), the beginning of the signal was thought to be complicated by the low-frequency component, but detailed analysis of the spectrum-forming oscillation has shown that the signal has a more complex, three-component structure. In addition to the low-frequency component, which is present in the very beginning of the signal, the signal is modulated in a region equal approximately to 20% of its entire duration (Fig. 3a).

As was expected, the spectrum of this amplitude-modulated region contains side frequencies (Fig. 3b). The lower side frequencies are hardly noticeable, i.e. have low amplitude, due, apparently, to specificity of the modulating oscillation.

Like in the case of *M. sibirica*, two periods of modulation t have been isolated from the signal (Fig. 3c), equal to 6.0 and 6.2 ms. Correspondingly, if we assume that the mean period of modulation equals 6.1 ms, the frequency of modulation (Ω) will amount to 164 Hz (1000 ms/6.1 ms = 163.9 Hz).

The spectrum of signal capacity, like the sonogram, confirms the presence of side frequencies. Five upper and five lower side frequencies can be distinctly seen in the capacity spectrum (Fig. 3d).

The values of carrier (F_0) and side frequencies ($F_0 \pm \Omega_i$) and of modulating oscillation frequencies (Ω_i) are presented in table. Note that, unlike the spectrum of the signal modulating oscillation in *M. sibirica*, that in *M. menzbieri* is markedly asymmetrical. All lower side frequencies, except the first upper band of the spectrum (Ω_i), are by approximately 10% higher than the corresponding higher side frequencies. Asymmetry of the amplitude of upper frequencies with references to the lower side frequencies is also quite distinct (Figs. 3b and 3c). Asymmetry of the spectrum of side frequencies appears to be related to the complex three-component structure of the signal spectrum in this species, which was not studied in this work.

M. caudata. The signal consists of amplitude-modulating sounds (Nikol'skii, 1976) (Fig. 4a). As was expected, amplitude modulation is accompanied by side frequencies (Fig. 4b).

Like in the two preceding cases, two periods of modulation t equal to 12 and 11.2 ms have been identified in the signal (Fig. 4c). Correspondingly, at the mean period of modulation 11.6 ms, the frequency of modulation (Ω) will be 86 Hz (1000 ms/11.6 ms = 86.2 Hz).

No less than five upper and five lower side frequencies can be distinctly seen on the capacity spectrum envelope (Fig. 4d).

The values of carrier (F_0) and side frequencies ($F_0 \pm \Omega_i$) and of modulating oscillation frequencies (Ω_i) are presented in table. The absolute values of the corresponding bands of upper and lower frequencies of the modulating oscillation little differ from each other, i.e., the bands of side frequencies are practically symmetrical with references to the carrier frequency.

The spectrum of the young marmot's signal with weakly expressed amplitude modulation (Fig. 5) looks different. As was already noted, amplitude modulation is absent or hardly noticeable in the signal of young marmots. In the sample used in this work, periodic regular amplitude modulation is absent (Figs. 5a and 5c) and, correspondingly, the spectrum lacks side frequencies.

DISCUSSION

The main result of this work was the confirmation of the control of amplitude modulation over the spectrum of sound signals of mammals: a relationship between the amplitude modulation of carrier frequency and the presence of upper and lower side frequencies in the signal spectrum was demonstrated.

The amplitude modulation depth measured by the coefficient of modulation (m) is an essential characteristic of amplitude-modulated signals (Sergienko, 2006):

$$m = (A_{\max} - A_{\min})/(A_{\max} + A_{\min}),$$

where $A_{\max}$ is the maximum amplitude of modulated oscillation and $A_{\min}$ is its minimal amplitude. When m = 1, amplitude modulation signals reach a maximum capacity (Baskakov, 2003).

In all three species, the coefficient of modulation approached the maximum but has reached unity in none of them: 0.75, 0.80, and 0.88 for *M. sibirica, M. menzbieri*, and *M. caudata*, respectively.

Since the efficiency of amplitude-modulated signals is relatively low (50% of the capacity of carrier frequency at the modulation depth equal to 1) (Baskakov, 2003), it can be stated that from the energetic standpoint, the marmots underuse the amplitude modulation possibilities, but effectively modify the spectrum structure of transmitted communication: in all cases, the amplitude of side frequencies is commensurable with the carrier frequency amplitude (Fig. 1, *3, 4*).

Significant interspecific differences in the amplitude modulation frequency are accompanied by great interspecific differences in the ratio of carrier frequency to modulating oscillation frequency, F_0/Ω: 10, 18, and 34, respectively. Thus, in *M. caudata* this ratio is markedly higher than in two other species. As a result, the signal spectrum of this species is more saturated with side frequencies. Side frequencies in its signal are more densely packed due to low modulating oscillation frequency than in *M. menzbieri* and, the more so, in *M. sibirica* (Figs, 1, 3, and 4).

At present, we are not ready to estimate these differences from the position of adaptive advantages. The signal amplitude modulation is not known for other marmots of the world fauna (Nikol'skii, 1976, 1984; Blumstein, 2003). Amplitude modulation of the *M. caudata* signal is especially expressive and is perceived by ear as a police whistle. It can only be proposed that amplitude modulation provides certain adaptive advantages for species with such signals but it is not known what these advantages are and what factors of selection led to its modulation in a limited number of marmot species. The ecology of marmots is monotypic. It is difficult to distinguish species-specific factors in ecology of species with amplitude-modulating signals, which could have been opposed to those without amplitude modulation.

On the other hand, the problem of adaptive advantages of amplitude modulation was not among the tasks of the present study, which was aimed to demonstrate a relationship between amplitude modulation and presence of frequencies in the sound signal spectrum. Taking into account that amplitude modulation occurs in acoustic signals of different mammalian orders, we believe that further studies of the influence of modulation on the sound signal spectrum can be promising for the investigation of the mechanisms of encoding infor-

mation and increased noise immunity of acoustic communications.

The modulating oscillation can, apparently, be considered almost periodical. In all three species, the modulating oscillation frequencies above 1 (Ω_2, Ω_3…) were almost multiple to the first order frequency (Ω_1). In the signals of *M. sibirica* and *M. caudata*, $\Omega_{2,\,3\ldots}/\Omega_1$ differed from 1 by 0.02–0.08; and in the signal of *M. menzbieri*, by 0.21–0.25.

Publications have recently appeared, in which spectra loaded with side frequencies (side bands) are referred to nonlinear phenomena (Wilden et al., 1998; Volodin et al., 2005). This classification is, in our opinion, erroneous. Side frequencies are a consequence of superposition of the carrier frequency and modulating oscillation, while superposition based on summation of linear equations has no application to nonlinear systems (Magnus, 1982). Cases of asymmetry of the upper and lower side frequencies may be referred to nonlinear phenomena (Bogatyrev, 1988), which are observed in the *M. menzbieri* signal. However, these cases require careful consideration.

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