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Bi-DIRECTIONAL CONTINUOUS WAVE DOPPLER FLOWMETER AND ITS APPLICATION IN INVESTIGATIONS OF DISTURBED BLOOD FLOWS

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The paper deals with a new two-way DOPPLER apparatus and with its clinical applications. A mathematical description is given of operations leading to the separation of a signal in dependence of the flow direction. Also a block diagram of an analogue realization of such a system, and a diagram of a broad-band phase shifter, which is the principal part of the system, are presented. The part of the paper dealing wth the applications shortly presents diagnostic methods and new clinical applications of flowmeters, in which the system of separating flow directions plays a significant part.

1. Introduction

This paper is concerned with a continuous wave ultrasonic flowmeter based on the DOPPLER effect, which allows the simultaneous determination of two directions of the blood flow – from and towards the ultrasonic probe. For this reason it is called a two-way flowmeter.

The method of determining the flow direction is the characteristic feature distinguishing the two-way continuous wave flowmeter from hitherto used directional flowmeters. A classical, widely applied coincidential flow detector, described by McLEOD [5], detects the flow direction, i. e. whether it is directed from or towards the ultrasonic head, with an assumption, that the whole signal reaching the receiver is related to only one of so defined flow directions. The detection system of flow directions, applied in the two-way apparatus and described in a paper by NIPPA et al. [6], separates the received signal into two independent components. Each one is related to one flow direction. Owing to this independent audio monitoring and flow velocity measurements for every direction are possible, even when they occur simultaneously.

A prototype of such an apparatus was constructed in the Department of Ultrasonics in 1980.

This paper contains construction principles of this flowmeter and a presentation of new diagnostic applications, enabled by this type of instrument.

2. Apparatus construction

The construction of a flowmeter, separating Doppler signals in dependence upon the flow direction, is based on a phase rotation system, described by NIPPA [6].

In the greater part of applications, the transmitting and receiving transducers are placed next to each other in the same casing, forming the so-called DOPPLER probe. The further discussion concers such a positioning of the transducers.

Let us recall the formula for the Doppler frequency of particle i, f_{di} [7]

$$\omega_i = 2(1/c)\pi f_0 v_i \cos\theta_i, \tag{1}$$

where v_i – velocity of particle i, θ_i – angle between the particle velocity and the propagation direction of an ultrasonic wave.

According as the particle dissipating the ultrasonic wave moves from or towards the transducer, what is expressed by the value of angle θ_i, the value of the Doppler frequency can be negative or positive.

Let us note the signal received by the flowmeter as the sum of three components arising from:

– dissipated waves originating from particles moving towards the transducer. In this case the Doppler frequency is positive,

$$U_+(t) = \sum_{i=1}^{N_+} A_i \cos(\omega_0 t + \omega_i t), \tag{2}$$

where A_i – amplitude of a wave dissipated from particle i, f_0 – fequency of carrier wave, f_{di} – Doppler frequency resulting from the particle velocity, according to formula (1), N_+ – quantity of particles moving towards the probe,

– scattered waves originating from particles moving away from the transducer, which have a negative Doppler frequency

$$U_-(t) = \sum_{i=1}^{N_-} A_i \cos(\omega_0 t - \omega_i t), \tag{3}$$

where N_- — quantity of particles moving away from the probe;

— so-called "*leakage*", which is a sum of the signal transmitted directly from the transmitter to the receiver, due to electric and acoustic couplings, and the signal generated by waves reflected by fixed structures. The frequency of these signals is equal to the carrier frequency of the instrument

$$U_p(t) = D\cos\omega_0 t, \tag{4}$$

where D — resultant amplitude of the "*leakage*" signal.

The complete signal received by the flowmeter is a sum of three mentioned above components: $U_+(t)+U_-(t)+U_p(t)$.

In order to obtain the spearation of signals corresponding to the velocity of particles moving from and towards the probe, several operations have to be conducted on the received signal $U_w(t)$.

In order to investigate the course of these operations in the further part of the paper, it was assumed that the received signal originates from only two particles one moving away from the probe, with a DOPPLER frequency f_{d-} and amplitude A_-, and second, moving towards the probe, with a DOPPLER frequency f_{d+} and amplitude A_+.

Quadrature demodulation, i. e. the multiplication of signal $U_w(t)$, independently by two functions with a frequency ω_0 and phase difference 90° is the first operation.

To simplify the notation, we assume the signals as sinusoidal and cosine. We receive:

$$U_1(t) = U_w(t)\cos\omega_0 t, \qquad U_2(t) = U_w(t)\sin\omega_0 t. \tag{5}$$

Writing equation (5) in respect to signal $U_1(t)$ for example we obtain:

$$U_1(t) = \frac{1}{2}\, D[\cos(2\omega_0 t)+\cos 0]+\frac{1}{2}\sum_{i=1}^{N_+} A_i[\cos(2\omega_0 t+\omega_i t)+\cos(\omega_i t)]+ \\ +\frac{1}{2}\sum_{i=1}^{N_-} A_i[\cos(2\omega_0 t+\omega_i t)+\cos(\omega_i t)]. \tag{6}$$

Performing the adequate summation and applying the filtration of factors related to pulsation $2_\circ$ and of the constant component we have:

$$U_1(t) = \frac{1}{2}\sum_{i=1}^{N_+} A_i\cos\omega_i t+\frac{1}{2}\sum_{i=1}^{N_-} A_i\cos\omega_i t \tag{7}$$

and similarly for $U_2(t)$

$$U_2(t) = -\frac{1}{2}\sum_{i=1}^{N_+} A_i\sin\omega_i t+\frac{1}{2}\sum_{i=1}^{N_-} A_i\sin\omega_i t. \tag{8}$$

It can be easily seen, that a 90° phase shift of one of these signals, and then summation and subtraction will cause the separation of the components related to different flow directions. After shifting the phase for signal $U_2(t)$ we obtain

$$U'_1(t) = U_1(t), \tag{9}$$

$$U'_2(t) = -\frac{1}{2}\sum_{i=1}^{N_+} A_i \sin(\omega_i t + 90°) + \frac{1}{2}\sum_{i=1}^{N_-} A_i \sin(\omega_i t + 90°)$$

so

$$U'_2(t) = \frac{1}{2}\sum_{i=1}^{N_+} A_i \cos\omega_i t - \frac{1}{2}\sum_{i=1}^{N_-} A_i \cos\omega_i t.$$

Summing and subtracting signals, $U_1(t)$ and $U_2(t)$, we achieve:

$$U_+(t) = U'_1(t) + U'_2(t) = \sum_{i=1}^{N_+} A_i \cos\omega_i t,$$
$$U_-(t) = U'_1(t) - U'_2(t) = \sum_{i=1}^{N_-} A_i \cos\omega_i t. \tag{10}$$

Consequently we obtain signal $U_+(t)$ from particles moving towards the head, solely, and $U_-(t)$ from particles moving away from the probe.

The practical realization of the signal transformation according to the given above method (Fig. 1) required the construction of electronic systems

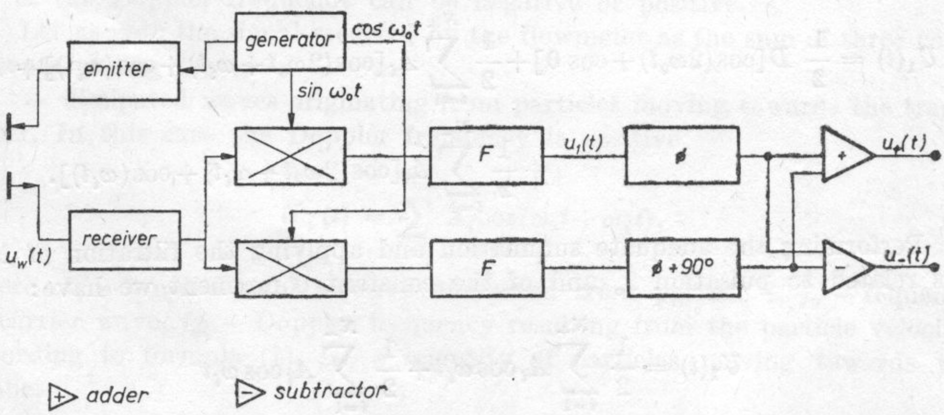


Fig. 1. Block diagram of the system separating a signal in dependence on the particle flow direction

NAD – transmitter, *ODB* – receiver, *GEN* – carrier frequency generator, *X* – multiplying systems, *F* – wide band filtres, $\left.\begin{matrix}\Phi \\ \Phi+90°\end{matrix}\right\}$ – two branches of the high frequency phase pass

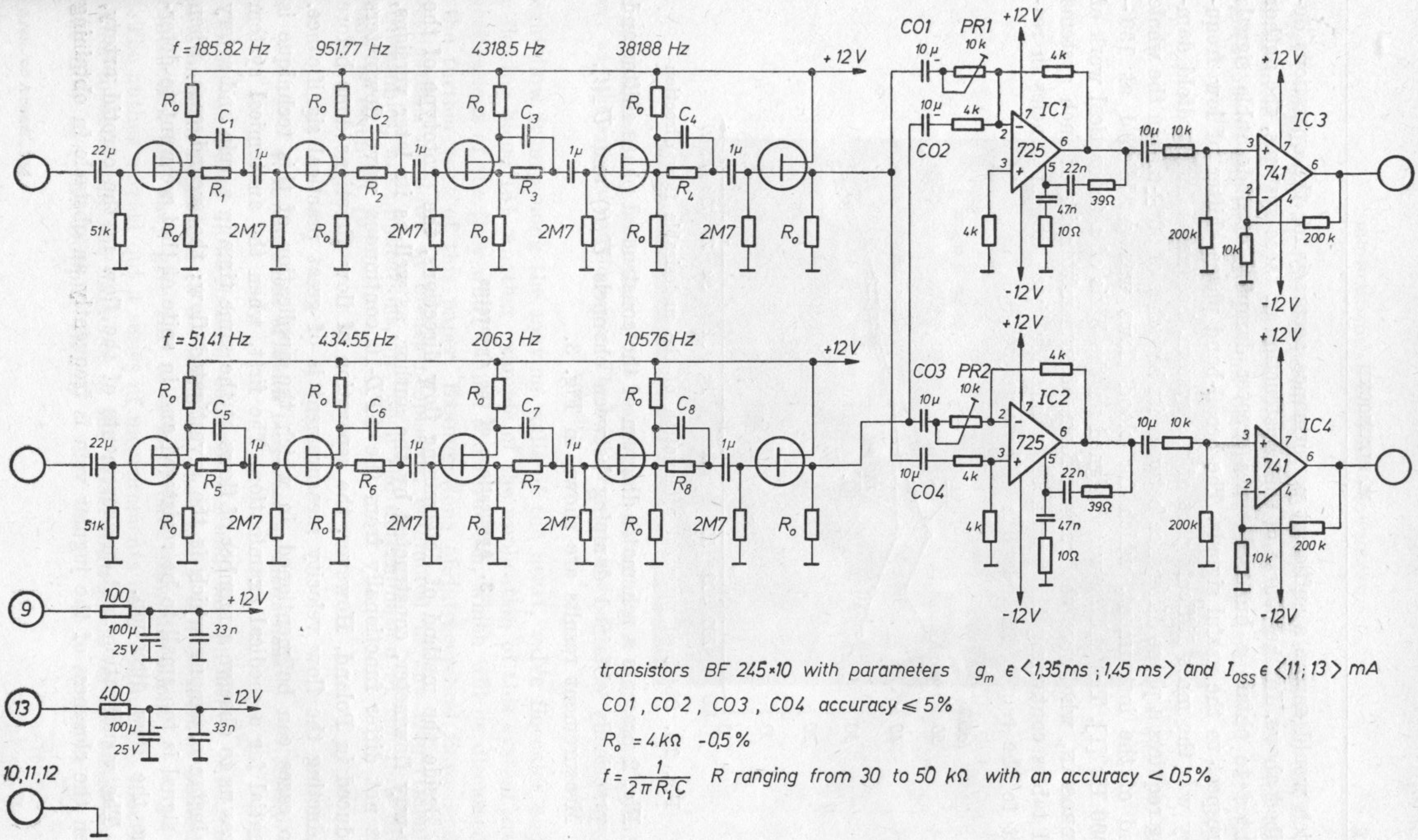


Fig. 2 A. Schematic diagram of the broad band phase shifter

which would ensure a sufficient performance accuracy for the operations described above. In the course of the construction of these systems, the author wanted to obtain a hundred times greater damping of undesirable signals in respect to the useful signals. The broad-band phase shifter of low frequency was the most difficult part of the system, because a hundredfold damping requires a phase difference between its branches of $90° \pm 0.5°$ in the whole band of the instrument, which for blood flows was established at 150 – 15000 Hz [1]. The shifter was designed on the basis of a theoretical work of BEDROSIAN, who gave the general form of transmittancies of such systems and tables containing the parameter values for these transmittancies in respect to the required bandwidth and accuracy [1].

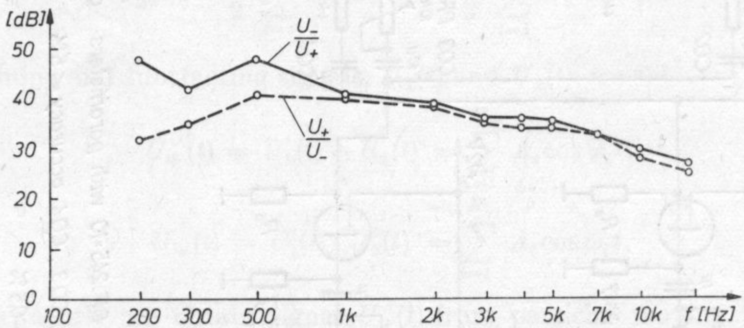


Fig. 2B. Obtained practical attenuation of the undesirable flow direction

Fig. 2 presents a schematic diagram of the constructed phase shifter and the practically obtained damping between channels $U_+(t)$ and $U_-(t)$. Measurement results are shown in Fig. 3.

3. Applications of the apparatus

Beside the method of determining flow directions, the prototype of the two-way flowmeter, constructed by the author, as well as its later versions, does not differ functionally from the *UPD*-10 continuous wave flowmeters produced in Poland. However, the separation of flow directions done before conducting the flow velocity measurement is of great practical significance. Two cases can be mentioned, in which the application of this technique is essential for a medical examination. The first, when the anatomical system forces us to observe a number of flows at the same time in a vein and artery for instance, among which is the investigated flow; the second case, when the signal is too small to be registered and in spite of that we want to determine the flow direction.

The visualization and measurements of the flow in the carotid artery, when the closeness of the jugular vein is frequently an obstacle in obtaining correct results [10], [3], [4], can be an example of the first case. Also the flow measurements in the heart and in large blood vessels are a lot easier with the application of the two-way system, because it enables us to *"fish out"* the

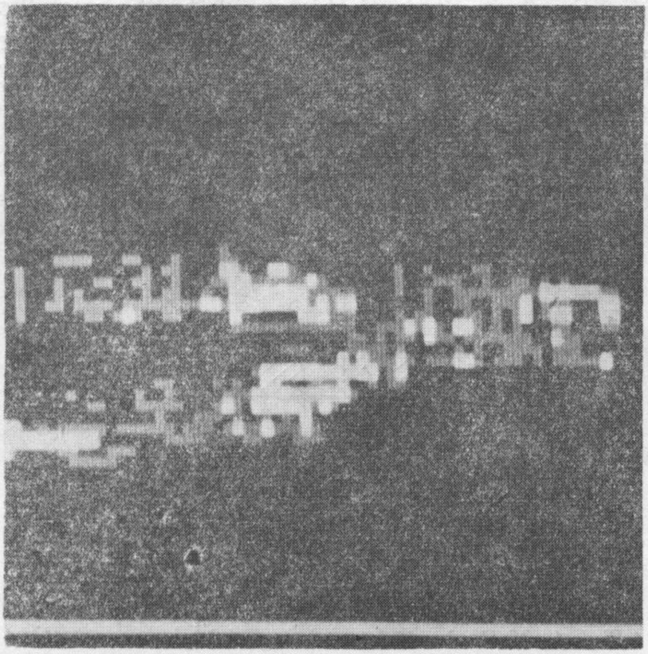


Fig. 3. Visualization of the division of the common carotid artery into the internal carotid artery and the external carotid artery. The brighter points show the flow with increased velocity

sought flow from among the moving walls of the heart, valve floccules and the flowing blood [8]. Another example of the application of this system are investigations of the flow whirl behind a contraction, which will be discussed in the further part of this paper. Examinations of intracerebral flows and investigations of flows in breast neoplasms, conducted in the Department of Ultrasonics, are applications, in which the determination of the flow direction is essential [9].

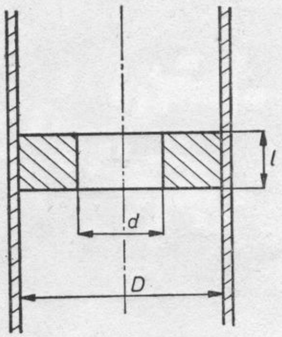
4. Investigations of whirls introduced by contractions

Observations of flows behind contractions and the published research results on such flows lead to a conclusion, that whirls can be formed behind a contraction and they give rise to a local back flow direction.

The author carried out a series of measurements on a contraction model in order to determine the influence of the vessel contraction on the character of the flow and the Doppler signal.

The use of the two-way instrument allowed the detection and measurement of the back flow velocities resulting from these whirls.

The analysis of the Doppler signal from such flows may be will enable the connection of the parameters of this signal to the vessel contraction degree. The pipe, applied for measurements, had an 8 mm diameter and had rings of 5 mm thickness and of four different internal diameters, placed half-way along its length. This way four different contractions, calculated as a proportional decrease of the flow cross-section area, were obtained. Fig. 4 shows the method of calculating the contraction.



$$ZW = \frac{D^2 - d^2}{D^2} \cdot 100\,\%$$

Fig. 4. Method of determining the pipe contraction

The flow was visualized in order to determine the character of the flow behind the obstacle. To faciliate this, a 17 mm diameter pipe and a ring of 10 mm thickness were used in order to preserve the scale of the mechanism disturbing the flow. A domestic salt solution was used as the liquid and two electrodes connected to a constant voltage source, were placed in the pipe. As a consequence of electrolysis gas bubbles were liberated on one electrode. They were entrained by the flow and marked the stream path of the liquid. Fig. 5 presents a photograph of the flow with a Reynolds number $Re = 500$ and contraction $ZW = 72\,\%$ and $32\,\%$. Three characteristic regions of the flow can be noted. The laminar flow is observed before the obstacle, where paths of the liquid elements are rectilinear and are curved next to the obstacle, forming the so-called inlet effect. Close behind the contraction the outlet stream with a high velocity and whirls by the pipe walls is observed. Further on this stream is disturbed and the liquid elements move with random paths.

Separated signals from individual flow directions were registered on magnetic tape with the application of a stereophonic tape recorder *M 2403 SD*, in order to carry out their analysis.

Signals from flows were registered for four different contractions: $ZW =$ 75, 61, 44 and 23%. For all of these contractions, measurements were conducted for three Reynolds numbers: 600, 1900 and 5300, with the signal

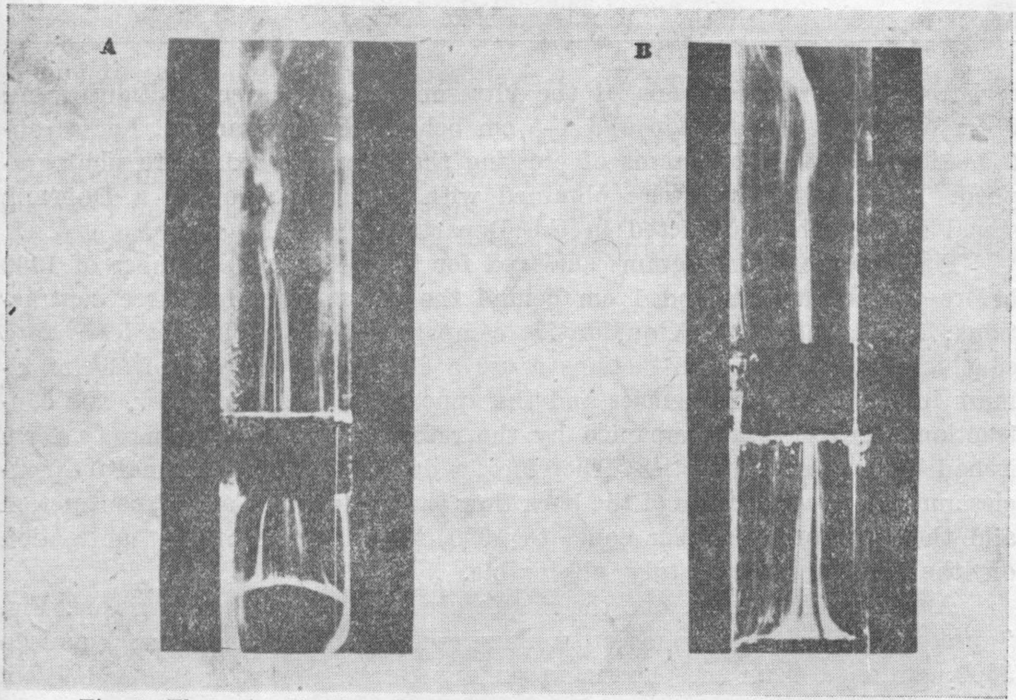


Fig. 5. Flow visualization, REYNOLDS number $Re = 1500$: A – $ZW = 72\,\%$, B – $ZW = 32\,\%$

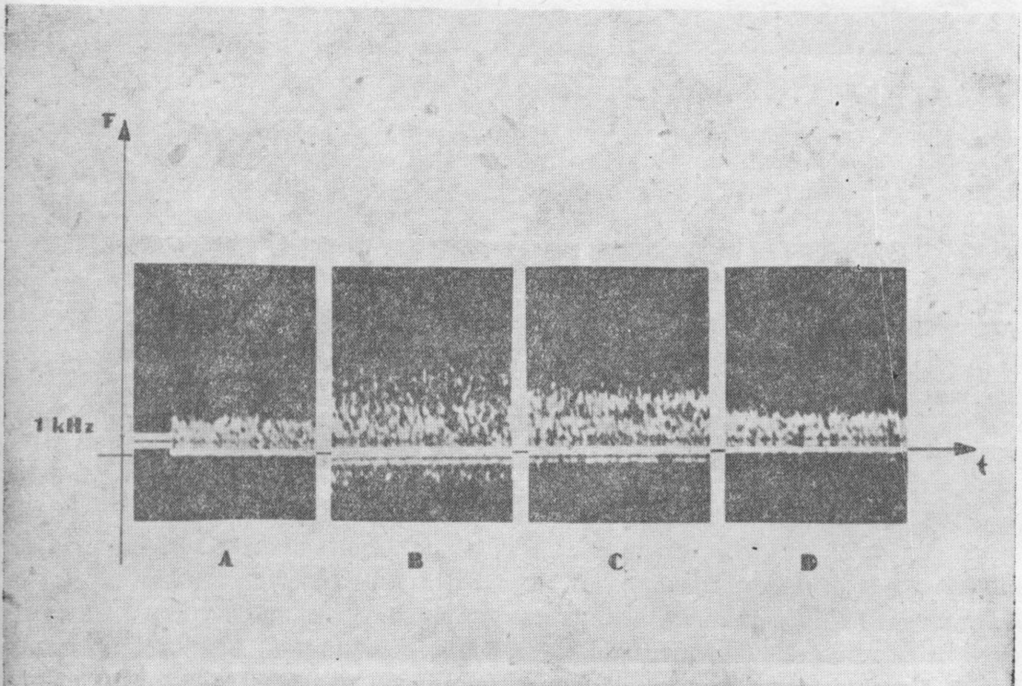


Fig. 6. Signal histogram for flows with REYNOLDS number $Re = 1900$. A) before the contraction, B) 1 cm behind the contraction, $ZW = 75\,\%$, C) 1 cm behind the contraction, $ZW = 61\,\%$, D) 1 cm behind the contraction, $ZW = 44\,\%$

registration for six positions of the ultrasonic head. These positions were: 2 cm before the contraction and 1–5 cm behind the contraction. For so obtained signals, the histograms of crossing the reference axis were photographed. These histograms were obtained with the application of a DOPPLER signal histograph constructed in the Department of Ultrasonics.

Fig. 6 presents histograms achieved for flows Reynolds number of 1900 before the contraction and 1 cm behind the contraction, for three contractions: 75, 61 and 44%. A qualitative comparison fo these images leads to a conclusion, that large contractions cause a significant increase of the maximum instantaneous frequencies and the appearance of a back flow. The contraction decrease is accompanied by the return of the histogram to a form it had before the contraction. Therefore, a decrease of the maximal frequencies and the disappearence of the back flow is observed. For a 44% contraction and the REYNOLDS number equal to 1900, the influence of the contraction on the histogram is hardly observable.

At higher flow velocities the whirls are even more clearly visible. Fig. 7 presents signal histograms from flows with REYNOLDS number equal to 5300, obtained from measurements done before the contraction and 1 cm

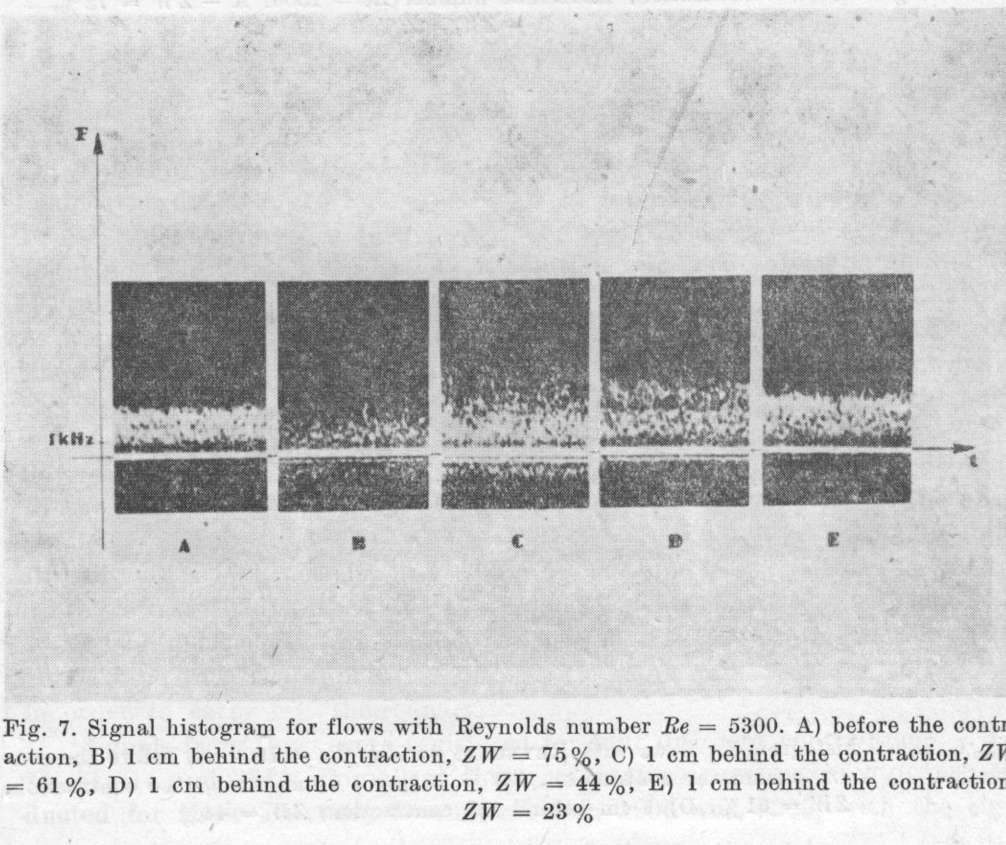


Fig. 7. Signal histogram for flows with Reynolds number $Re = 5300$. A) before the contraction, B) 1 cm behind the contraction, $ZW = 75\%$, C) 1 cm behind the contraction, $ZW = 61\%$, D) 1 cm behind the contraction, $ZW = 44\%$, E) 1 cm behind the contraction, $ZW = 23\%$

behind the contraction, for contractions: 75, 61 and 23%. These results are similar to those shown in Fig. 5. However, a 44% contraction gives a distinct back flow.

Studying the DOPPLER signal in successive points along the vessel we observe similar changes in the histogram as during the decrease of the contraction. This is shown in Fig. 8, where histograms are presented for flows

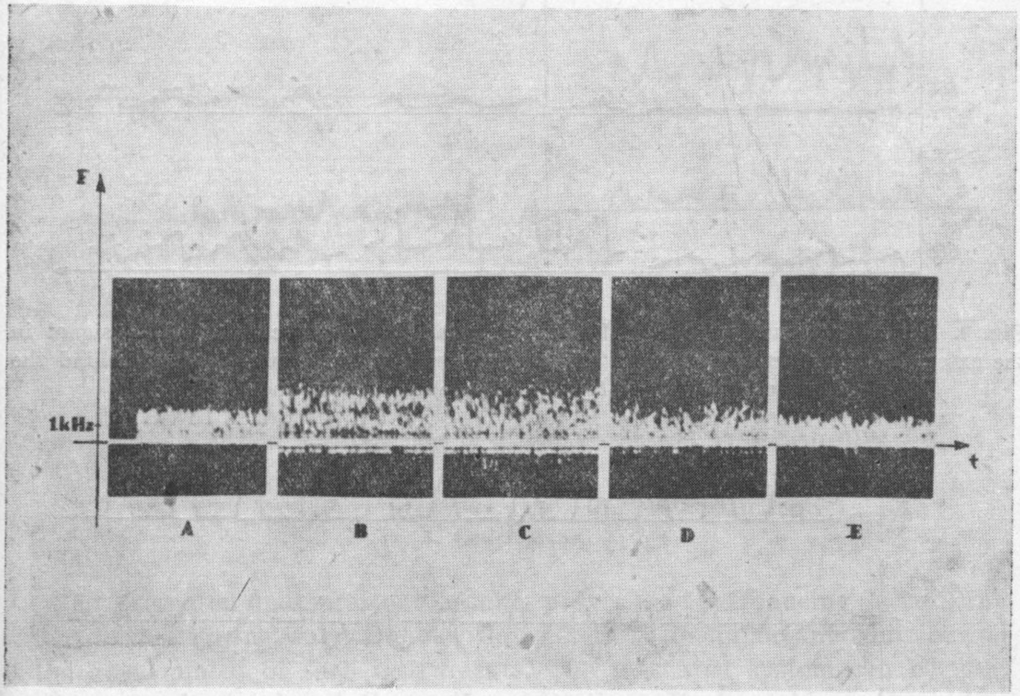


Fig. 8. Signal histograms for flows with REYNOLDS number $Re = 1900$, $ZW = 61\%$. A) before the contraction, B) 1 cm behind the contraction, C) 2 cm behind the contraction, D) 3 cm behind the contraction E) 5 cm behind the contraction

with $Re = 1900$ and in positions: before the contraction, 1, 2, 3 and 5 cm behind the contraction. Again we observe the decrease of the maximal frequencies and the decay of the back flow. This corresponds to the image obtained during the flow visualization.

It should be noticed, that histograms for a position before the contraction and 5 cm behind the contraction are similar, even though in the second case the flow was undoubtedly much more disturbed. This leads to a conclusion, that the influence of homogeneous disturbances on a signal histogram, obtained with the aid of a flowmeter with a continuous emission, is scarcely noticable in the qualitative presentation shown here. The following conclusions can be drawn on the basis of the presented above observations of flows and histograms originating from them:

1. Flow disturbances introduced by a contraction applied in the experiment depend on the degree of contraction, but also on the distance from the contraction and flow velocity, represented by the Reynolds number in our investigations;

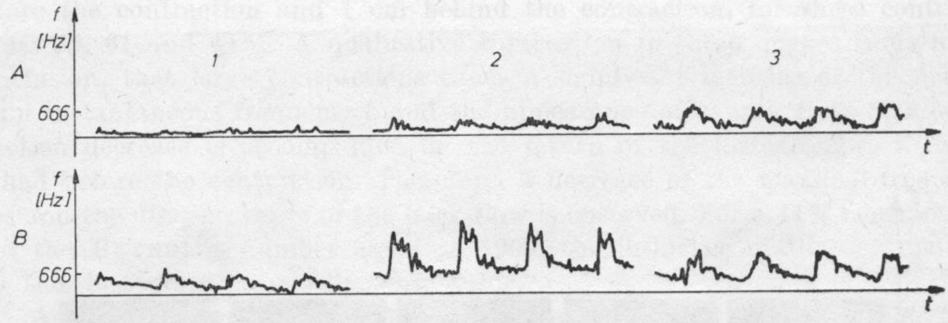


Fig. 9. Results of measurements of the average quantity of zero-crossing of a signal in the external carotid artery. a) before the contraction, b) in the contraction, c) behind the contraction, d) flow to the head, e) flow from the head

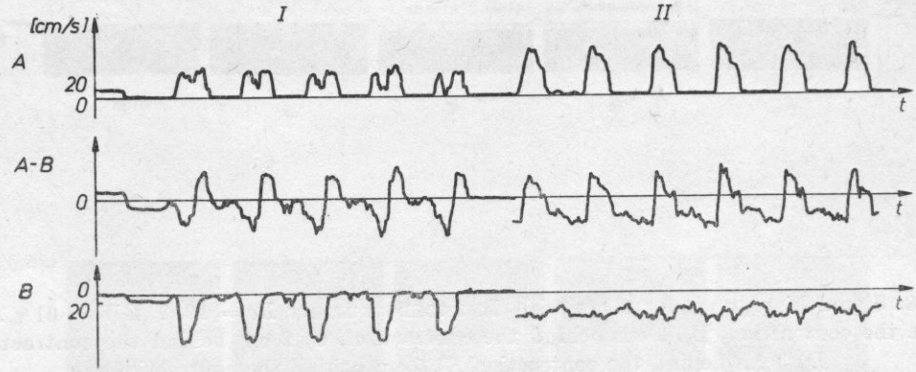


Fig. 10. Results of measurements of the average quantity of zero-crossing. I. descending aorta: A) flow to the probe (artefacts from the common carotid artery), B) folw from the head (aortic flow) A-B difference of flows (here: without practical significance). II. ascending aorta: A) flow to the head (aortic flow), B) flow from the head (artefacts from one of the veins), A-B difference of flows (without practical significance)

2. At a fixed flow velocity and fixed positioning of the probe in respect to the contraction, the degree of the contraction has a significant influence on the existance of the back flow, as well as on the shape of the histogram, what Figs. 6 and 7 prove.

The next stage of research will be concerned with the qualitative relations between the histogram parameters, the Doppler signal spectrum and the degree of the pipe contraction.

Although the flow applied in the experiment greatly strays from the flows in arteries, the obtained results correspond to the results obtained for coarctations of the carotid artery.

Fig. 9 presents the measurement results of the zero-crossing density in a carotid artery. Its Doppler visualization was shown in Fig. 3. A distinct back flow can be observed behind the contraction.

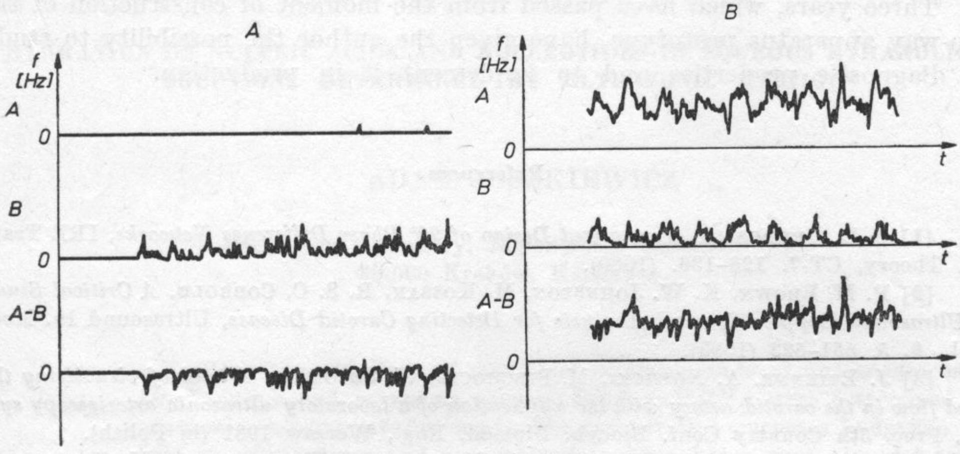


Fig. 11. Results of flow investigations in a breast neoplasm A) benign, B) malignant

5. Conclusions

The presented measurement results prove that introducing a two-way system to continuous wave Doppler flowmeters is an important contribution to the development of such instruments. The presented system can be used in all previously developed diagnostic applications. It also enlarges the utility of diagnostic DOPPLER flowmeters.

The separation of flow directions greatly facilitated the investigations of flows in the carotid artery branching, by eliminating the influence of the vein flows on the measurement results. Presented research of the flow in model contractions led to a fuller interpretation of the flow velocity records obtained practically. The experimental confirmation of the occurence of back flows behind local vessel contractions was a very important result of these investigations. The two-way system allowed the application of continuous wave flowmeters to heart and large blood vessel examinations, as well as the possibility of measuring very high flow velocities, what was impossible with the pulse Doppler apparatus.

The two-way system enabled the application of continuous wave flowmeters in heart and large blood vessel examinations, thanks to the possibility of measuring very flow velocities. The maximal flow velocity occuring in heart defects can reach several meters per second and are the basis of determining the pressure gradient in contractions.

Stereophonic audio monitoring of the Doppler signal, resulting from the two-way system, ensures great facility of the determination of flow directions, even for very small signals, no longer possible to register with the application of zero-crossing detectors.

Three years, which have passed from the moment of construction of the two-way apparatus prototype, have given the author the possibility to study its diagnostic properties and to implement it in production.

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