ARCHIVES OF ACOUSTICS
15, 3-4, 499-514 (1990)

PSEUDORANDOM ULTRASONIC DOPPLER METER OF LIQUID FLOW AND PROFILE WITH DIGITAL SERIAL SIGNAL PROCESSING

Z. TRAWIŃSKI, D. J. CATHIGNOL[1]

Department of Ultrasonic Institute of Fundamental Technological Research Polish Academy of Sciences
(00-049 Warszawa, Świętokrzyska 21)

[1] Institut Nationale de la Santé et de la Recherche Medicale, Unite 281
(151 Cours Albert Thomas, 69003 Lyon, France)

This paper presents a new method and new ultrasonic device for "real-time" measuring velocity profiles of liquid flow in vessel. Previously a flowmeter with pseudorandom coding of the transmitted signal made it possible to measuring point on a precisely determined depth with respect to the position of the ultrasonic probe. In order to obtain data for the entire penetration depth of the ultrasonic beam with that method, a system consisting of so many delay-receiving systems as there is measuring points, in which we need data for, would have to be built. While the presented original method applies only one transmitting-receiving system, enabling a measurement in all measuring points independently and at the same time.

W pracy zaprezentowano nową metodę i nowe urządzenie ultradźwiękowe do pomiaru profili prędkości przepływu cieczy w czasie rzeczywistym. Dotychczas przepływomierz z kodowaniem pseudolosowym sygnału nadawanego umożliwiał pomiar prędkości przepływu krwi tylko w jednym wybranym punkcie pomiarowym, na ściśle określonej głębokości względem położenia głowicy ultradźwiękowej. Chcąc uzyskać dane na całej głębokości penetracji wiązki ultradźwiękowej używając tej metody, należałoby zbudować system złożony z tylu układów opóźniająco-odbiorczych w ilu punktach pomiarowych pożądany jest wynik. Prezentowana oryginalna nowa metoda pozwala na stosowanie tylko jednego układu nadawczo-odbiorczego umożliwiającego pomiar we wszystkich punktach pomiarowych niezależnie i jednocześnie.

1. Introduction

Non-invasive ultrasonic Doppler methods of blood flow velocity measurements have become very useful for examination diseases of the circulatory system during the last 20 years. Methods of flow velocity visualisation of blood in a vessel are those worth noticing among them. The method of blood flow velocity visualization elaborated by NOWICKI and REID in 1978 [12] was based on the principle of "real-time" analog serial signal processing. In the Department of Ultrasonics of the Institute of Fundamental Technological Research of the Polish Academy of Sciences in Warsaw a UDP 30-TES ultrasonic Doppler flow and profile meter of liquid [13] was constructed according to this method. Next constructions of meters with "real-time" digital serial signal processing BRANDESTINI in 1978 [1], HOEKS in 1982 [3], MEISTER in 1983 [10] were complicated realizations, but they visualized blood profiles in a wide measuring range (in the analog method this range was limited by the delay time of applied television delay lines – 64 μs). Produced now most modern devices visualize a blood vessel and measure blood flow velocity in a chosen vessel at the same time. However, they do not have simultaneous visualization of the flow velocity profile in a vessel in "real-time".

The newly developed method of pseudorandom coding of transmitted signals, may become a basis for the widespread of blood flow profile visualization. This new method will be described in this paper.

2. Physical foundations and principle of operation of a pseudorandom flowmeter

For the first time the Doppler correlation technique was applied 30 years ago in radar systems [5, 14], and then it was transferred to ultrasonic engineering: WAAG in 1972 [16], NEWHOUSE in 1973 [11] and JETHWA in 1975 [9]. Gaussian noise with limited spectrum, white noise and signal with linear frequency modulation were used as the modulating signals at first. Yet, these systems had small dynamics. This seriously limited the application of this technique in cases with strong echoes from quasi-stationary object. In 1980 CATHIGNOL [3] proposed an original solution which avoids mentioned above problems by using a sinusoidal wave modulated by the two pseudorandom codes as the transmitted signal. The block diagram of such a pseudorandom Doppler flowmeter is shown in Fig. 1. The emitted signal, $X(t)$ is a result of phase modulation of a sinusoidal signal with frequency f_0 by a pseudorandom rectangular signal

$$X(t) = A(t)\cos[\omega_0 t], \tag{1}$$

where: $A(t)$ – envelope of emitted signal.

The pseudorandom signal can be generated by the system presented in Fig. 2. The pseudorandom code generation system is based on a synchronous bistable logic element. It's chosen outputs were connected with an exclusive-or adder. The adder's output is connected with the input of the system. A signal with $f_0/4$ frequency is sent to the clock's input. The pseudorandom sequence consists of N states following each other in a series. Fig. 10a presents an example of an output sequence of a pseudorandom code.

An acoustic signal with frequency f_0, emitted by a sending ultrasonic transducer, is subject to dissipation on mobile morphologic blood elements. A part of this signal

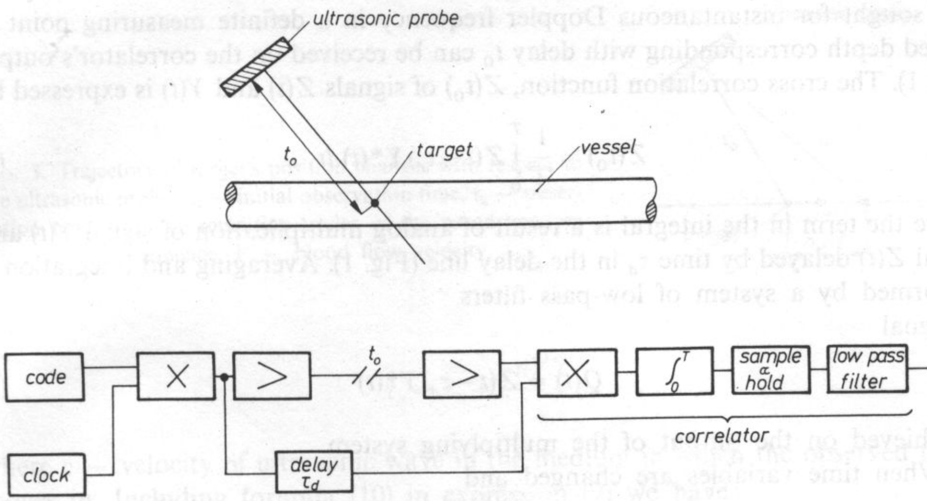

FIG. 1. Block diagram of pseudorandom flowmeter, t_0 – time of flight, τ_d – delay time of delay line, X – multiplier, $>$ – amplifier, $\int$ – integrating system

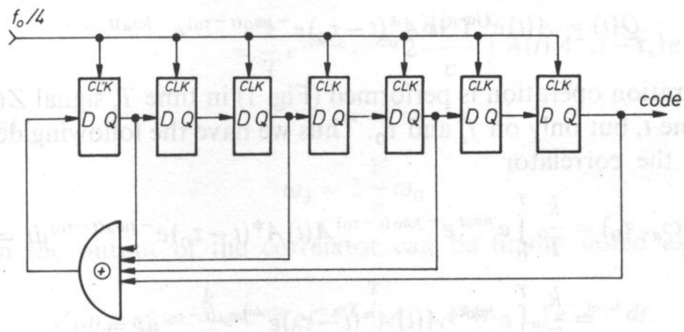

FIG. 2. Principle of generation of the pseudorandom code sequence, L – synchronous M-bite bistable logic element with initial state 1111111

returns to the receiving transducer with changed instantaneous frequency in accordance with the Doppler effect taking place in the blood vessel. If we present the transmitted signal in analytical form

$$Z(t) = A(t)\exp(j\omega_0 t), \tag{2}$$

where: $\omega_0 = 2\pi f_0$, $A(t)$ – complex envelope of transmitted signal,

then the signal received by the receiving transducer of the ultrasonic probe can be noted as

$$Y(t) = kA(t-t_0)\exp[j\omega_d(t-t_0)], \tag{3}$$

where: (t) – analytical form of received signal, k – transmission coefficient (influence of the attenuation effect of the medium on the amplitude of the ultrasonic wave propagating in it), $\omega_d = 2\pi f_d$ – Doppler pulsation, f_d – Doppler frequency.

The sought for instantaneous Doppler frequency in a definite measuring point at a fixed depth corresponding with delay t_0 can be received on the correlator's output (Fig. 1). The cross correlation function, $Z(t_0)$ of signals $Z(t)$ and $Y(t)$ is expressed by

$$Z(t_0) = \frac{1}{T}\int_0^T Z(t-\tau_d)\,Y^*(t)\,dt, \tag{4}$$

where the term in the integral is a result of analog multiplication of signal $Y(t)$ and signal $Z(t)$ delayed by time τ_d in the delay line (Fig. 1). Averaging and integration is performed by a system of low-pass filters.
A signal

$$Q(t) = Z(t-\tau_d)\,Y^*(t) \tag{5}$$

is achieved on the output of the multiplying system.
When time variables are changed and

$$\tau_0 = t_0 - \tau_d \tag{6}$$

is included, we have

$$Q(t) = A(t)e^{(j\omega_0 t)}k\,A^*(t-\tau_0)e^{-j\omega_0(t-\tau_0)}e^{-j\omega_d(t-\tau_0)}. \tag{7}$$

After the integration operation is performed (Fig. 1) in time T, signal $Z(t_0)$ no longer depends on time t, but only on f_d and τ_0. Thus we have the following dependence on the output of the correlator

$$\begin{aligned} Z(\omega_d, \tau_0) &= \frac{k}{T}\int_0^T e^{j\omega_0 t}e^{-j\omega_0(t-\tau_0)}A(t)A^*(t-\tau_0)e^{-j\omega_d(t-\tau_0)}dt = \\ &= \frac{k}{T}\int_0^T e^{j\omega_0\tau_0}A(t)A^*(t-\tau_0)e^{-j\omega_d(t-\tau_0)}dt = \\ &= \frac{k}{T}\,e^{j2\pi(f_0+f_d)\tau_0}\int_0^T A(t)A^*(t-\tau_0)e^{-j\omega_d t}dt. \end{aligned} \tag{8}$$

Assuming $f_d \ll f_0$, we have $f_0 + f_d \cong f_0$, so

$$Z(\omega_d, \tau_0) = \frac{k}{T}\,e^{j\omega_0\tau_0}\int_0^T A(t)A^*(t-\tau_0)e^{-j\omega_d t}dt. \tag{9}$$

This operation is performed for every repetition period T of signal $X(t)$.

From the set of natural numbers a number corresponding to succeeding repetitions of the sequence of the pseudorandom code can be noted as n. Assuming that the target moves with velocity V, as it is shown in Fig. 3, then the target after the n repetition cycle of the pseudorandom code sequence will travel a path with length equal to nVT. The time τ_n, measured from the beginning of ultrasonic wave emission to the current moment is in direct relationship with velocity V of the observed target, according to the following relation

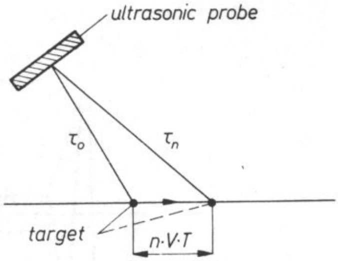

FIG. 3. Trajectory of target's position changes with respect to the ultrasonic probe, τ_0 – initial observation time, τ_n – observation time after "n" repetition cycles of the pseudorandom code sequence, V – blood flow velocity

$$\tau_n = \tau_0 + 2\frac{nVT}{c}, \tag{10}$$

where c – velocity of ultrasonic wave in the medium in which the observed target moves in. Including formula (10) in expression (9) we have

$$Z(\omega_d, \tau_n) = \frac{k}{T} e^{j\omega_0 \tau_n} \int_0^T A(t) A^*(t-\tau_n) e^{-j\omega_d t} dt =$$

$$= \frac{k}{T} e^{j\omega_0 \tau_0} e^{j\omega_0 2\frac{nVT}{c}} \int_0^T A(t) A^*(t-\tau_n) e^{-j\omega_d t} dt. \tag{11}$$

Knowing that

$$\omega_d = 2\frac{V}{c}\omega_0 \tag{12}$$

the signal on the output of the correlator can be finally noted as

$$Z(\omega_d, \tau_n) = \frac{k}{T} e^{j\omega_0 \tau_0} e^{j\omega_d nT} \int_0^T A(t) A^*(t-\tau_n) e^{-j\omega_d t} dt. \tag{13}$$

Three terms can be distinguished in expression (13):

a) $\frac{k}{T}\exp(j\omega_0\tau_0)$ – constant component, related with constant echoes,

b) $\exp(j\omega_d nT)$ – component of Doppler frequency f_d sampled and held with frequency $1/T$,

c) integral expression which is the value of the signal's envelope on the output of the correlator for τ_n in plane $\omega = \omega_d$.

The form of dependence (13) indicates that there is a three-dimensional ambiguity function of the following form on the correlator's output

$$\chi(\vartheta, \tau) = \int_{-\infty}^{+\infty} A(t) A^*(t-\tau) e^{-j\omega_d t} dt = \int_{-\infty}^{+\infty} \mathscr{A}(f) \mathscr{A}(f-\vartheta) e^{j\omega_d \tau} df, \tag{14}$$

where $\mathscr{A}(f) = \mathscr{F}[A(t)]$ is a Fourier transform [6], (Fig. 4).

The function of ambiguity (14) becomes an autocorrelation function of the complex function $A(t)$ when the observed target is motionless, i.e. $\vartheta = 0$

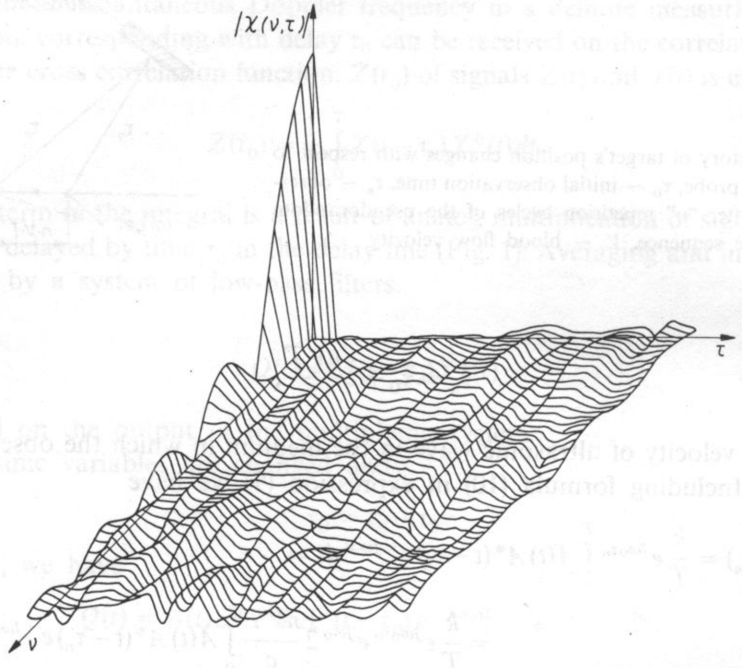

FIG. 4. Spatial distribution of the ambiguity function $\chi(\vartheta, \tau)$ of the pseudorandom code, with $N = 127$ states (according to G. GARAMPON, 1968 [6]). τ — relative time shift, ϑ — relative change of Doppler frequency

$$\chi(0, \tau) = \int_0^T A(t)\, A^*(t-\tau)\, dt. \tag{15}$$

In order to achieve high longitudinal resolution, this function should possibly closely resemble the Dirac distribution. Similarly, we have the following function for delay $\tau = 0$

$$\chi(\vartheta, 0) = \int_{-\infty}^{+\infty} \mathscr{A}(f)\, \mathscr{A}(f-\vartheta)\, df. \tag{16}$$

Expression (16) is an autocorrelation function in the frequency domain. Also expression (16) should be maximally close to the Dirac distribution in order to achieve high resolution during velocity measurements of the moving target. It is worth mentioning here that longitudinal resolution, as well as resolution during velocity measurements in the domain of frequency depends only on the ambiguity function of the transmitted signal. Studies on the choice of an adequate emitted signal have resulted in the choice of a pseudorandom binary signal which meets mentioned above criteria [7].

Fig. 5 presents the signal achieved on the output of the correlator in terms of time for a case of one target moving with constant velocity V. This corresponds to only one Doppler frequency f_d.

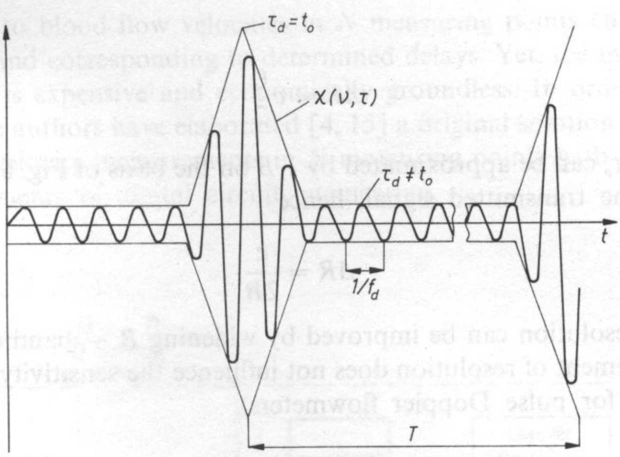

FIG. 5. Time function $Z(t)$ on the output of the correlator for one target moving with constant blood velocity V, T – repetition period of pseudorandom code sequence, t – time

3. Basic parameters of a pseudorandom flowmeter

3.1. Longitudinal resolution

For a motionless target, $\chi(\vartheta = 0, \tau)$, the ambiguity function for a pseudorandom binary code is a triangle with base equal to $2\,t_e$ (t_e is the shortest duration time of the pseudorandom code – see Fig. 6). In such a case, longitudinal resolution ΔR is

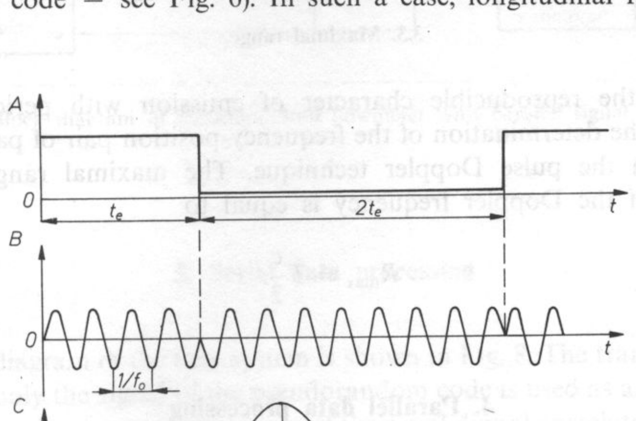

FIG. 6. Modulation effect of carrier wave f_0 by pseudorandom code sequence, a) fragment of pseudorandom code, b) phase modulated carrier wave, c) spectrum of power density of emitted signal

noted as

$$\Delta R = c\frac{t_e}{2}. \tag{17}$$

Dependence $1/t_e$ can be approximated by $1/B$ on the basis of Fig. 6, where B denotes the band of the transmitted signal, hence

$$\Delta R = \frac{c}{2B}. \tag{18}$$

Longitudinal resolution can be improved by widening B – band of emitted signal. So, the improvement of resolution does not influence the sensitivity of the apparatus (as it happens for pulse Doppler flowmeters).

3.2. Maximal measured Doppler frequency

Samples of the Doppler signal f_d appear on the output of the correlator every period of repetition of the pseudorandom code sequence T. The output voltage in the integrating circuit becomes steady during this period. This corresponds to a time interval between two succeeding samples of the Doppler signal on the output of the correlator. Therefore, the measurement of the maximal Doppler frequency depends directly on time T in accordance with Shanon's theorem concerning sampling f_d

$$f_d \max = \frac{1}{2T}. \tag{19}$$

3.3. Maximal range

Because of the reproducible character of emission with period T there is a ambiguity in the determination of the frequency-position pair of parameters, as it also happens in the pulse Doppler technique. The maximal range of univocal determination of the Doppler frequency is equal to

$$R_{\max} = T\frac{c}{2}. \tag{20}$$

4. Parallel data processing

The block diagram of a pseudorandom flowmeter with parallel data processing is presented in Fig. 7. The method consists in the construction of N parallel receiving lines. Values of Doppler frequencies are achieved on individual outputs of correlators for suitably chosen delays of the transmitted signal in delay lines. These frequencies are proportional to blood flow velocities in N measuring points chosen along the ultrasonic beam and corresponding to determined delays. Yet, the multiplication of measuring paths is expensive and economically groundless. In order to overcome this drawback the authors have elaborated [4, 15] a original solution to the problem of simultaneous velocity measurements in N measuring points with the application of latest achievements of digital circuit engineering.

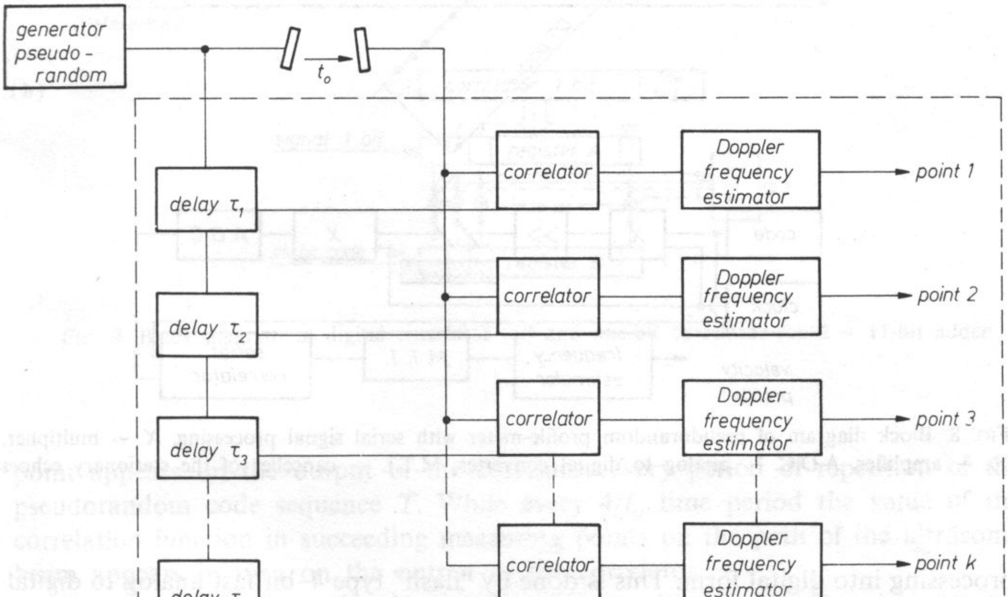

FIG. 7. Block diagram of pseudorandom flowmeter with parallel signal processing

5. Serial data processing

The block diagram of the new system is shown in Fig. 8. The transmitting system is as in Fig. 1, only the signal of the pseudorandom code is used as a reference signal, what is necessary for correct functioning of the serial digital correlator. The receiving system lacks delay lines. While the analog part contains an analog multiplier to demodulate-reproduce the sequence of the pseudorandom code. The reproduced sequence of the pseudorandom code is modulated in phase and amplitude due to the Doppler effect which takes place when mobile targets are encountered on the path of the ultrasonic beam. The signal on the output of the multiplier is subject to

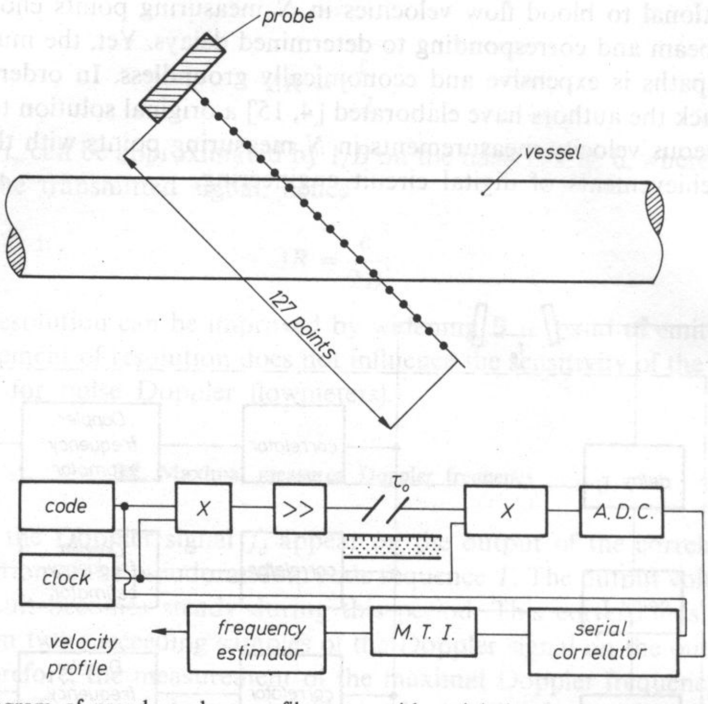

FIG. 8. Block diagram of pseudorandom profile-meter with serial signal processing, X — multiplier, $\rangle\rangle$ — amplifier, A.D.C. — analog to digital converter, M.T.I. — canceller of the stationary echoes

processing into digital form. This is done by "flash" type 4–bit fast analog to digital converter. The digital correlator, multi target indicator (MTI) and digital multichannel estimator of Doppler frequencies are completely newly applied systems.

5.1. Digital correlator

This new digital correlator (Fig. 9) contains integrated one-bit correlators connected with succeeding outputs of the A/D converter. Every one-bit correlator consists of two serial registers — measuring and reference, multipliers and adders. The reference register has a sequence of pure pseudorandom code, while a weighted sequence of the pseudorandom code after demodulation is passed through the measuring register. The length of both registers corresponds to the length of the used pseudorandom code and unequivocally determines the number of measuring points N in the full measuring range R_{max}. The same reference signal is sent to all one-bit integrated correlators which determine weights of individual bits in the process of adding. A 11-bit information about the value of the crosscorrelation function of the reference signal and signal received after demodulation is achieved on the output of the correlator. The new value of the correlation function for a definite measuring

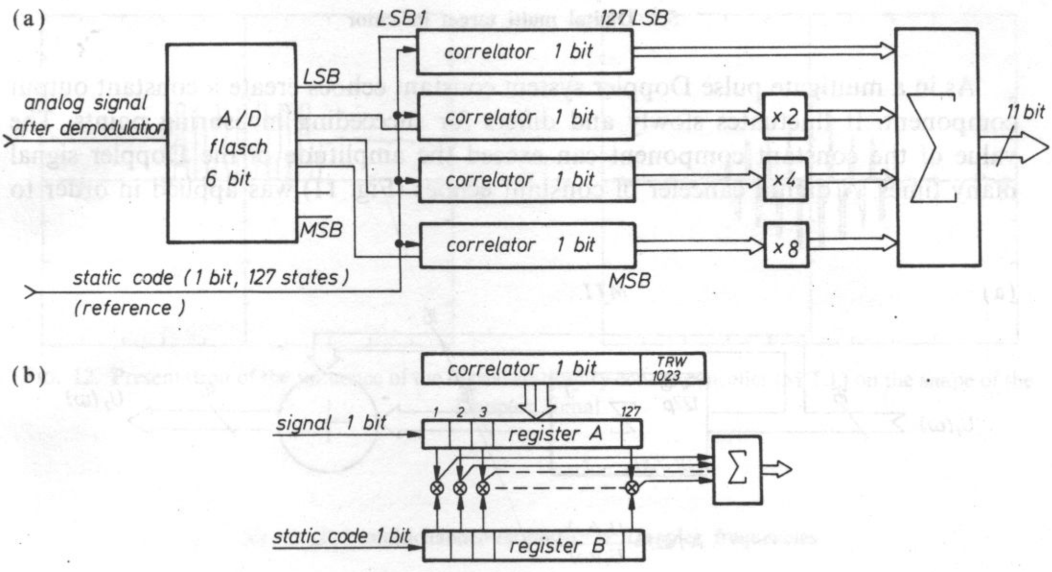

FIG. 9. Block diagram of digital correlator (a/) and one-bit correlator (b). Σ – 11-bit adder

point appears on the output of the correlator every period of repetition of the pseudorandom code sequence T. While every $4/f_0$ time period the value of the correlation function in succeeding measuring points on the path of the ultrasonic beam appears in turn on the output of the correlator.

The advantage of such signal processing over a multigate pulse Doppler system is the application of a cheap converter with low 4-bit conversion dynamics. Fig. 10b presents the autocorrelation function of the signal of pseudorandom code achieved on the output of the described correlator.

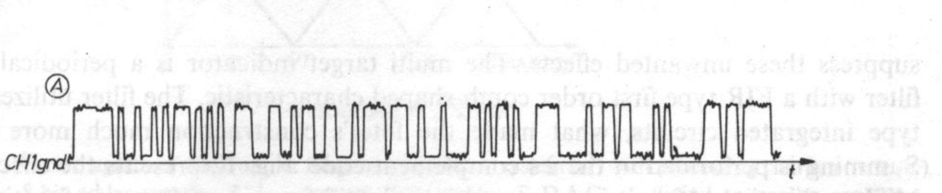

FIG. 10. Autocorrelation function (b/) of the pseudorandom code (a/) on the output of the digital correlator

5.2. Digital multi target indicator

As in a multigate pulse Doppler system constant echoes create a constant output component. It fluctuates slowly and differs for succeeding measuring points. The value of the constant component can exceed the amplitude of the Doppler signal many times. A digital canceler of constant echoes (Fig. 11) was applied in order to

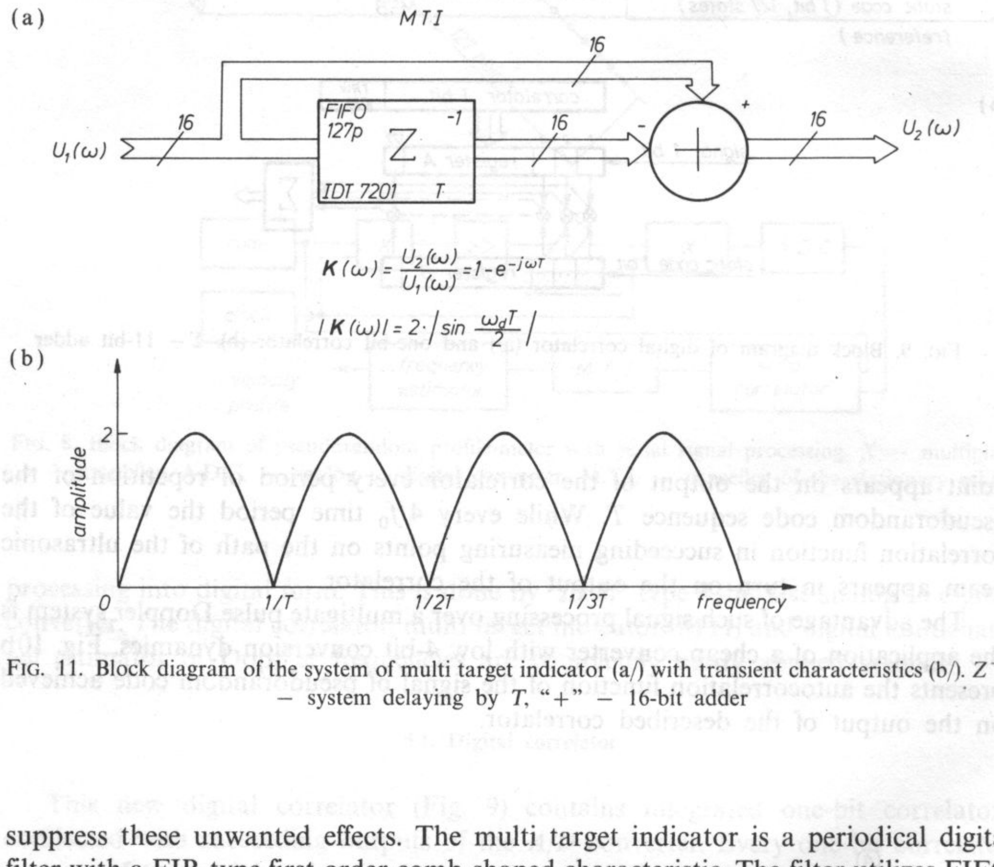

FIG. 11. Block diagram of the system of multi target indicator (a/) with transient characteristics (b/). Z^{-1} – system delaying by T, "+" – 16-bit adder

suppress these unwanted effects. The multi target indicator is a periodical digital filter with a FIR type first order comb-shaped characteristic. The filter utilizes FIFO type integrated circuits, what made the filter's construction much more simple. Summing is performed in the 2's complement code. Fig. 12 presents the effect of the MTI application. After it is processed into digital form, a rectangular function with constant component with $f_d = 1$ kHz frequency is sent to the output of the canceler. A function with the same frequency is obtained on the output of the canceler. A function with the same frequency is obtained on the output of the canceler after it is processed into analog form. However it has an envelope resembling a triangular function but without the constant component. A change of the envelope's shape is a typical effect of comb-shaped transient characteristic of the digital filter.

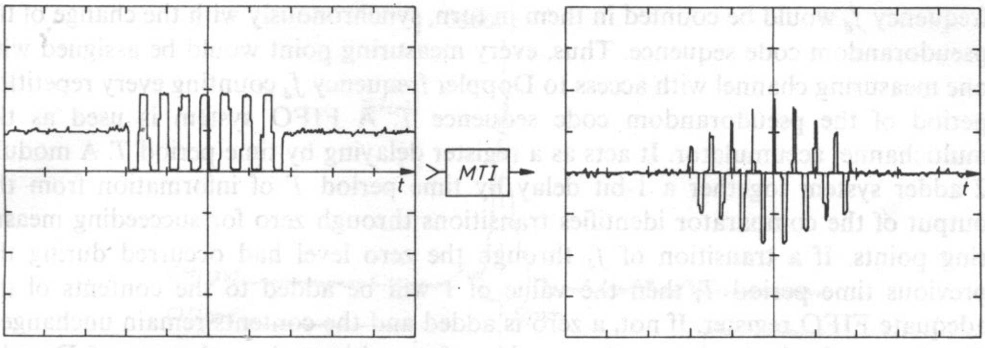

FIG. 12. Presentation of the influence of the digital stationary echoes canceller (M.T.I.) on the shape of the Doppler signal

5.3. Digital multichannel estimator of Doppler frequencies

Fig. 13 presents the block diagram of the system which estimates Doppler frequencies in N channels at the same time. The design utilizes the "zero-crossing" conception in measurements of the number of transitions through the zero level of

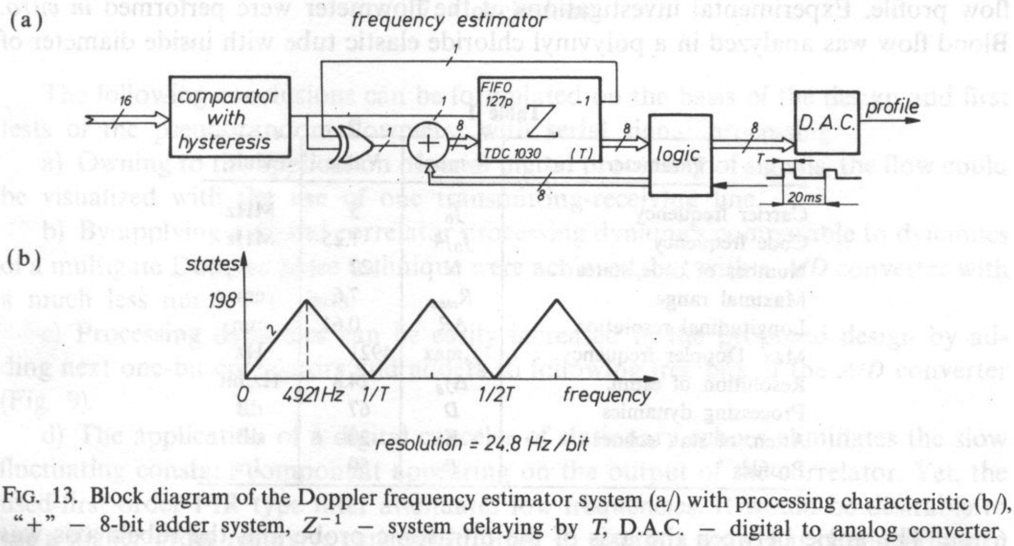

FIG. 13. Block diagram of the Doppler frequency estimator system (a/) with processing characteristic (b/), "+" — 8-bit adder system, Z^{-1} — system delaying by T, D.A.C. — digital to analog converter

the output signal from the canceler of stationary echoes. In order to free the system from effects of noises of the analog path and quantization noise a multibit comparator system with a hysteresis, with comparation threshold setting was introduced. The idea of a multichannel frequency counter lies in the creation of N serial channels. The number of transitions through the zero level of Doppler frequency f_d would be counted in them in turn, synchronously with the change of the pseudorandom code sequence. Thus, every measuring point would be assigned with one measuring channel with access to Doppler frequency f_d counting every repetition period of the pseudorandom code sequence T. A FIFO system is used as the multichannel accumulator. It acts as a register delaying by time period T. A modulo 2 adder system together a 1-bit delay by time period T of information from the output of the comparator identifies transitions through zero for succeeding measuring points. If a transition of f_d through the zero level had occurred during the previous time period T, then the value of 1 will be added to the contents of the adequate FIFO register. If not, a zero is added and the contents remain unchanged. Owning to the logic system the number of transitions through zero of Doppler frequency f_d is counted during about 20 ms. After this period the contents of N registers from the FIFO system are written out to the digital to analog converter. Values, written out one after the other, are registered on a X–Y plotter giving the image of one of the instantaneous flow velocity profiles of blood encountered by the transmitted ultrasonic beam.

6. Results

Table 1 contains technical data of the designed pseudorandom meter of blood flow profile. Experimental investigations of the flowmeter were performed *in vitro*. Blood flow was analyzed in a polyvinyl chloride elastic tube with inside diameter of

Table 1

Parameter	Symbol	Value	Unit
Carrier frequency	f_0	5	MHz
Code frequency	$f_0/4$	1.25	MHz
Number of code states	N	127	–
Maximal range	R_{max}	7.6	cm
Longitudinal resolution	ΔR	0.61	mm
Max. Doppler frequency	$f_d$max	4921	Hz
Resolution of estim.	Δf_d	24.8	Hz/bit
Processing dynamics	D	67	dB
Atten. of stat. echoes	K	20	dB
Profiles	P	50	1/s

6 mm. The angle between the axis of the ultrasonic probe and the tube's axis was equal to 60°. The transmitter and receiver were connected with the ultrasonic probe – separately to two piezoelectric transducers with dimensions 2 × 3 mm. A specially prepared blood simulating liquid was used in measurements. It was set in cyclic motion with a pump. An example of a flow profile achieved in these conditions is shown in Fig. 14. The maximal Doppler frequency occurred in the centre of the tube and was equal to about 1.7 kHz. Fluctuation visible outside the tube are result of the ambiguity function $\chi(\vartheta, \tau)$ (14).

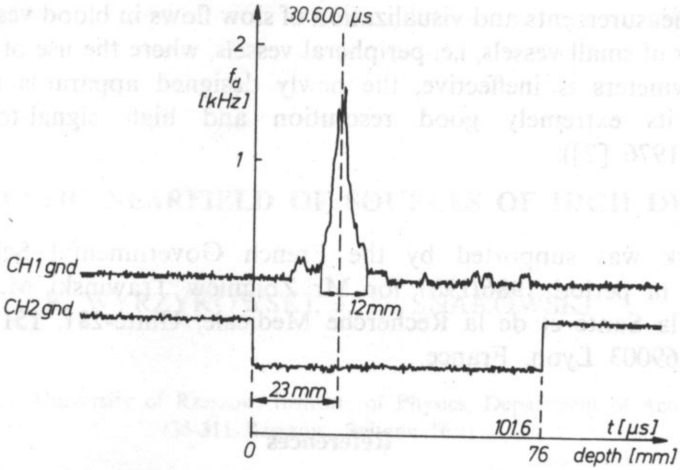

FIG. 14. Visualization of an exemplary flow profile in a light — wall tube, obtained with the designed pseudorandom flowmeter with digital serial signal processing, f_d — measured Doppler frequency

7. Conclusions

The following conclusions can be formulated on the basis of the design and first tests of the pseudorandom flowmeter with serial signal processing:

a) Owning to the application of serial digital processing of signals, the flow could be visualized with the use of one transmitting-receiving line.

b) By applying a digital correlator processing dynamics comparable to dynamics of a multigate Doppler pulse technique were achieved, but with a *A/D* converter with a much less number of bits.

c) Processing dynamics can be easily increased in the proposed design by adding next one-bit correlators and adders to following free bits of the *A/D* converter (Fig. 9).

d) The application of a digital canceler of stationary echoes eliminates the slow fluctuating constant component appearing on the output of the correlator. Yet, the used first order FIR type filter attenuates low frequencies. It would be desirable to use a higher order recursive canceler in order to obtain a more flat characteristic in the filter's transmission band.

e) The design of the 127-channel system of Doppler frequency estimation is more integrated owning to the introduction of serial digital signal processing.

f) Using FIFO registers, recording and read-off control in elements delaying by time period T (denoted by Z^{-1} in block diagrams) was considerably simplified.

g) Presented parameters and results of investigations of the pseudorandom flowmeter with serial signal processing indicate practical possibilities of its application in measurements and visualization of slow flows in blood vessels Especially in diagnostics of small vessels, i.e. peripheral vessels, where the use of classical pulse Doppler flowmeters is ineffective, the newly designed apparatus can find wide application, its extremely good resolution and high signal-to-clutter ratio (CATHIGNOL 1976 [2]).

This work was supported by the French Governmental Scholarship and I.N.S.E.R.M. in period 1986/1987 for Mr Zbigniew Trawiński M.Sc. in Institut National de la Santé et de la Recherche Medicale, Unite-281, 151 Cours Albert Thomas 151,69003 Lyon, France.

References

[1] M. BRANDESTINI, *Topoflow — a digital full range Doppler velocity meter*, IEEE Trans. Sonics and Ultrasonics SU–25, 287 (1978).

[2] D. J. CATHIGNOL, *Signal-to- clutter ratio in pseudo random Doppler flowmeter*, Ultrasonic Imaging, **8**, 272–284 (1986).

[3] D. CATHIGNOL, C. FOURCADE, J. Y. CHAPELON, *Transcutaneous blood flow measurements using pseudorandom noise Doppler system*, IEEE Trans. on Biol. Engineer, BME–27, 1, 1980.

[4] D. CATHIGNOL, Z. TRAWIŃSKI, J. Y. CHAPELON, *Pseudo-random Doppler flowmeter using serial processing*. Proceedings of 1987 IEEE Ultrasonic Symposium, Denver, pp. 889–892.

[5] C. E. COOK, M. BERNFELD and C. A. PALMIERI, *Radars, vol. 3: Pulse compression*, [Ed.] D. K. Barton, Dedham, MA: Artech House, 1975, pp. 127–129.

[6] G. J. GARAMPON, G. BONNET, *Extension de la notion de function d'ambiguite à des signaux aléatoires.* Ann. Tèlécom. T–23 Juin 1968.

[7] G. J. GARAMPON, *Considerations sur la function d'ambiguité dans le cas de signaux aléatoires — Etude et gènération de certains signaux*. Thèse de Docteur Ingènieur, Grenoble, mai 1970.

[8] A. P. G. HOEKS, *On the development of a multigate pulsed Doppler system with serial data processing,* Dissertation, University of Limburg, Maastricht 1982.

[9] C. P. JETHWA, M. KAREN, G. R. COOPER, *Saggiof, Blood flow measurements using ultrasonic pulsed random signal Doppler systems*, IEEE Trans. Sonics and Ultrasonics, **22**, 1 pp. 1–10 (1975).

[10] J. J. MEISTER, *Mesure par èchographie Doppler et modèlisation théorique de l'effet de troubles cardiaques sur la pression et le débit artérliels.* Thèse Lausanne EPFL 1983.

[11] V. L. NEWHOUSE, G. R. COOPER, H. FEIGEUBAUM, *Ultrasonic blood velocity measurement using random signal, correlation techniques.* Digest of the Xth ICMBE, Dresden 1973.

[12] A. NOWICKI, J. M. REID, *An infinite gate pulse Doppler*, Proc. of 23 rd. AIUM, 139, Oct. 20–23, San Diego (1978).

[13] A. NOWICKI, *Ultrasonic methods of visualization of blood vessels and blood flows* (in Polish), Qualifying thesis, IFTR Reports, Warsaw, Poland. 65 (1979).

[14] H. O. RAMP and E. R. WINGROVE, *Radars*, Vol. 3, *Pulse Compression*, [Ed.] D. K. Barton, Dedham, MA: Artech House. 1975, p. 75.

[15] Z. TRAWIŃSKI, D. CATHIGNOL, *Pseudorandom ultrasonic Doppler meter of blood flow profile with serial data processing* (in Polish), Proc. of XXXV Open Seminar on Acoustics, Białowieża, Poland, 1988 r.

[16] R. C. WAAG, J. B. MYKLEBUST, W. L. and R. GRAMIAK, *Instrumentation for noninvasive cardiac chamber flow rate measurements.* in 1972 IEEE Ultrasonic Symposium Proceedings; pp. 74–77, IEEE Cat N° 72CH0708-8SU.

Received on February 24, 1989