SOME ASPECTS OF HIGH-ACCURACY ANALOG FUNDAMENTAL - FREQUENCY RECORDING

MIROSLAV FILIP*

Fundamental frequency recording represents an area in which the interests of phonetics join with those of musical acoustics. However, a quantitative difference between these two aspects still remains being affected, in general, by the well-known principle of uncertainty (1, 2): while considerably higher *time* resolution, of the order of few milliseconds, is mostly required in speech research, in musicology, on the other hand, an extreme *frequency* resolution is primarily claimed.

It is hoped that some comment concerning high-accuracy frequency recording, given by a musicologist, may perhaps be of interest to phoneticians.

In speech intonation research, as well as, for example, in ethnomusicology, a durable analog record of fundamental frequency as a function of time proved to be a most valuable aid. Disregarding for the present purpose the spectral, autocorrelation, and digital methods we have at disposal two classes of simple analog means: first, integration methods which, however, are inferior in recording rapid changes of instantaneous frequency; second, timing methods, first described by Grützmacher and Lottermoser (3), which make use of particular timing waveforms to determine the duration of each fundamental period.

It is the logarithmic frequency scale that has been found most advantageous in several respects; one additional will be given later. Apparently, in the field of our interest, only the methods yielding the logarithm of the *instantaneous* value of the input quantity are to be taken into account.

I shall now briefly discuss three basic methods for obtaining the logarithmic display at the output of a frequency recorder.

(a) application of a logarithmic four-terminal network with inherent logarithmic characteristic (4, 5)
(b) approximation by a piecewise linear (polygonal) function (6, 7)
(c) approximation by a linear combination of exponential functions (8, 9)

(a) Logarithmic networks are based on more or less accurate logarithmic relation between two physical quantities in vacuum tubes or semiconductors. The former can

* Department of Musicology, Univerzita Komenského, Bratislava.

hardly be exploited economically in the problem under consideration, due to large drift. The latter are easier to use, despite of the undesired temperature dependence. There were many semiconductor logarithmic networks described in the literature, covering often as much as seven decades of the input quantity with an accuracy of several per cent. For the present purpose one decade would be far enough but a higher accuracy is required. I would like to present a very simple circuit giving good logarithmic response over two octaves with unselected general-purpose germanium diodes. The average error of approximation was estimated to be about one half per cent.

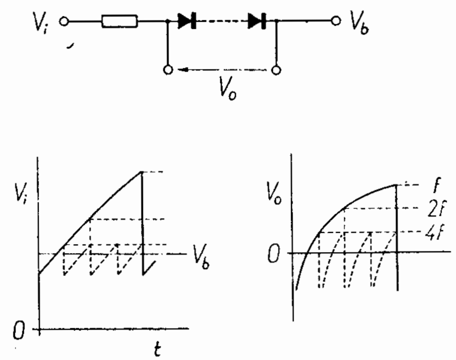

Fig. 1. Simple quasilogarithmic network transforms the initial, approximately linear, portion of an exponential function into logarithmic function within the range from f to $4f$. V_i — input voltage from an instantaneous frequency meter based on (3). V_0 — logarithmic output fed to a differential amplifier with high input impedance, V_b — fixed bias voltage. Instead of one, several diodes are connected in series to increase V_0.

(b) Piecewise linear approximation based on nonlinear voltage dividers known from diode function generators is to be preferred when large frequency range (up to two decades) is needed along with relatively suppressed claims to accuracy. In high-precision instruments this technique tends to become somewhat complicated. It is often employed in biological research, for example, in cardiotachometers and in pulse rate meters for electromyography, usually approximating the hyperbolic function (10, 11).

(c) Third fruitful approach to the problem is in approximating the logarithmic function by a linear combination of exponential functions with different decay constants which are available with high accuracy and reproducibility by charging capacitors in simple RC circuits connected to a common output. Very good results were obtained in wide frequency range instruments.

On the other hand, it may be shown that in two-octave range the improvement resulting from application of *two* different time constants, as compared to a single RC circuit, is not substantial. Approximation by a *single* exponential curve (3, 12, 13) is, of course, only very rough for ranges greater than, say, sixteen semitones. A phonetician and a musicologist would naturally welcome very large frequency ranges operated without switching, even more than two octaves. However, the errors in measurement due to the limited accuracy of analog display will generally be expressed as a constant fraction of the full scale deflection. The experimenter is thus forced to reduce reasonably the display range. A compromise must be made in order to improve the accuracy without sacrificing a sufficiently wide range. (The instruments are almost always designed as multirange ones.)

Fortunately, as anticipated above, the logarithmic frequency scale has an extra advantage with regard to the problem just discussed. I would like to suggest that *one-octave* range could be entirely satisfying since melodies exceeding that interval may simply be recorded by repetition employing successively all contiguous one-octave bands occupied by the melody as a whole. Finished records are then properly combined (fastened, glued) in parallel with respect to the time axis so that they form a composite record having just the range needed by the melody but, of course, with the accuracy valid for one-octave range.

Then, *one single* exponential function will be sufficient for the high-accuracy approximation. The calculated nonlinearity of the semitone scale does not exceed 5 cents in terms of musical intervals or, in other words, maximum error amounts approximately 0.4 % of the full scale deflection, assuming that the time constant equalled the reciprocal of the center frequency of the range.

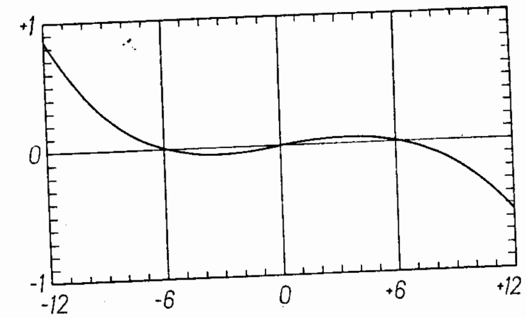

Fig. 2. Departure from linearity of the semitone scale obtained by an exponential approximation with the time constant equal to the period of the center frequency. Horizontal axis: log frequency in semiones re center frequency; vertical axis: deviation of the actual scale from a linear one, in semitones. This may be taken into account when calibrating the instrument or, in one-octave range, it may be neglected being less than ±5 C.

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