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THE HARMONIC INTERVAL: FACT OR ARTIFACT IN SPECTRAL ANALYSIS OF PULSE TRAINS

by

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THE HARMONIC INTERVAL FACT OR ARTIFACT IN SPECTRAL ANALYSIS OF PULSE TRAINS*, †

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THE HARMONIC INTERVAL: FACT OR ARTIFACT IN SPECTRAL ANALYSIS OF PULSE TRAINS*, †

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THE harmonic interval indicated during spectrographic analysis of a rapid train of pulses may be used to determine the pulse repetition-rate. If the pulse rate is regular, but too rapid to be separated, the repetition-rate may or may not be represented on such analysis as a line at the repetition frequency, but will always be indicated by the separation between harmonic bands, the harmonic interval.

The sound spectrograph was an outgrowth of work done at the Bell Telephone Laboratories, and was described in 1946 by W. Koenig, H. K. Dunn, and L. Y. Lacy. Refinements have been built into new instruments as the years progressed. The best known of these sound analyzers have been those made by the Kay Electric Company (Pine Brook, New Jersey), such as the Vibralyzer and the Sona-graph. These machines have been used extensively in sound analysis of many types, but they have been especially valuable in bio-acoustics, where this sort of spectrum analysis has become nearly a standard for representing biological sounds.

The complexity of bio-acoustic phenomena has made the sound spectrograph popular, because this analyzer can portray such a large variety of sounds. The very complexity of animal sounds has led to the description of these sounds largely in terms of their appearence after spectrographic

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analysis. The traces produced by the analyzer have been carefully measured and compared, but the tendency of workers to avoid more complete physical descriptions has led to confusion in the interpretation of the sound spectrograms. Relatively simple sounds may have complex spectral representations in such analysis. The sound spectra provide reliable clues to the actual physical composition of these sounds.

The interpretation of spectrographic analysis of sounds that are composed of pulse trains is especially fraught with confusion. Sounds that are formed by a rapid series of pulses are often described simply as having many harmonics. The fact that these harmonic bands appear not to be really harmonically related may be ignored. Unequal emphasis, with certain harmonics apparently much more intense and those above and below progressively less intense, is only occasionally noted. It is sometimes stated that the fundamental frequency is "missing" and that certain harmonics are "enhanced". Perhaps a full complement of harmonics appear above the fundamental tone, or at other times the second and fourth (the even harmonics), are missing with only the odd harmonics present.

Fourier's theorem may be used to explain such phenomena. It is possible to choose parameters to fit a theoretical model of the sound being analyzed. However, it would appear more practical to examine the spectrographic analysis already made, and then describe the sound from the clues noted there. The reason for spectrographic sound analysis in the first place is to provide a convenient graphic description of that sound.

Analyses of sounds (pulses for example) having increments that are too short for the analyzing filters do not give a direct portrayal of the original wave-forms. However, the analyzer should be stable enough to react in essentially the same way each time the same sound is encountered. This would seem to allow us, through experience, to derive an indication of the original sound composition.

A simple uncomplicated 1000-Hz sine-wave tone is portrayed spectrographically on a machine such as the Kay Electric Company Vibralyzer (using the 20-Hz filter-bandwidth) as a single straight line across the paper. The tone is not pulsed and no other frequencies are present; therefore, no harmonics are indicated.

Now, let a 1000-Hz sine-wave tone be pulsed at the rate of approximately 166 pulses per second, with each pulse having only two cycles of the 1000-Hz tone, and separated by an interval equal to four cycles of 1000 Hz. An analysis of this would yield a spectrogram (Fig. 1,A) having parallel lines 166 cycles apart on the ordinate, the central and darkest line being at 1000 Hz. The repetition rate of 166 pulses per second appears not as a line at 166 Hz, but as the separation between the lines drawn at approximately 668, 834, 1000, 1166, and 1332 Hz. The analyzer portrays the difference and the sum of the pulse repetition-rate and the pulse tone. These are the beat-frequencies or side-bands of the two signal components. The 1000-Hz tone (frequency) of the pulses is the most prominent line drawn. The lines

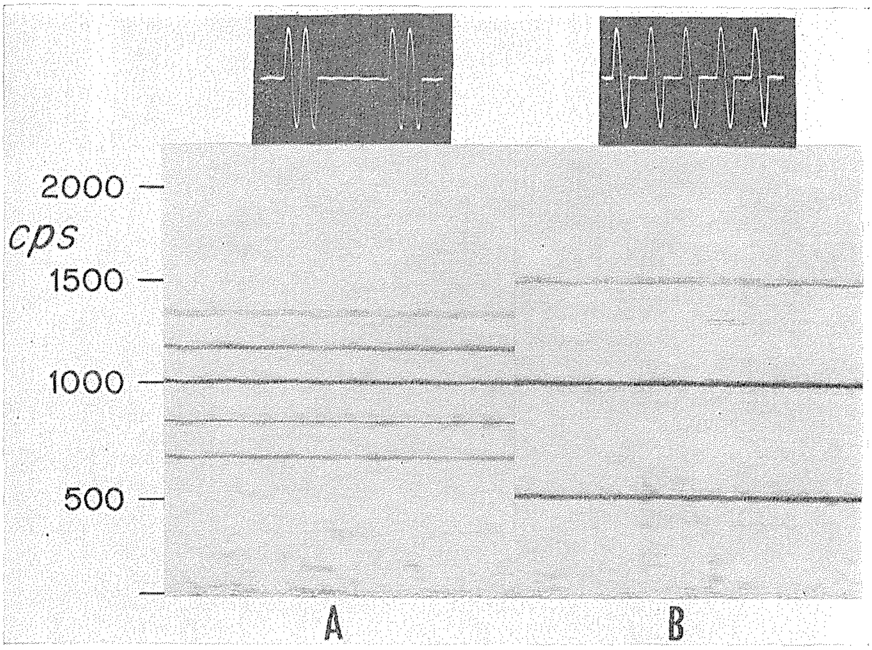

FIG. 1. A is a 1000-Hz tone pulsed at a rate of 166 pulses per second, each pulse containing two cycles of the 1000-Hz tone and each interval equal to four cycles. B is a 1000-Hz tone pulsed at a rate of 500 pulses per second, with one-cycle pulses and one-cycle intervals. The pulse repetition-rate is indicated by the harmonic interval. The analyzing filter bandwidth is 20 Hz.

at 1166 Hz and at 834 Hz are the sum and difference frequencies of the 1000-Hz tone and the 166-Hz repetition frequency. The lines at 1332 Hz and at 668 Hz are the sum and difference frequencies of the second harmonic of the repetition-rate (twice 166 Hz) relative to the 1000-Hz pulse tone.

The repetition-rate of 166 pulses per second was chosen in order to avoid coincidence between harmonics of the pulse repetition-rate and the tone frequency. Such a confusion might be possible, for example, with a 1000-Hz tone that is pulsed at a rate of 500 per second, each pulse containing one cycle, with an interval between pulses of one cycle (Fig. 1,B). The three prominent lines drawn on analysis would be at 500, 1000, and 1500 Hz. The 1000-Hz line would be relatively darker than the other two. A first interpretation of such a spectrogram might be that 500 Hz is the fundamental frequency, that 1000 Hz is an "enhanced" second harmonic, and 1500 Hz, a third harmonic.

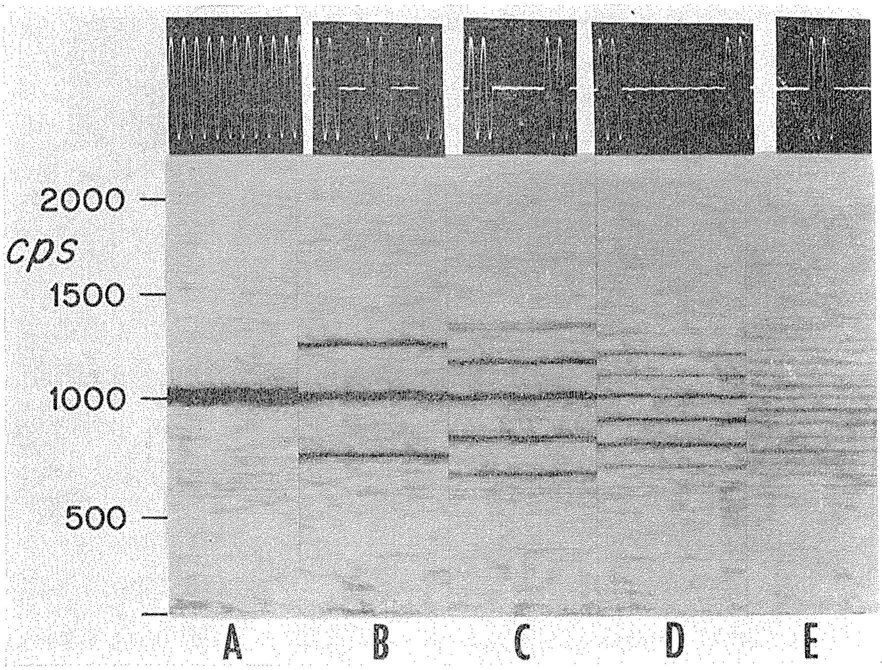

FIG. 2. A is a 1000-Hz tone; in B it is pulsed two cycles on and two cycles off; in C, two cycles on and four cycles off; in D, two cycles on and eight cycles off; and in E, two cycles on and sixteen cycles off. The amplitude of the 1000-Hz tone has remained constant throughout these analyses, yet note the decrease in intensity of the 1000-Hz pulse tone as the interval between pulses is lengthened. The pulse repetition-rate is again indicated by the harmonic interval. The analyzing filter bandwidth is 20 Hz.

The tone-frequency of the pulses becomes less prominently displayed and more harmonics of the repetition-rate appear as the interval between pulses becomes longer in relation to pulse duration (Fig. 2). Thus, a 1000-Hz tone that is pulsed two cycles to each pulse, with progressively longer intervals between pulses (two, four, eight, and sixteen cycles) on analysis appears to have an increasing number of parallel lines above and below the 1000-Hz line and progressively less emphasis of this line. The separation between these harmonic bands indicates the pulse repetition-rate. This repetition-rate structure is based on the sum and difference frequencies (the beat-frequencies of the pulse-rate to pulse-tone frequency) with additional harmonic lines being drawn below as well as above these frequencies at intervals equal to the pulse repetition-rate.

The analysis used here has been performed at a very low amplitude in order to eliminate distortion due to the magnetic recording system. This has, however, restricted the writing of harmonic bands only to those that are of relatively high amplitude. As the gain is increased on playback, other harmonics will appear. The energy levels in these harmonics are not equal and vary enormously with pulse repetition-rate and relative pulse duration (duty-cycle). Such an unequal harmonic energy distribution may be demonstrated mathematically, by using Fourier's theorem (and several pieces of paper). See, for example, Kinsler and Frey (1962). A train of pulses, each having one cycle of a 1000-Hz tone and intervals of three cycles (Fig. 3,A), when submitted to a Fourier computation, would have the following energy content in its various harmonics. Assigning a value of one to the total energy of the unpulsed tone:

The fundamental frequency of the pulse repetition-rate, the bottom line on Fig. 3,A, at 250 Hz would have an energy value of	0.014
The second harmonic (500 Hz) of the repetition-rate (second line from bottom) would have	0.044
The third harmonic (750 Hz), or the difference side-band frequency (of the repetition-rate and the pulse tone) would have	0.065
The fourth harmonic (1000 Hz) coinciding here with the pulse tone would have	0.062
The fifth harmonic (1250 Hz), or the sum side-band frequency (of the repetition-rate and the pulse tone) would have . .	0.028
The sixth harmonic (1500 Hz) would have	0.016

Additional higher harmonics may show if analysis is performed at greater amplitudes, but these will contain little energy.

The spectrographic analysis (Fig. 3,A) agrees quite well with the results of the Fourier computation (though the reproduction processes do not permit small differences in amplitude to show in the figures). The pulse tone here is actually fainter than the third harmonic, the difference side-band frequency. The fundamental of the repetition-rate (250 Hz) has relatively little energy and only barely writes in this analysis. Sections A B and C of Fig. 3 have the same 1000-Hz pulse tone and the same 250-cycle, repetition-rate, but different pulse durations (or duty-cycles). Section B is an analysis of two-cycle pulses with two-cycle intervals, and Section C is an analysis of three-cycle pulses with one-cycle intervals. Note the different amounts of energy in the harmonics in these three analyses.

Symmetry of the individual pulses and the intervals between pulses in a pulse train may be noted by the absence of even-numbered harmonics during their analyses (symmetrical pulses are those that have the pulse dura-

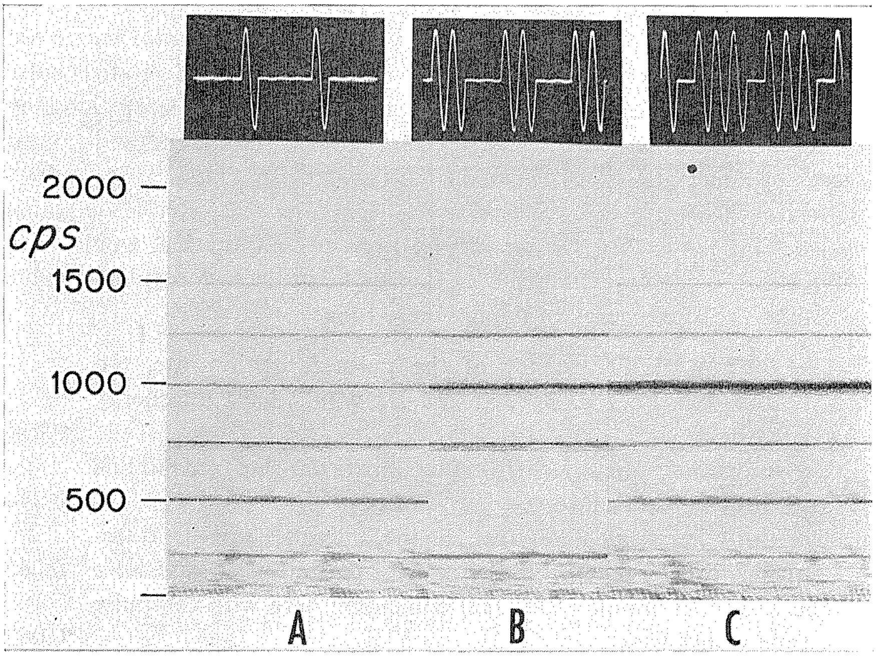

FIG. 3. A is a 1000-Hz tone pulsed one cycle on and four cycles off; in B it is pulsed two cycles on and two cycles off, and in C it is pulsed three cycles on and one cycle off. The repetition-rate of 250 pulses per second is the same for all three analyses. Note that the second harmonic of the repetition-rate is absent due to the symmetry of the pulses and pulse-intervals. The analyzing filter bandwidth is 20 Hz.

tion and interval between pulses equal, this is a duty cycle of one-half). The even-numbered harmonics (second, fourth, sixth, etc.) have no energy and are therefore not found in spectrum analysis of trains of symmetrical pulses (unless these harmonics coincide with the pulse tone or the sum and difference frequencies). This agrees with the results of a Fourier analysis computation, for example, of a 1000-Hz tone pulsed one-cycle-on and one-cycle-off (as in Fig. 1,B). Assigning an energy value of one to the unpulsed tone:

The fundamental of the repetition-rate (500 Hz, the bottom line of Fig. 1,B), coinciding here with the difference side-band frequency (of the pulse-tone and the repetition-rate), would have an energy value of	0.178
The second harmonic of the repetition-rate (1000 Hz), coincides with the pulse-tone frequency, and would have . . .	0.250
The third harmonic of the repetition-rate (1500 Hz), coinciding with the sum side-band frequency (of the pulse-tone and the pulse repetition-rate), would have	0.064
The fourth harmonic (2000 Hz) would have	0.000
The fifth harmonic (2500 Hz) would have	0.004
The sixth harmonic (3000 Hz) would have	0.000

Figure 1,B is such a symmetrically pulsed 1000-Hz tone. The pulse tone coincides with the second harmonic of the repetition-rate and so a line is drawn at 1000 Hz, but the fourth harmonic (2000 Hz) is absent.

Figure 3,B is also a 1000-Hz tone pulsed symmetrically, two cycles per pulse with intervals between pulses equal to two cycles. Here the fourth harmonic coincides with the pulse-tone, but the second and sixth harmonics are absent.

The fewest harmonics appear during analysis when pulses in a pulse train are symmetrical (duty-cycle of one-half). The energy spectrum in many trains of symmetrical pulses is such that only three bands are indicated, including the pulse-tone and the sum and difference frequencies of the repetition-rate, as in Fig. 1,B. The greatest number of harmonics appear when the pulse duration is either very long or very short relative to the interval between pulses (asymmetrical).

The pulse duration relative to the interval between pulses (duty-cycle) largely controls the amount of energy in the pulse tone-frequency. Figure 2 is an example of a series of analyses of pulse trains in which the pulse is made progressively shorter in relation to the interval between pulses (shorter duty-cycle) with a corresponding reduction in intensity at the pulse-tone frequency of 1000 Hz. On the other hand, Fig. 3 shows the opposite characteristic, because here the pulse is lengthened relative to the interval between pulses. Consequently, the pulse tone is more and more prominently written. All of the pulse trains in Fig. 3 have the same repetition-rate for the sake of comparison.

The analysis of sine-wave pulse trains whose tone-frequencies and repetition-rates vary is illustrated by Figs. 4, 5, and 6. The pulse repetition-rate continues to show as the separation between harmonic bands. Figure 4

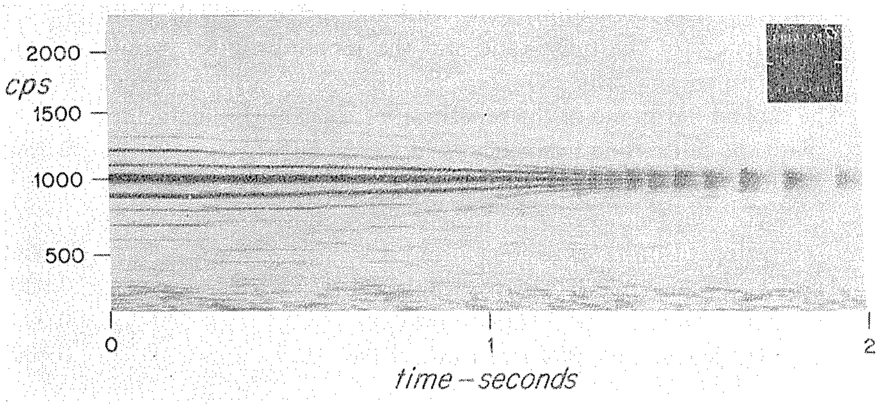

FIG. 4. The intervals between eight-cycle pulses at 1000 Hz is varied in two-cycle steps from two cycles to about 100 cycles (of the 1000 Hz). The pulse repetition-rate may be read from the harmonic interval until the pulse becomes separated. The analyzing filter bandwidth is 20 Hz.

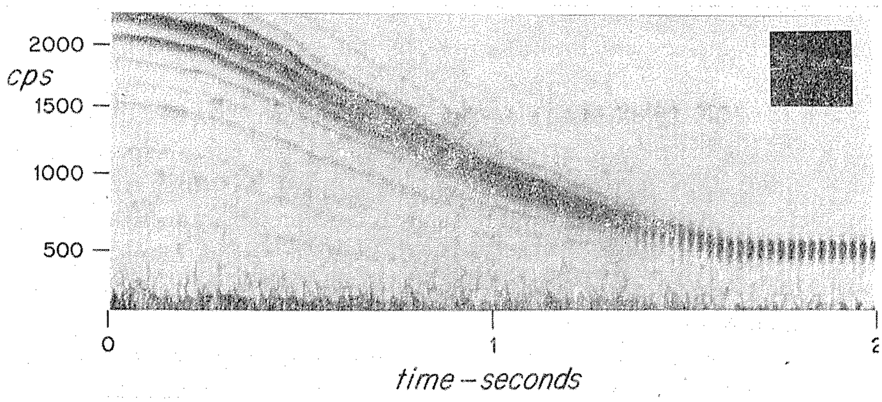

FIG. 5. Eight-cycle pulses at changing frequency are separated by about ten-cycle intervals. The repetition-rate is progressively lowered as the tone frequency is dropped. The analyzing filter bandwidth is 200 Hz.

shows an analysis of a series of sine-wave pulses at 1000 Hz, each pulse composed of eight cycles of 1000 Hz. The interval between pulses is varied in two-cycle steps from two cycles (of 1000 Hz) to approximately 100 cycles, slowly at first and then more rapidly.

When both the pulse-tone frequency and the pulse-repetition-rate are progressively and simultaneously lowered, a sloping frequency pattern is produced along with converging harmonic bands. Figure 5 shows an analysis of a series of sine-wave pulses, eight cycles in duration with approximately ten cycles between pulses, dropping from a pulse-tone frequency of over 2200 Hz to about 500 Hz.

The pulse tone-frequency may, of course, vary independently from the changes occurring in the repetition-rate. Figure 6 shows an analysis of a series of sine-wave pulses; each pulse is two cycles in duration, composed of

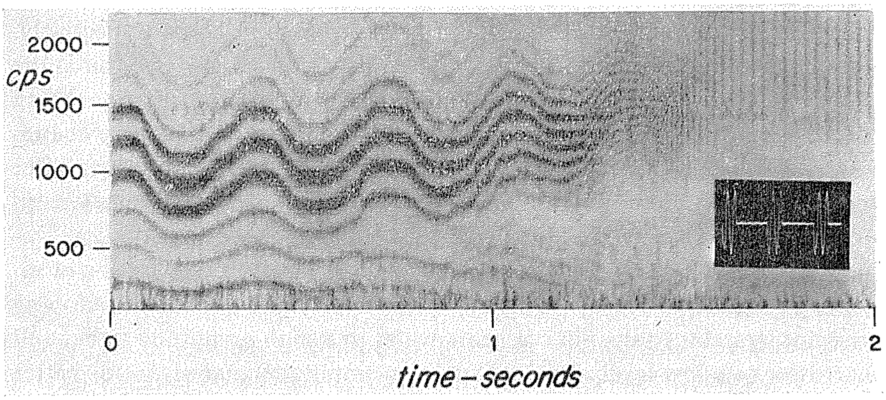

FIG. 6. The pulse tone and the repetition-rate are varied separately here. The pulses are two cycles in duration and the repetition-rate is progressively slowed from approximately 400 pulses per second to about 50 per second as is indicated by the harmonic interval. The analyzing filter bandwidth is 200 Hz.

varying tone-frequency (and, of course, of varying duration with frequency) the pulse repetition-rate progressively slows from approximately 250 pulses per second to 30 per second.

The "wide" analyzing filter (200-Hz) bandwidth has been used in these last two examples (Figs. 5 and 6); all the other analyses figured above have been made with the "narrow" filter. The 200-Hz filter discriminates pulses much more readily than the 20 Hz filter used in Fig. 4, for example. These latter pulses are actually 8 msec in duration, but are occupying nearly 100 msec of the record. The narrow filter, however, gives a better indication of the frequency of the pulses, even though it does not resolve time as well. Conversely, the wide filter provides a better time discrimination, but a relatively poorer frequency plot (compare pulses in Figs. 4 and 6). Note that there is a difference in the time and frequency spread of the pulses in Figs. 5 and 6. These analyses are made with the identical filter bandwidth (200 Hz). The eight-cycle pulses of Fig. 5 show a strong indication at the pulse tone-frequency, but the relatively short two-cycle pulses of Fig. 6 are more spread-out in frequency.

The resolution of both frequency and time, as noted above, is dependent on the filter-bandwidth used during analysis. The Vibralyzer has basic 60 and 600-Hz bandwidth filters at 15,000 Hz (see Kay Electric Company's instruction manuals), but are modified by various speed changes. The filters are effectively made narrower as the turntable speed is slowed, thus, "Lo" at one-third the speed of "Hi" gives effective filter widths of 20 Hz (one-third of 60) and 200 Hz for "Narrow" and "Wide" filters, respectively. Since the total information bandwidth is also reduced (by one-third) the filter time-constants remain the same relative to the information being processed. Similar shifts in frequency and time may be effected by changing the tape speed of the material under analysis. If the analyzer filter system had perfect non-band-pass rejection and perfect pass-band acceptance, then for example, the wide 200-Hz filter-range would allow frequency discrimination to no closer than 200 Hz, and pulse separation of no more than 200 per second. However, the filter skirts are actually sloping and not straight, so the filter appears wider to a high-amplitude signal and narrower to a low-level signal. Thus, low-amplitude analysis yields better frequency and time resolution. Also a steady signal or a steady repetition-rate allows some interpolation and improves the apparent resolution of analysis of these sounds.

Three clues are necessary for intelligent reading of spectrographic analysis: (1) filter bandwidth, (2) frequency scale; (3) time scale. Unfortunately, only the last two of these appear in most published spectrograms. The effective filter bandwidth is required to assess the resolution. This is especially important with the advent of analyzers permitting expanded scales with different portions of the spectrum opened and drawn full-width during analysis. The statement of the effective filter bandwidth (as was given by Koenig, Dunn and Lacy, 1946) reduces ambiguities resulting from speed changes and helps keep in focus some of the various artifacts of the machine. The filter bandwidth just as surely labels the parameters of the discrimination of frequency and time as the scales define which frequencies and times are portrayed. The filter bandwidth should be indicated on every published spectrogram!

The above remarks apply in general to the Kay Electric Company Spectrum Analyzers and in particular to the "Vibralyzer". However, they also apply in principle to all spectrum analyzers. The effective filter bandwidth defines the limits of the reliability of these analyzers.

This effective filter bandwidth should be given in a way that takes into account all speed variations during analysis. For example, the 600-Hz bandwidth filter on the Kay Vibralyzer becomes 200 Hz wide (one-third of 600) when used in the Hi-Lo range (which is one-third the turntable analyzing speed), and this 200-Hz filter becomes effectively an 800-Hz bandwidth filter when recorded sounds are played to the analyzer at one-fourth original speed. Both the internal turntable speed changes and the external tape-speed changes have to be considered in deriving the effective filter bandwidth used during analysis.

To recapitulate, several descriptive features may be indicated by spectrum analysis of a rapid series of sine-wave pulse bursts:

1. The repetition-rate of the pulses may be determined accurately by the separation between harmonic bands.
2. The pulse tone-frequency may usually be determined by the central "harmonic" line drawn, or by the darkest line if the pulse duty-cycle is relatively long.
3. The pulse duration (duty-cycle) relative to the interval between pulses may be estimated by the darkness or lightness of the pulse tone-frequency compared to that of the repetition-rate harmonics.
4. Symmetry of the pulses may be noted by the absence of even-numbered harmonics.
5. The relative increase or decrease of pulse length to pulse interval (long or short duty-cycle) may be indicated by the increasing number of repetition-rate harmonics (during low-level analysis).
6. Variation in the above parameters may be noted within the limits imposed by the effective filter bandwidth used during analysis.

So far the discussion in this paper has been confined to sine-wave signals. Other wave forms, however, are encountered in animal sounds. These sounds are composed, in large part, of impulses and trains of pulses that are usually not sine-wave in character; although nearly pure-frequency sine-wave pulses have been noted, for example from *Balaenoptera* (Schevill, Watkins, and Backus, 1964). Spectrum analysis of trains of pulses of a wide variety of wave forms, however, have many of the same characteristics as those listed above for sine-wave bursts.

There are two extremes in bio-acoustic pulses: the sine-wave which exhibits a single-frequency characteristic and the spike (a very short pulse of energy) which during analysis appears as if it were composed of all frequencies. All other pulse-types appear to fall somewhere in between these two extremes. (See Broughton, 1963, for a discussion of the use of these pulse terms.)

A single spike in spectrum analysis appears as a vertical line with energy displayed at all frequencies. A rapid train of spikes, however, resolves into discrete harmonic bands. The interval between these harmonics, again,

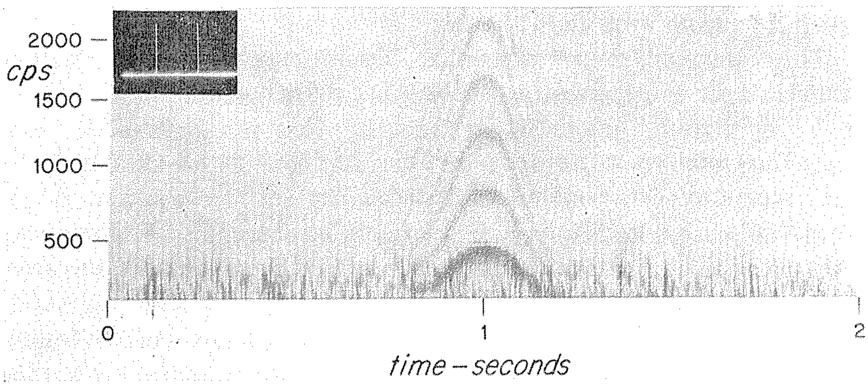

FIG. 7. A train of spikes whose repetition-rate of about 50 per second is momentarily speeded-up to nearly 400 per second and then returned to its 50-per-second rate. The harmonic interval as well as the fundamental indicates the repetition-rate when pulses can no longer be separated. The analyzing filter bandwidth is 200 Hz.

indicates the repetition-rate but in contrast to sine-wave pulse-trains, there is considerable energy at the fundamental frequency of the repetition-rate. Figure 7 shows an analysis of a series of spikes whose repetition-rate is momentarily speeded up to about 400 pulses per second and then returned to its 50-per-second repetition-rate.

A train of spikes may in turn be pulsed in bursts (just as a train of sine-waves may be produced in bursts) and an analysis of such a series of burst-pulsed spikes is similar to analyses of pulsed sine-waves. Compare Fig. 8 with Fig. 3 (note the different scale of Fig. 8). Here a 1000-spike-per-second signal is pulsed at a repetition-rate of 250 per second, the number of spikes per burst changing from one to three in A through C respectively. The burst repetition-rate is indicated by the interval between harmonic bands.

The sum and difference sideband frequencies of the burst repetition-rate and the frequency of the spike tone are shown, as well as harmonics of the 250-per-second burst repetition-rate. These are all centered on the tone-frequency of 1000 Hz on the scale, and unlike sine-wave bursts, they are repeated at each harmonic of the 1000-Hz signal tone (at 2000, 3000, and 4000 Hz). Note in Section B of Fig. 8 that the even-numbered harmonics of the 250-per-second pulse-burst repetition-rate are missing, due to the symmetry of the train of two-spike-pulses and two-spike-intervals; yet since the spikes themselves are not symmetrical, the even-numbered as well as the odd-numbered harmonics of the 1000-spike-per-second tone are present.

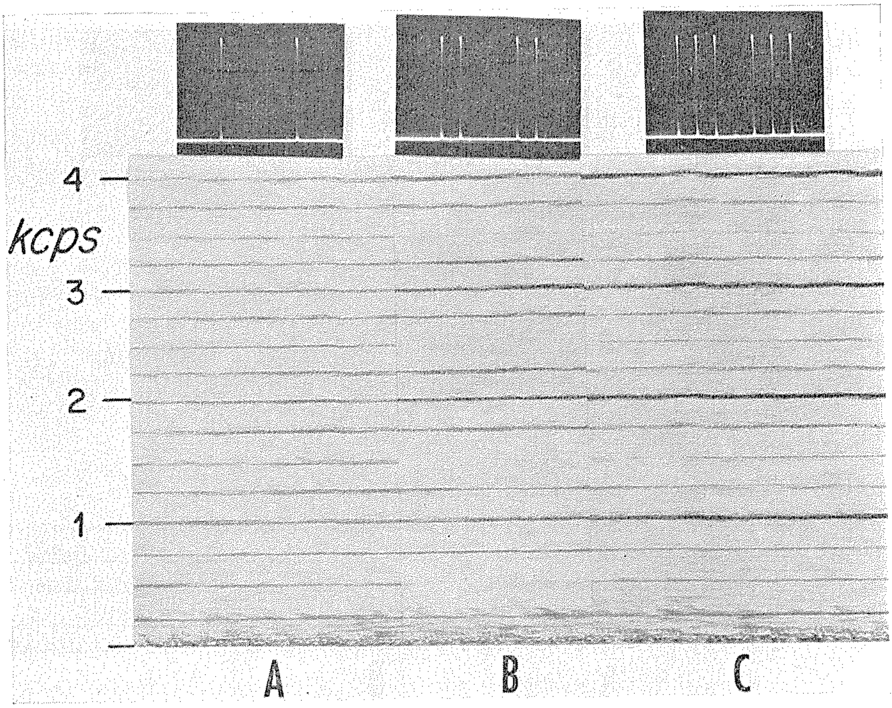

FIG. 8. A 1000-spike-per-second signal is burst-pulsed at a repetition-rate of 250 per second, with one spike per burst in A, two spikes per burst in B, and in C, three spikes per burst. The second harmonic of the repetition-rate is missing in B because of the symmetry of the pulse burst relative to the interval between bursts. The 1000-spike-per-second tone of the pulse-burst is established even though there are only two spikes per burst. The analyzing filter bandwidth is 20 Hz.

In contrast, Fig. 9 is an analysis of a symmetrical square-wave pulse train. Again, the 1000-pulse-per-second signal is in turn pulsed in bursts at a repetition-rate of 250 per second; the number of square-wave pulses per burst is varied from one to three in Sections A through C respectively. The harmonic-structure of the pulse-burst repetition-rate resembles the analysis of similar trains of spikes and of sine-waves (see Figs. 8 and 3). The square-wave pulses contain much more energy for a given duty-cycle and so, at the same amplitude of analysis, the fundamental of the pulse-burst repetition-rate is much more prominently displayed. The square pulses have strong harmonics; yet, because of the symmetrical shape of the individual pulses, only the odd-numbered harmonics of the pulse tone are indicated. The 250-per-second harmonic structure of the pulse-burst

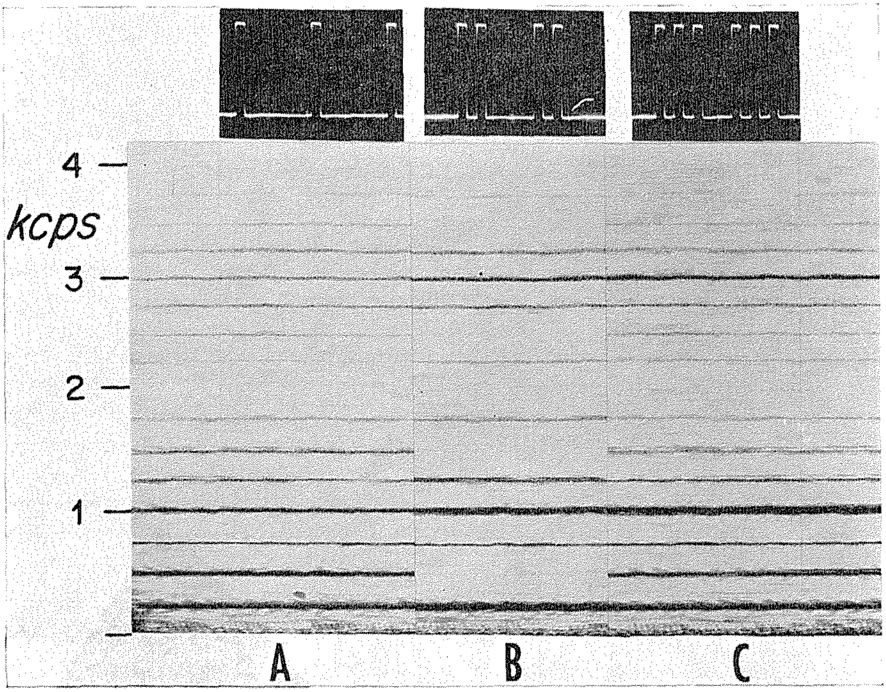

FIG. 9. A train of 1000 square-wave pulses per second is burst-pulsed at a rate of 250 bursts per second. A has one pulse per burst, B has two pulses per burst and C has three pulses per burst. Note that (in A, B and C) the second harmonic of the pulse tone (at 2000 Hz) is missing due to the symmetry of the individual square pulses relative to the intervals between pulses, and in B the second harmonic of the repetition-rate is also missing because of the symmetry of the pulse bursts relative to the intervals between bursts. The analyzing filter bandwidth is 20 Hz.

repetition-rate is centered on 1000 Hz (the pulse tone) and on 3000 Hz the third harmonic of the pulse tone.

Spikes or other pulses, that are short or long (in duty-cycle) compared to the interval between pulses, will produce a spectrogram that exhibits many harmonics (true of pulse asymmetry of any sort).

In natural sounds there is no sharp line of demarkation between a pulse train of closely spaced pulses and one of widely spaced pulses. The train of closely spaced pulses, in analysis that does not separate the pulses, will show a fundamental at the repetition frequency (if the pulses are not like sine waves) and harmonics of that frequency that are a result mostly of the repetition-rate. A train of more widely spaced pulses (with lengthened intervals between pulses) will exhibit a repetition-rate harmonic structure having the character of a train of pulse-bursts; the pulse tone is established by the duration of the individual pulses and the harmonic spacing by the repetition-rate. The high frequency limit of the repetition-rate structure in both cases depends on the high frequency content of the individual pulses. Any short pulse produced at relatively longer intervals will produce a spectrogram having a burst-pulsed character. Our experience has been that most sounds (in low-level undistorted analysis) having more than three or four well-defined harmonics appear to be pulsed, i.e. the wave-trains have intervals between wave segments (as determined by oscilloscopic photography).

Generally, information may be obtained more readily about these pulsed sounds if analyzing filter bandwidths are chosen to bring out the repetition-rate harmonic structure, than is possible when pulses are separated during spectrum analysis. Gross repetition rates usually are more easily read from the harmonic interval than from a count of discrete pulses. A narrower filter during analysis or a slower analyzer recording speed will allow a train of rapid but discrete pulses to be resolved into banded harmonic structure (see Schevill, 1964, p. 309).

The term "pulsed" has been used throughout, indicating that the tone frequency is modulated from cutoff, or nearly so, to 100 per cent of the signal tone. This modulating frequency or pulse repetition-rate is not another frequency mixed with or added to the first. Instead, it is an effect on the first frequency (of gating) repeated regularly enough to assume the character of a second frequency but has little energy of itself. On the other hand, a real second frequency mixed with the first would have energy components of its own and upon spectral analysis would separate readily into two discrete frequencies[4] (with no sum and difference side-band components). It is perfectly possible to have modulation that does not go to 0 per cent or to 100 per cent, and in such cases the spectrographic analysis would look quite similar to the burst-pulsed pattern except for relatively more or less energy displayed at the tone frequency (see Hund, 1942, and Terman, 1955, for modulation theory).

Figure 10 shows a series of 1000-Hz pulses whose shape is typical of a damped resonant system. The pulse repetition-rate is increased from 50 to about 320 per second. The repetition-rate of the rapid pulses may be read from the harmonic interval.

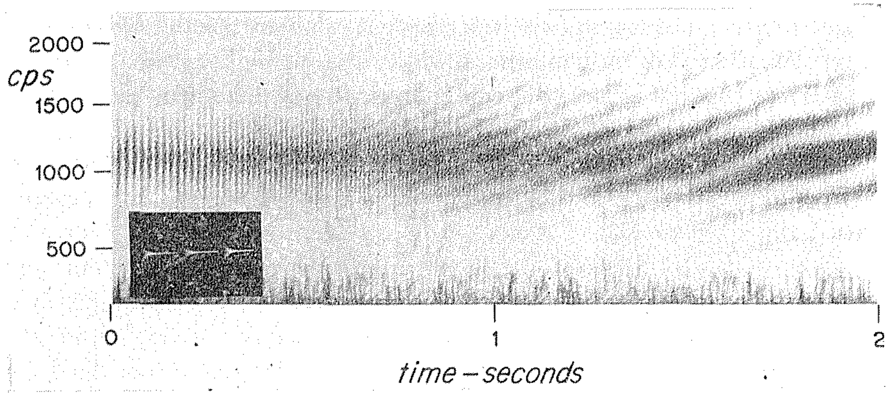

FIG. 10. A train of 1000-Hz damped sine-wave pulses is produced at an increasing repetition-rate from 50 per second to about 320 per second. The analyzing filter bandwidth during analysis is 200 Hz.

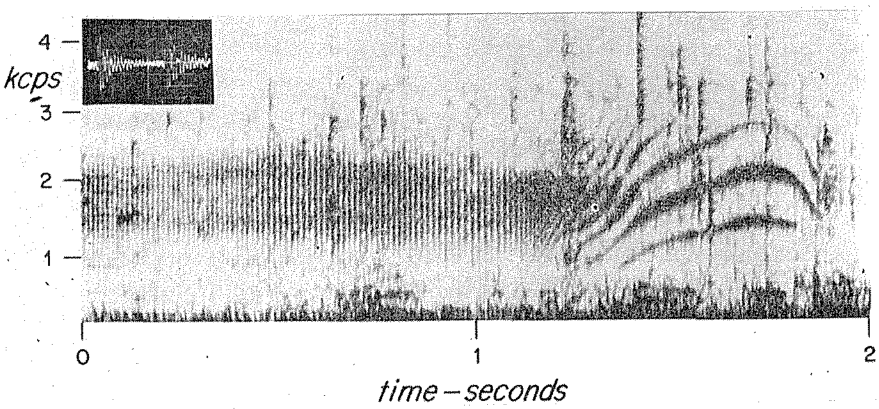

FIG. 11. A click series produced by *Phocoena phocoena* has burst-pulsed structure as the click rate is increased from about 60 clicks per second to a maximum rate at about 700 per second. This recording was made by Dr. Carleton Ray in Passamaquoddy Bay, Maine. The analyzing filter bandwidth is effectively 200 Hz.

Phocoena phocoena (harbor porpoise) produces a narrow-band click that is fairly low in frequency (Busnel, Dziedzic, and Andersen, 1963; Schevill, Watkins, and Ray, MS.). The repetition-rate of these pulses may be varied over quite a wide range. Figure 11 shows a change in the repetition-rate of *Phocoena* clicks from about 60 per second to approximately 600 clicks per second (compare with Fig. 10). The clicks are nearly single frequency in character, at about 2000 Hz. The repetition-rate structure indicates that at the time of the highest click-rate there was close to a condition of symmetry between the clicks and the intervals between the clicks; no second harmonics are shown.

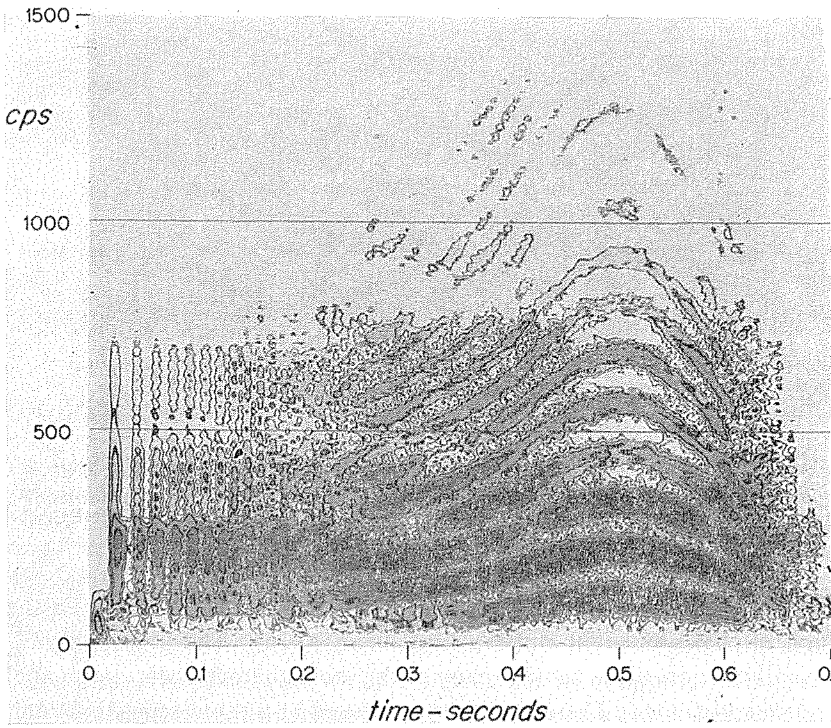

FIG. 12. Clicks produced by *Tursiops truncatus* are reduced to harmonic structure as the click rate is increased. The highest repetition-rate here is about 110 clicks per second and may be read from the harmonic interval. This is a contoured spectrogram, with 6 db between adjacent contours, made by Signatection Research, Inc., Waltham, Mass. on their Spectral Contour Plotter (Model ST-701). The recording was made by the Marine Biology Facility of the Naval Missile Center at Point Mugu, California. The effective bandwidth of the analyzing filter is 60 Hz.

The contoured spectrogram (Fig. 12, made by Signatection Research, Inc.) is of a similar series of *Tursiops* clicks. This demonstrates that even widely different types of spectrum analyses produce the same sort of spectrogram of equivalent sounds. In this analysis, amplitude-level contours are arranged with 6 db between adjacent contours. The *Tursiops* clicks are not single-frequency clicks and are generally characterized by short rise-times. The pulse repetition-rate harmonics effectively obscure much of the information about the individual clicks; the dominant frequency in the original pulses appears as the pulse tone. The repetition-rate varies in this sample from about 45 per second to approximately 110 clicks per second, as indicated by the interval between harmonic bands.

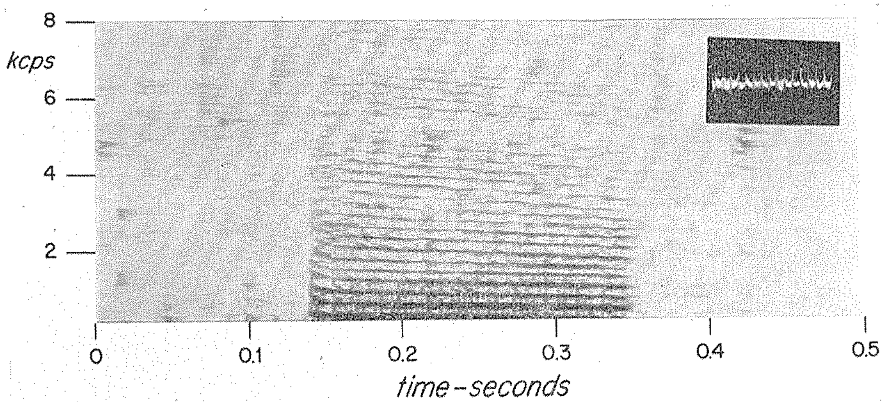

FIG. 13. A rasp produced by *Grampus griseus* shows a simple pulsed pattern at a repetition-rate of about 250 clicks per second. This recording was made on 29 July 1959 about 150 miles SE. of Cape May, N.J., WHOI Cruise BEAR 219. The effective bandwidth of the analyzer filter is 80 Hz.

Grampus griseus, as a part of its repertory, habitually produces a short burst of clicks (Schevill and Watkins, 1962, p. 16). The *Grampus* click is typically a short pulse having many of the same characteristics upon analysis as a spike does. These clicks are produced at a rapid repetition-rate to form the rasp sound. Figure 13 is a *Grampus* rasp whose clicks are produced at a repetition-rate of approximately 250 per second; this is not burst-pulsing, but is simply a steady repetition of broad-band clicks. The duration of this rasp is approximately 0.2 sec; therefore, the rasp contains about 50 clicks. Figure 14, on the other hand, is also a *Grampus* rasp but here there is an indication of burst-pulsing. The pulse tone is at approximately 2500 Hz on the scale. The pulse-burst repetition-rate is approximately

330 per second as is indicated by the harmonic interval; it is slowly changing downward. The duration of this rasp is about 0.33 sec, and so the rasp contains nearly 110 click-bursts. Solitary *Grampus* clicks from other animals are in the background; note their wide-band spike-like characteristic emphasizing nearly all frequencies equally.

Burst-pulsed sounds, however, may have the same spectrum as do pulsed sounds in the presence of resonances at the particular harmonics of the pulse repetition-rate. Such a harmonic resonance is excited by a lower frequency sound and has much of the same character as a high frequency sound that is modulated at a lower frequency rate. Spectrographic analysis by itself cannot tell the difference between these two harmonic systems if

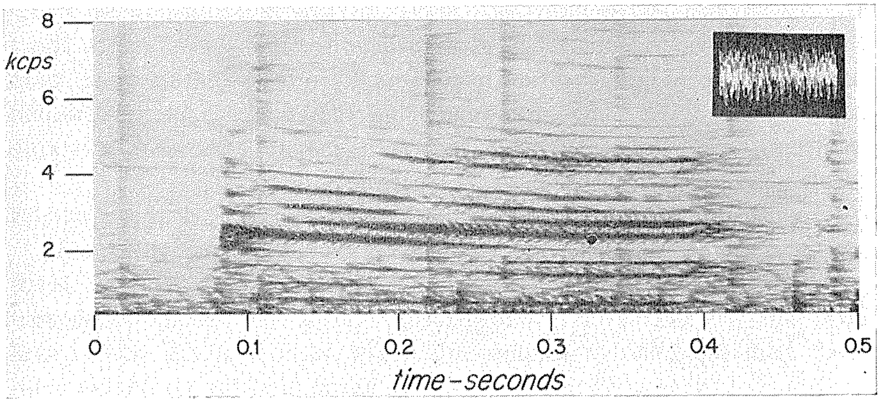

FIG. 14. A rasp produced by *Grampus griseus* shows a burst-pulsed pattern at a repetition-rate of about 330 clicks per second; the pulse tone is at about 2500 Hz. Note the solitary spike-like clicks in the background. This recording was made on 26 July 1959, 150 miles SE. of Cape May, New Jersey, WHOI Cruise BEAR 219. The effective filter bandwidth of the analyzer is 80 Hz.

the emphasis in both happens to coincide, but a knowledge of the sound source can perhaps indicate which would be the most appropriate. Burst-pulsed (or modulated) tones and tones with harmonic resonances are both sound systems that derive their spectral energy essentially from one tone frequency, hence the confusion of similar spectrographic analysis. For example, a fish having muscle movement at one frequency (or repetition-rate) could perhaps excite a swimbladder as a resonator at a second higher frequency. If the swimbladder were a more efficient sound radiator than the muscle movement, per se, the combined sound could have the character of a burst-pulsed or modulated tone, the tone being the natural frequency of the swimbladder and the muscle motion providing the modulation. If, on the other hand, the resonant frequency of the swimbladder coincided with one or more of the harmonics of the muscle repetition-rate and acted instead simply to emphasize those particular harmonics, the pulsed sound could have much the same character on analysis as it would for burst-pulsed sounds. The two systems cannot be readily distinguished on a spectrogram and consequently the latter has been the usual explanation for pulsed sounds having harmonics of varying intensity. (If noise backgrounds do not mask the sound structure, oscillographic presentations may distinguish between these two systems.) I offer that burst-pulsed modulation may be the commonest of the two systems in natural sounds.

It is not necessary to have particularly complicated biological systems, however, to produce sounds that could have complicated side-band structure during spectral analyses. Any mechanism that can create a short duration pulse and then wait a while before it produces another pulse could do it, the higher frequency pulse tone being created by the pulse duration in the train of short pulses, and the lower frequency repetition-rate structure formed by the relatively long intervals between pulses.

Repetitive patterns in the relatively slow clicking rates of sperm whales have been noted and called burst-pulsing by Backus and Schevill (1966).

One type of call produced by *Trichechus* (Schevill and Watkins, 1965) upon analysis has several wide-spaced harmonics at higher amplitude-levels than the 2500-Hz fundamental. The authors give a very careful catalogue of the relative intensity of these harmonics, but no further comment is made regarding the composition of the call. It was a pulsed call and could have been produced by a broad resonant system (resonating at second, third, and fourth harmonics). It could also have been a burst-pulsed call with the 7500-Hz pulse-tone modulated at a 2500-per-second rate. Oscilloscope photography appears to confirm the latter.

The "boatwhistle" sounds from *Opsanus tau* as described by Tavolga (1958, 1960), Winn (1964), and Fish (1958) are other examples of pulsed sounds and perhaps they are burst-pulsed. Most of these calls resolve (in the published analyses) into at least three strong harmonically related bands with additional harmonics present at lower amplitudes depending perhaps on environmental reflections and analysis and recording amplitudes (Tavolga, 1964). The fundamental frequencies vary depending on the locality at which the toadfish are found; the northward populations having progressively lower frequencies (Tavolga, 1965). The Woods Holz *Opsanus tau* has an average lowest frequency around 130 Hz; this is 10 He lower than the sounds from the Narragansett Bay toadfish. The interval between harmonics appearing in spectrograms of this sound averages 130 Hz, indicating the pulse repetition-rate. These appear to be burst-pulsed sounds with the pulse tone at 260 Hz. This gives a pulse duty-cycle of one-half, having one pulse and then an interval equal to one pulse. A variety of *Opsanus tau* boatwhistles recorded in Woods Hole are shown in Fig. 15 as matching oscillographic and spectrographic records. All of these have a predominant component at about 260 Hz, the pulse tone, and all are pulsed or modulated at a rate of 130 per second; every other cycle of the tone is emphasized. In A (Fig. 15) this emphasis is such that the

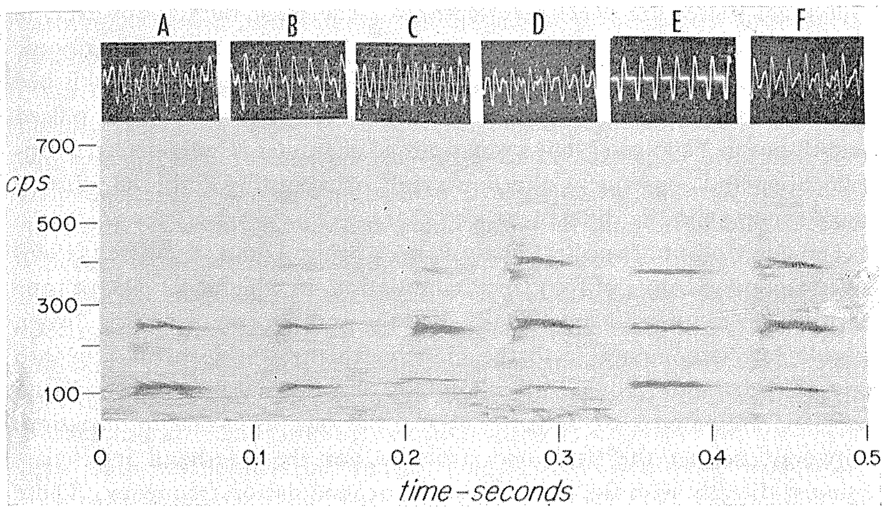

FIG. 15. A series of boatwhistle calls from *Opsanus tau* recorded in Woods Hole during 1960 and 1961, each call (in A, B, C, D, and F) probably from a different fish; E is an artificial call. All these show some pulsing or modulation of a basic 260-Hz tone, at a pulse repetition-rate of 130 per second. The oscilloscope photographs are of the central portion of the corresponding spectrograms below. The filter bandwidth of the analysis is 6 Hz.

repetition-rate or modulating frequency is predominant (though indicated in the oscillographic record as pulsing of the 260-Hz tone). In B the third harmonic of the repetition rate is beginning to show. In C the pulse tone is predominant with only a suggestion of the repetition-rate modulation appearing. Single-cycle pulses with intervals equal to one cycle between pulses are shown in D and F. For comparison, an artificial toadfish call with a 260-Hz tone pulsed at a rate of 130 per second is shown in E.

Opsanus beta, the Gulf coast form of this fish has the same type of "boatwhistle" call, though different in frequency. In the published spectrographs of the sound of this fish by W. N. Tavolga (1960, pp. 119–120), for example, the harmonic arrangement appears to have the typical burst-pulsed character and here is not as confusing as *Opsanus tau* whose call is low in frequency, with a repetition-rate structure that coincides with a possible simple pulse-fundamental and harmonic system. The *Opsanus beta* call appears to have a pulse tone at approximately 1000 Hz, and a pulse repetition-rate of about 330 per second. The third harmonic of the pulse tone with its associated repetition-rate structure reappears at 3000 Hz, the second harmonic of the pulse tone is missing, indicating that the individual pulses are nearly symmetrical. The pulse-bursts, however, in this recording appear not to be symmetrical since the second harmonic of the repetition-rate is quite strongly indicated. The older published spectrograms of *Opsanus beta* in Tavolga (1958) show a simple pulsed sound, but in Tavolga (1960) a burst-pulsed character is indicated; perhaps reflections and consequent phase reversals or recording amplitude distortions can explain the differences.

The description of spectral analysis by Koenig, Dunn, and Lacy (1946) gives a good example of frequency modulation, in which a sine-wave tone is varied (in frequency) sinusoidally, and the authors comment that "when warble rate is comparable to the filter width the warble breaks up into discrete side-band frequencies". Analysis of a varying rate of broadband pulses is presented also, showing clearly the repetition-rate information. However, neither the harmonic structure nor the side-band interval is equated directly with the repetition-rate, or modulation frequency. There have been many other examples in the literature of various properties of pulse trains and their spectral compositions, although these have generally not been applied directly to instrumental spectrum analysis (see, for example, von Békésy, 1961; Small and McClellan, 1963; Campbell, 1963). Potter, Kopp and Green (1947, p. 414) in one instance refer to a spectrogram of a speeded-up heart beat, and state that "the 'overtones' of the beat rate appear as clean-cut horizontal lines", but in other examples this phenomenon appears to have been only partly understood (see pp. 311 and 312). These repetition-rate and pulse-burst features are readily noted from spectral analysis of sounds and certainly they follow all the theoretical rules of harmonic composition of periodic waves; yet they have been ignored by most workers. The presence of many harmonics or of varying harmonic intensities in an analyzed sound may be missed completely, even when it would appear that useful information may be contained in the harmonic structure.

Tavolga (1964, p. 202 and 1965, pp. 41–45) has worried in print about "harmonic sounds" and has catalogued many variables in the harmonic structure recorded from *Opsanus* depending on distance, location, depth of water, etc. His conclusion that these harmonics may not be reliable is appropriate, since great care is required during both recording and analysis to avoid the introduction of artificial sound structure and wrong emphasis of existing harmonics (a result of transient overload of equipment, see Watkins, 1966). However, if repetition-rate information is desired, these harmonics do need attention.

The only reference noted in the bio-acoustic literature to the use of the harmonic interval in obtaining modulation or pulse-rate is found in the description of a curious noise called the "boing" by Wenz (1964). A few other authors have connected the banded structure with modulation or pulsing; but apparently have not recognized repetition-rate. Fish and Mowbray (1962) recognized one instance of side-band structure from *Delphinapterus leucas* as a possible indication of modulation, but did not note the connection between rate and harmonic interval in other sounds. Vincent (1960) said that a rapid click series sounded like "un miaulement", but did not take note of the repetition-rate information available in the spectrographic analysis. Van Bergeijk commented in the discussion following Winn's paper (1964, p. 230) on fish sounds that more rapid pulses would, of course, resolve into harmonic frequencies. Gales (1966) and Busnel and Dziedzic (1966) gave spectrographic evidence that the narrow filter made harmonic structure for trains of pulses that could be separated by a wide analyzing filter. The possibility, however, that side-band structure in bio-acoustic analysis may be a result of burst-pulsed sound has apparently not been noted previously in the literature.

Other authors in discussing published spectrum analyses of apparently pulsed and burst-pulsed sounds with many close harmonics and typical pulsed patterns have simply described these as "harmonic" or else ignored this property completely. The following list demonstrates the widespread occurrence of the pulsed quality of natural sounds even though they have not been recognized:

For fishes, these include—Winn (1964), Tavolga (1958, 1960, 1962, 1964), Hazlett and Winn (1962), and Fish (1964).

For cetaceans—Lilly (1962), Lilly and Miller (1961), Evans and Prescott (1962), Rehman (1961), Fish and Mowbray (1962), Tavolga (1965), and Busnel, Dziedzic and Andersen (1963).

For amphibians and reptiles—Littlejohn (1959), Littlejohn and Martin (1965), Zweifel (1959, 1964a, 1964b, 1965), Frishkopf and Goldstein (1963), Marler (1963), Blair (1956, 1957, 1958, 1963), Blair and Pettus (1954), and Bogert (1960).

For birds—Thorpe (1954), Marler (1957), Snow (1963), Borror (1954), Collias (1960, 1964), Collias and Joos (1953), Bremond (1963), and Lanyon (1960).

For insects—Alexander (1957), Alexander, Moore, and Woodruff (1963).

For mammals (other than cetaceans and including some human voiced sounds)—Andrew (1963), Bartholomew and Collias (1962), Steinberg and French (1946), Ladefoged and Broadbent (1957), Halle, Hughes and Radley (1957).

Griffin (1958, p. 240) suggests that "the ideal way" to describe some of the bat pulsed sounds would "be in terms of a frequency spectrum"; and indeed spectral analysis should yield a great deal of information about repetition-rates and pulse-modulation-rates as described for example from the bat *Carollia.*

In areas other than bio-acoustics the repetition-rate information available from the harmonic interval has been missed during spectral analysis, even though appearing to be potentially of interest to the authors. For example, see Agilides, Bernardini, and Zinsmeister (1964), in their investigations of electric pulses produced by fishes. It seems likely that spectral analysis could benefit any investigation of periodic phenomena, if the repetition-rates can be fitted by expansion or compression to the scale of the sound spectrograph.

CONCLUSIONS

Pulse train information and burst-pulse modulation is readily available from spectral analysis, if the analyzing filter bandwidth is made sufficiently narrow to resolve the repetition-rate into its harmonic equivalents. The ability of spectrum-analysis equipment to give descriptions of pulsed sounds that are repeatable and consistent with Fourier plots has been demonstrated. This repetition-rate information has been rarely noted by investigators, and only partly understood. Burst-pulse structure has apparently not been noted in the literature before. It is suggested that burst-pulse modulation is a common bio-acoustic phenomenon.

The limits of resolution of both time and frequency depend directly on the filter bandwidth used during spectrum analysis. It is, therefore, obvious that the effective filter bandwidth must be stated for each published spectrogram.

EQUIPMENT

The equipment used in programming the pulse trains for analysis included an audio oscillator (Hewlett Packard Model 200 CD), a calibrated frequency counter (Hewlett Packard Model 5233L), a pulse generator (Tektronix Type 161), a Tone Burst Generator (General Radio Type 1396A), and (for spikes) a Schmitt Trigger (WHOI). Oscilloscope photographs were made by a Fairchild Type 535A oscilloscope camera; spectrum analysis was performed on a Kay Electric Company Vibralyzer. Figure 12 is a spectrogram made on a Model ST–701 Spectral Contour Plotter by Signatection Research, Inc.

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DISCUSSION

Mr. Mowbray: We've just seen from Mr. Watkins that the Vibralyzer and other related spectrum analyzers can do a fast and fairly good job of sound analysis, but I think the point to be made clear is that these instruments are not the infallible cure-all for sound analysis, and I'd like to suggest that a sonagram by itself is not enough in a published report to define a sound. It needs an additional description or presentation, such as the oscillogram, as previously shown on each of the figures. The oscillogram should have a time base indicated on it to give increased accuracy.

Specifying the filter bandwidth is also necessary on these presentations, and it should be emphasized that if you change the speed of the tape recording, the effective shift of the filter bandwidth is proportional to the speed shift on the tape recorder. This should also be stated some place in the legend for the figure.

If you feed a rather large signal into the input of the analyzer device and the amplifier stages overload to the point where the signal is clipped and perhaps driven into cutoff, you can get some rather distressing artifacts.

Consider the situation where you might have phase shifts due to environmental or equipment factors. Each phase shift will vary the effective characteristics, the timbre of the sound, by changing the phase relationship among the harmonics. But the Vibralyzer may not catch it. You may see the amplitude differences, but you will not catch the phase differences.

It should be pointed out that these machines are heterodyne analyzers. The output is printed as a result of a second modulation process which is built into the machine which, when strained somewhat, can give you various cross products and artifacts which have no existence in fact, but are printed. The dynamic range of these machines, using good paper and intelligent settings of the controls is about 30 dB. If you print the blackest component at a saturated black level, you can get out as a faintest trace something that is about 30 dB down.

Unfortunately, some of the artifacts which are generated in the machines are also on the same order of magnitude, so that if you push the mark level up, you can get a very fat trace on the loudest sounds, but apparently weaker and weaker harmonics farther up the paper. Some of these may not be in existence, and some of them will come out with rather strange relationships to the others.

In Fig. 15, p. 35, each one of these actual sounds in the left side, (A, B, C) can be produced by sine waves. The A and the B can be simply made, by shifting phase of the second harmonic. Anyone can produce, with standard equipment, such wave forms simply by taking the first and second harmonics, varying the amplitude and phase relationships and come up with these two different patterns.

There is very little difference in the output upon the Vibralyzer trace at the bottom. When you come over to the C, the intervals are periodic. What looks like a pretty good sine wave, up around 260 cycles is in fact an alternation of long and short cycles, the period of which is still the 130 cycles per second.

People use these machines, feed the input with acoustic signals from marine organisms, and then try to interpret the black and white marks on the paper afterwards, and perhaps publish on them. It really requires a little bit of discussion on each one to the person who has to interpret it later, to actually get a true picture. Obviously, all published reports can't be accompanied by a tape recorder or a phonograph record.

I've found a terribly embarrassing situation at times of having the internal calibration signals shift rather dramatically and also having the base line shift. In other words, the bottom of the picture is not actually at 0. It may be above or below. Without a careful double check of the system, it is very easy to shift the apparent analysis by a rather large percentage.

Some of the signals which are reported as having frequency modulation have been the result of flutter and wow of the idlers inside the machines. The machine are quite temperature sensitive. Not only do they have speed fluctuations, but the calibration can shift over a period of time. It may be good in the morning, but by the time afternoon comes, the frequency may have shifted or the particular line on the chart may have shifted up the chart a quarter of an inch. If you use a common scale or legend on one side, you may be off by quite a large percentage.

It's also difficult to recognize on these machines the differences in black levels, both on the upper and lower extremes. You can easily miss a 3 or more dB change in amplitude, and certainly you may have a collective result of changes of tape recorders, hydrophones, and other instrumentation of more than 3 dB in a given octave. These may add or may accidentally cancel one another.

You have to watch out where you have multiple signals arriving at the same time at a different frequency. You may accidentally get cross modulation. In other words, many of these machines have 60 or 120 Hz hum built right into them which, of course, gives you an immediate start for modulation processes if you're in an environment such as a ship where you have engine noises, and other extraneous noises which are fairly loud and fairly constant. You may get cross products of these in some of your animal sounds so they show on the traces as artifacts.

Harmonic intervals, of course, are a fact. Raspy, squealing dolphin sounds show broad horizontal bands. These are truly pulsed sounds and a quick measurement of the spacing between a number of these bands will give you the repetition rate of the pulses.

There is one other combination which was shown in Fig. 1. It shows quite clearly that at times there is a definite modulation process. You have side bands about a central frequency which are the sums and differences of the central frequency and the modulating frequency which is lower. Be careful when you measure these various intervals. If you have a pulsed sound, each frequency component should be evenly divisible by the repetition rate. In other words, each one of them is simply the *n*th harmonic of the repetition frequency. In some cases you may not see the lowest one.

In many of the modulated whistles, the apparent oscillogram is a sine wave, modulated with lower frequency sine waves, which may, in themselves, have distortions and produce multiple side bands, that is a central frequency plus or minus the repetition rates and their harmonics.

I think more emphasis on a combination of presentations and more observations of oscilloscopes should be encouraged to try to differentiate some of these signals which can print identical pictures on these analyzers.

The ear in many cases can easily detect the difference, but the reader cannot.

DR. MANIWA: This burst-pulse modulation is a common bio-acoustic phenomenon. It is important to note the pulse tone under a repetition rate. Mr. Watkins showed us how to recognize the pulse tone frequency and the repetition rate and showed that filter bandwidth is important. The pulse train frequency and repetition rate may have some meaning for fish so exact analysis is important for my studies on attracting fish by sound.

I also think that in the analyses, we must use a cathode ray tube. The exact pulse train frequency and repetition rate are important for the study of sound produced by marine animals. I have one question for Mr. Watkins. How accurately can we read the pulse tone frequency and the repetition rate on the spectograph?

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