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DIGITAL VELOCITY PROFILE ESTIMATOR OF BLOOD FLOW IN THE HEART AND LARGE BLOOD VESSELS

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The paper discusses principles of a digital multigate system for Doppler frequency measurements. The conception of a system with serial data processing, based on the Doppler frequency measurement with the "zero crossing" method, is described. Problems with the recognition of the direction of flow in the digital system are presented, as well as two solutions, tested in practice, which limit occurring measuring errors. An example of an actual flow measurement made with the application of a model of the presented device is described, and possible errors resulting from the "zero crossing" technique are given. In order to improve properties of the system the use of a digital low-pass filter is proposed. The conception of such a filter is described.

W artykule omówiono podstawy cyfrowego systemu wielobramkowego pomiaru częstotliwości dopplerowskiej. Opisano koncepcje układu z przetwarzaniem szeregowym opartego o pomiar częstotliwości dopplerowskiej metodą „zero crossing". Przedstawiono problemy z rozpoznawaniem kierunku przepływu w systemie cyfrowym oraz dwa praktycznie wypróbowane rozwiązania pozwalające ograniczyć występujące błędy pomiaru. Pokazano przykład pomiaru rzeczywistego przepływu z wykorzystaniem modelu opisywanego urządzenia oraz mogące występować błędy wynikające z techniki „zero crossing". Zaproponowano zastosowanie cyfrowego filtru dolnoprzepustowego do polepszenia własności układu i opisano koncepcje takiego filtru.

1. Introduction

As in many other fields, the development of ultrasonic Doppler apparatus is related with the widespread of digital technique application. It makes possible the construction of multigate systems and construction apparatus for colour flow visualization, i.e. colour Doppler on their basis.

The simultaneous measurement of blood flow velocity at many different depths (at different distances from the ultrasonic probe is called a multigate system [1]. In a traditional pulse flowmeter the receiver's gate is switched with certain delay after every pulse of the transmitter. This is a cyclic process and the received signal is used to determine the Doppler frequency. If we would accept such a receiving system as a single channel and would build several such channels for which the gate of the receiver is switched on with different delays in relation too the transmitter, then we would obtain a multichannel system. Results of a multichannel measurements of Doppler frequency can be presented in terms of depth in the patient's body as a so-called velocity profile, or it can undergo further processing. Information processing in every gate takes place at different time intervals, so the process of Doppler frequency measurement can be performed by one measuring system. The system functions in cycles repeated for all successive gates. Such a system is called a system with serial processing [2]. If we accept a rather general assumption that the range of investigated depths is of about 10 cm and resolution in depth (thickness of a layer in which a measurement in one gate is performed) is of the order of 1 mm, then we reach the number of 100 necessary gates (channels) with opening time of each for average velocity of an ultrasonic wave in a human body (1540 m/s) of approximately 1.5 μs. Only digital technique makes the realization of such a system possible, because it makes it possible to process signals in one system not only for successive value in one gate, but also values from other gates which can be considered as absolutely independent. A digital solution also ensures the identity of all channels as well as small dimensions of the device.

2. Multichannel system with serial processing

Ultrasonic signals are reflected in a human body from boundaries of tissues with different acoustic impedance and are scattered on blood particles. Signals reflected from motionless or slow moving structures can be more than a hundred times larger from signals dissipated in blood. These last signals contain a Doppler information about flow velocity. Hence, to fish out the information about the flow we either need a signal's path with very high dynamics prevent small components from the flow distortion of, or the method of elimination of stationary echoes has to be applied. This second solution is much better from the first one – it significantly simplifies the further part of the path of the signal, bacause processing of signals with low dynamics decrease the essential number of bits of signal's digital representation. Therefore, the elimination of constant echoes is practically an essential element of a multigate system.

We can come across two fundamental types of eliminators: digital and analogue [3, 4]. Digital systems require very fast elements including big (e.g. 12 bit) a/d converters – expensive and attainable with difficulty (embargo). An analogue suppression stationary echoes canceller (SEC) system was previously developed in the Department of Ultrasonics and it is applied in the UDP–30–TES flowmeter, produced by Experimental Department "Venpan". A version of a pulse Doppler flowmeter, equipped with a SEC system, for heart examinations was created in the Department of Ultrasonics during the last five years. This flowmeter will be used as an analogue block (flowmeter system and constant echo eliminator system included, Fig. 1) of the developed apparatus for colour flow visualization. At this stage it is advisable to base the multigate system on an analogue eliminator of constant echoes. After the signals from the receiving unit pass through demodulation and through the eliminator, they have to be changed into digital form. Then the Doppler frequency in

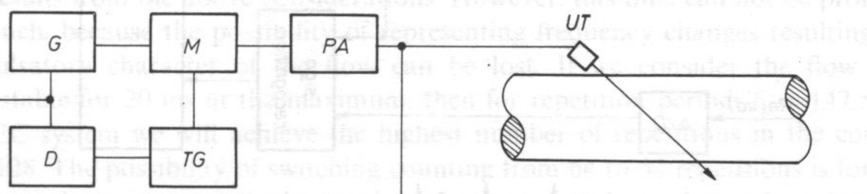

FIG. 1. Block diagram of the SEC system

individual gates has to be determined in the multigate system. The method of counting the number of crossings through zero "zerocrossing" [5] is the method of determining frequency most generally applied in classical Doppler flowmeters. In the "zerocrossing" method the detected frequency is defined by the number of crossings of the signal through the zero level, counted in a definite period of time. Figure 2 presents a general block diagram of a zerocrossing system adapted to a multigate system.

Doppler signals in a quadrature (shifted with respect to each other by $+\pi/2$ or $-\pi/2$, depending on the direction of flow) are changed into digital form. One of them is delayed by the pulse repetition time of the transmitter T_p. The so obtained value S_1 is compared by the system of detection of crossings through zero with the actual, not delayed value S_2 (Fig. 2). If a crossing through zero occured, then the number of crossings through zero in a given channel, stored in the memory, is increased by one. At the same time the system of sign recognition determines which signal was the

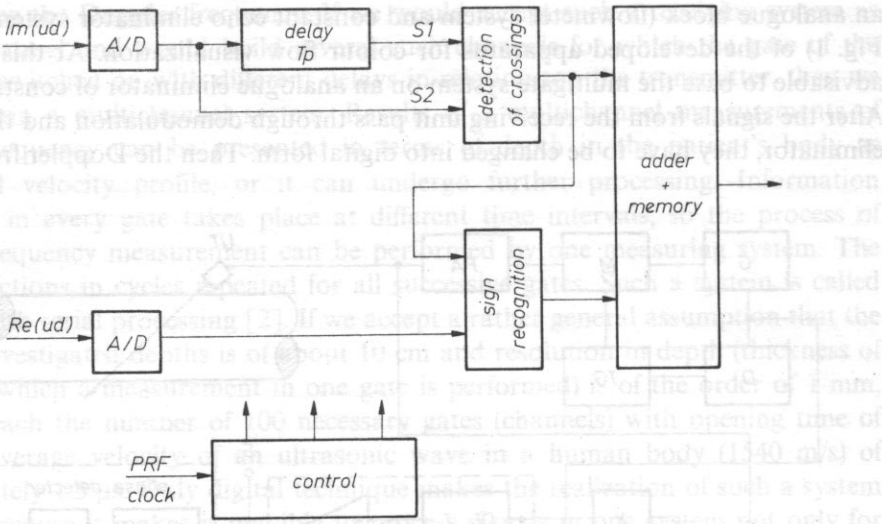

FIG. 2. Block diagram of a multigate "zero crossing" system

leading one and uses this information to determine the direction of flow in the given channel. Also this information is stored. Operations discribed above are repeated 128 times during one repetition. Hence, the Doppler frequency in all 128 channels can be determined in turn with one system of signal processing. The maximal frequency detected in this system approaches half of the pulse repetition frequency of the transmitter.

Detection system of crossings through zero

There are two methods of counting crossings through zero. We either only count the number of crossings through zero of a signal in one direction (e.g. from minus to plus), or in both. When the method of counting the number of crossings through zero in both directions is applied, then measured frequency remains unchanged while measuring accuracy, determined by the so-called quantization grain increases. Therefore, both directions of crossings through zero will be counted. The function of output a/d converters will be fulfilled by comparators, because a one bit information about the signal is sufficient to determine the sign of the signal. Their hysteresis are so chosen, that crossings through zero resulting from noises generated in earlier elements of the system are not recognised. The delay by repetition time is realized by the memory consisting of 128 storage cells, which stores during the period of repetition time the information about the sign of the signal for individual channels. The 128 storage cells are also used during counting. In every repetition cycle the information about the number of counted so for crossings through zero in a given gate is read-out in turn and if a crossing is detected it is increased by one and stored anew. The detection of a crossing through zero consists in the determination whether S_1 and S_2 are different (Fig. 2). This is continued during the entire counting time, which is a multiplicity of the repetition time T_p. After the counting time, the numbers crossings through zero in individual channels are read-out and the memory is cleared. A dependence between the accuracy of frequency detection and counting time results from the above considerations. However, this time can not be prolonged too much, because the possibility of representing frequency changes resulting from the pulsatory character of the flow can be lost. If we consider the flow to be quasi-stable for 20 ms at the maximum, then for repetition period $T_p = 147.5$ μs in the SEC system we will achieve the highest number of repetitions in the counting cycle 128. The possibility of switching counting from 64 to 32 repetitions is foreseen. The control system controls the number of counting cycles and sampling times, and addresses adequate memory cells for all of the 128 gates.

System of direction recognition

The system of direction recognition requires a separate description. The quadrature detection of high frequency Doppler signals is most generally applied. It gives us a real part Re (u_d) and imaginary part Im (u_d) of low frequency Doppler signal. They are shifted with respect to each other by + or − $\pi/2$, depending on the direction of flow [6]. The level of the shifted signal is investigated during zero crossing of the Doppler signal. If the original signal is ahead of the shifted signal, then the measured flow is directed to the probe while if the shifted signal is ahead of the original signal, then the measured flow is directed from the probe. The information about the Doppler signal comes from sampling (during the opening of the gate) in a pulse flowmeter. In analogue systems signals from sample and hold systems are passed through low pass filters which approximately reproduce their waveform. In a digital system the information about a zero crossing comes from two successive samples; the sampling time is accepted in the moment of zero crossing.

By adding crossings through zero in successive gates, taking into account the sign obtained from the phase shifted signal during the counting period we reach the value of velocity of the flow together with its direction. However because of the determination of crossings through zero on the basis of samples only the interpretation of the direction is correct for Doppler frequencies below 1/4 of the repetition frequency (while Doppler frequencies are measured unambigously up to 1/2 of the repetition frequency). Figure 3 presents an example to explain this effect. It shows components of two Doppler signals with frequencies equal to 1/5 (signal U_{d1}) and 1/3 (signal U_{d2}) of the repetition frequency. Phases of these signals were chosen in such a manner that an error occurs in the determination of the direction of flow. Sampling times and values of signal samples have been marked. Samples S_1 and S_2 for both signals differ with the sign − the detection system of crossings through zero will state

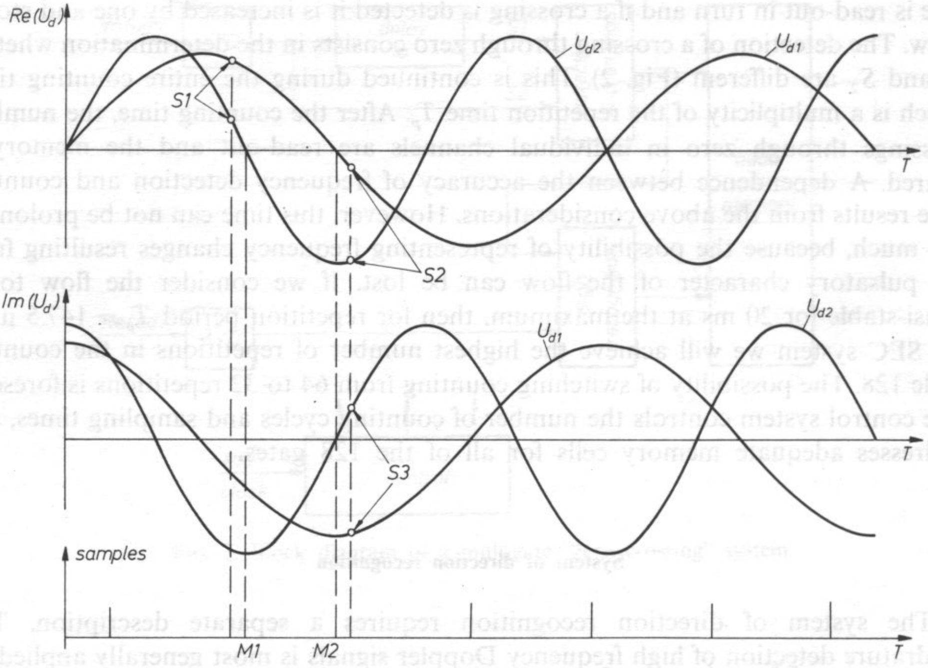

FIG. 3. Example of Doppler signal with frequency 1/3 and 1/5 f_p

a zero crossing but samples S_3 in these cases are different. The system for direction determination will state different directions of flow. This is a result of a too great delay of sampling with respect to the actual crossing through zero of the signal Re (U_{d1}) time M_1). We should notice that in an analogue system described above problems do not have place, because the determination of direction occurs practically at the same time as the actual crossing through zero (times M_1 and M_2 in Fig. 3). The only situation in which the sign can be determined falsely is when the Doppler signal has enough time to change by more than a quarter of a period between successive samples: so it's frequency has to exceed 1/4 of the pulse repetition frequency. Moreover we should notice that the effect of false determination of direction of flow occurs randomly with probability the greater, the higher the Doppler signal frequency. The probability distribution function of the above phenomenon is presented in Fig. 4.

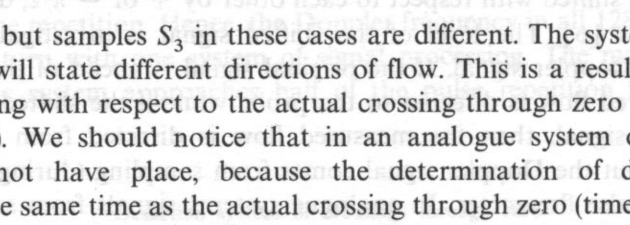

FIG. 4. Probability distribution function of the occurence of a false sign of the direction of flow

Two solutions limiting the described above drawback have been analysed and tested in practice. The first one is based on the observation that the recognition of the direction of flow is correct up to 1/4 of the repetition frequency. Up to a frequency, called threshold frequency, somewhat lower than 1/4 of the repetition frequency, the system's functioning remained unchanged. Whereas, when the threshold frequency was exceeded, the sign of the previously occurring direction was maintained artificially. This was carried out on the basis of an assumption that it is impossible in such a short period of time (shorter than the accepted counting time) for a quick flow to change rapidly into an equally quick one but moving in the opposite direction. Forces necessary to perform such a change do not occur in the blood-vascular system. Unfortunately however velocities with Doppler frequencies exceeding the repetition frequency can occur, here. The sign maintaining system can only function correctly for Doppler frequencies which do not exceed the repetition frequency minus threshold frequency (Figs. 5 and 6). This significantly limits the application of the above system.

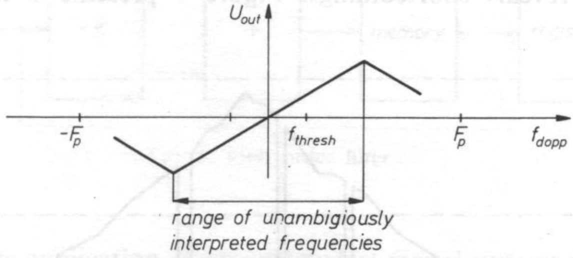

FIG. 5. Frequency characteristic of system with the maintenance of the sign of the direction of flow for $f < F_p - f_{\text{thresh}}$

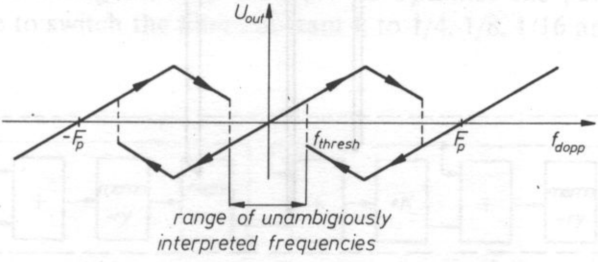

FIG. 6. Frequency characteristic of system with the maintenance of the sign of the direction of flow for $f > F_p - f_{\text{thresh}}$

The second absolutely original solution is based on a different observation. An increase of the Doppler frequency was accompanied by an increase of signs of the phase shifted signal, read-off for zero crossings, and causing misinterpretation of direction. Yet, incorrect signs appeared more rarely than correct ones up to 1/2 of the repetition frequency, for which their number becomes equal. Therefore, a certain trend of the direction of flow can be observed for obtained signs. And this was the origin of the idea of "averaging of signs". The system based on this idea functions as follows. One path was used to sum up zero crossings, which determine the velocity modulus after counting time. In the second path signs obtained during zero crossings were summed. If the number of positive signs exceeds the number of negative ones during counting time, then the direction of flow was accepted as positive. In a contrary case the direction is negative. The information about the direction and the absolute value of the flow are joined together on the output of the system after every counting cycle.

3. Modification of the system

During measurements of actual flows, when the relation between the useful signal, and noise and disturbances changes, the frequency measurement with the zero crossing method reveals shortcomings. Figure 7 presents a Doppler frequency

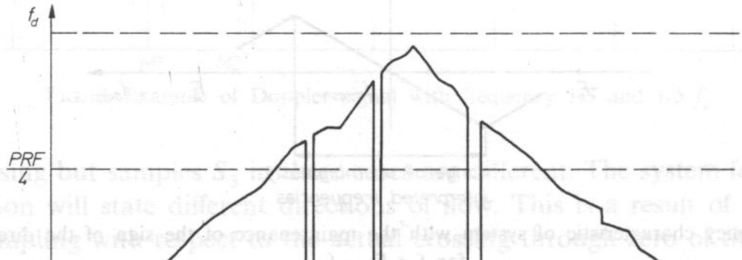

FIG. 7. Example of actual in one gate

measurement in one out of 128 gates for an exemplary actual flow, with visible measuring errors. Thus, trials have been undertaken of improving the functioning of the system. To this end a digital low-pass filter is foreseen in the described system. Such a filter can operate with a directional Doppler signal. Also two filters can be applied – one in the velocity modulus path, the other in the path of direction determination, and then both filtered informations can be joined together. Figure 8 presents the method of forming a digital filter. The memory acts as a delay element and the filter constant k is realized by binary division (shift of bits). The configuration of a second order filter, formed from a connection in series of two first order filters, is

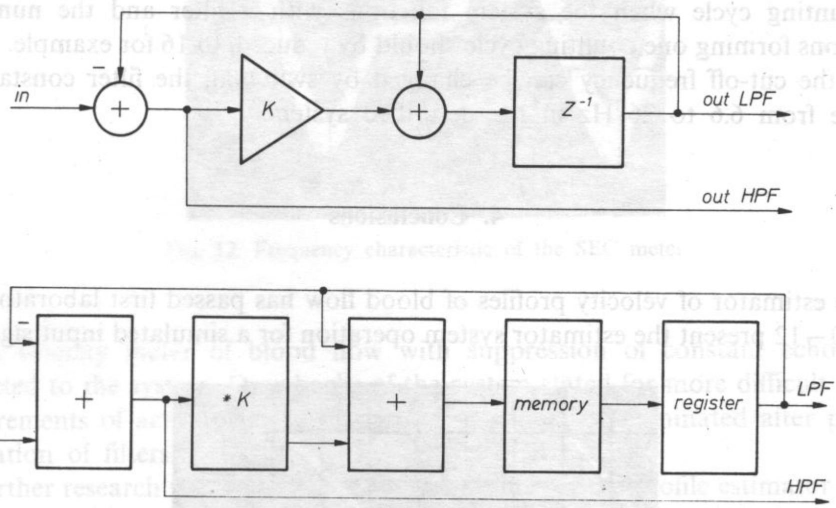

FIG. 8. First order filter

shown in Fig. 9a. The application of adequately fast digital systems makes it possible to realize such a filter as a filter functioning in series in time, i.e. with repeated information cycle in it's loop. We can see from Fig. 9 b that this allows the number of essential elements to be significantly reduced. To optimize the parameters of the system it is possible to switch the filter constant k to 1/4, 1/8, 1/16 and what follows

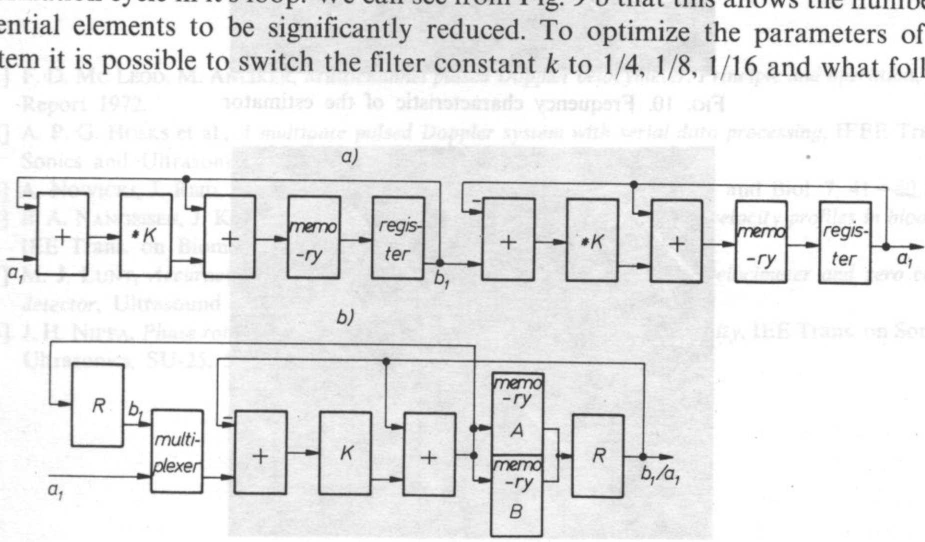

FIG. 9. Second order filter forming

cut-off frequency is then defined by

$$f_c = k \cdot \frac{f_{\text{repetition}} : \text{number of repetitions in a cycle}}{4}. \tag{1}$$

As we can see from expression (1) the cut-off frequency depends on the lenght of the counting cycle when the system functions with a filter and the number of repetitions forming one counting cycle should by reduced, to 16 for example. In such a case the cut-off frequency can be changed by switching the filter constant k in a range from 6.6 to 26 Hz in the described system.

4. Conclusions

The estimator of velocity profiles of blood flow has passed first laboratory tests Figs. 10 – 12 present the estimator system operation for a simulated input signal and

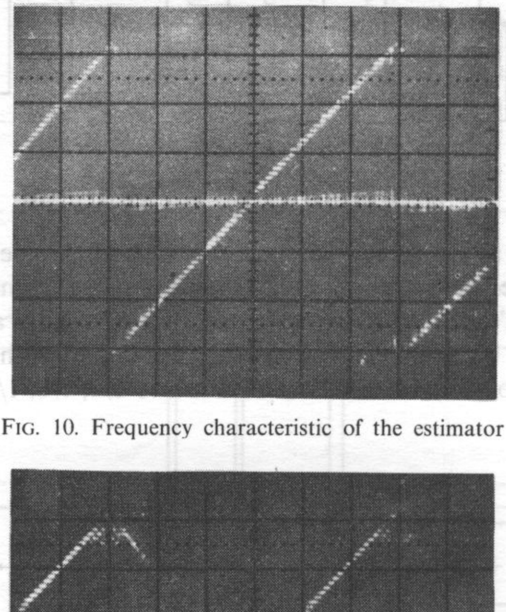

FIG. 10. Frequency characteristic of the estimator

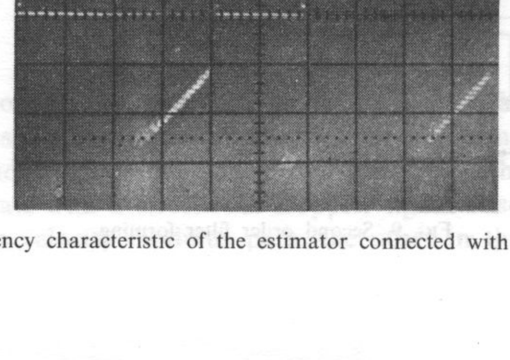

FIG. 11. Frequency characteristic of the estimator connected with flowmeter SEC

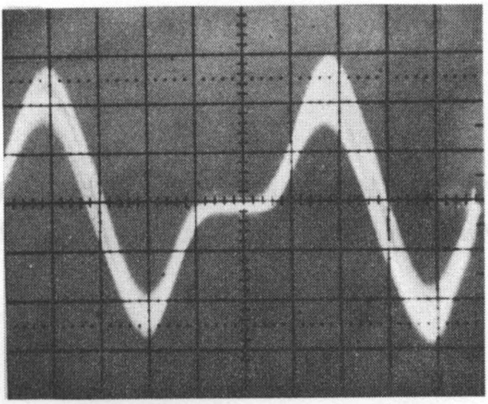

FIG. 12. Frequency characteristic of the SEC meter

with a velocity meter of blood flow with suppression of constant echoes SEC connected to the system. Drawbacks of the system stated for more difficult cases of measurements of actual signals, in particular, should be eliminated after practical application of filters.

Further research will be aimed at the connection of the profile estimator with an ultrasonocardiograph in order to present the flow on the background of echoes from body structures in the *M*-mode system. The dynamic development of the "colour Doppler" technique in the world confirms the purposefulness of these studies.

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