ARCHIVES OF ACOUSTICS
10, 3, 273-280 (1985)

APPLICATION OF A PHASE LOOP SYSTEM TO ANALYSIS OF A DOPPLER SIGNAL IN ULTRASONIC SYSTEMS

MACIEJ PIECHOCKI

Institute of Fundamental Technological Research, Polish
Academy of Sciences
(00-049 Warsaw, ul. Świętokrzyska 21)

MICHEL XHAARD, PIERRE PERONNEAU

Instrumentation et Dynamique Cardiovasculaire INSERM U265, Hopital Broussais
(75674 Paris, 96, rue Didot)

This paper presents a way of applying a phase loop system to the measurement of the instantaneous frequency of a Doppler signal in ultrasonic systems. This system was used to verify experimentally the dependence proposed by Angelsen [1], connecting the instantaneous probability distribution of the signal with its power spectrum. It presents measured results for two, laminar and turbulent, flows, and also an example of the operation of the phase loop system for a signal with a low signal to noise power ratio.

1. Introduction

The tendency to extend applications of ultrasonic flowmeters in medical diagnosis has brought about developments in the methods of analyzing signals they provide. Generally, it is assumed that a good mathematical description of such a signal is the Gaussian stochastic process, which is stationary for stationary flows [1-3]. Full information on the properties of this process, i.e., also on those of the flow observed, is contained in the power spectrum or the auto-correlation function of this process. Since, however, the spectral analysis requires sophisticated equipment, it is still essential to carry on studies on the possibilities of measuring the flow properties through the analysis of zero crossings, or that of its instantaneous frequencies.

In 1976 Sainz *et al.* published the results of their investigations on the use of the phase loop system (*PLL*) to analyze a Doppler signal [7]. In the interpretation of the results, however, no account was taken of the stochastic nature of the signal, thus, making it hardly convincing. Because of a lack of a theoretical description of the measured phenomenon, the conclusions are intuitive in nature.

The present paper is devoted mainly to an experimental verification of a dependence connecting the properties of the instantaneous frequencies of a signal with its power spectrum. The instantaneous frequency of a signal is defined by the time derivative of the instantaneous phase of the signal [1]. This dependence was proposed by ANGELSEN in 1981; it permits the determination of the mean value and standard deviation of the signal power spectrum from the probability distribution of its instantaneous frequencies. The ratio between these quantities, i.e. the ratio between the standard deviation of the power spectrum and its mean frequency, is called the turbulence index — accepted in medical diagnosis as the index of the degree of flow turbulence [4, 5].

The dependence, proposed by ANGELSEN, between the parameters of the signal power spectrum and the probability distribution of its instantaneous frequencies is given by the formula

$$p(\omega_c)=\frac{\sigma_s^2}{2\left[(\omega_c-\overline{\omega})^2+\sigma_s^2\right]^{3/2}}, \tag{1}$$

where $p(\omega_c)$ is the probability distribution of the instantaneous frequencies of a signal, ω_c is the instantaneous frequency of a signal and $\overline{\omega}$ is the mean frequency in the power spectrum.

It follows from formula (1) that by knowing $\overline{\omega}$ — the mean frequency in the power spectrum, and σ_s^2 — the variance in the signal power spectrum, it is possible to calculate $p(\omega_c)$, the probability distribution of the instantaneous frequencies of this signal. Conversely, by knowing the distribution $p(\omega_c)$, the values of $\overline{\omega}$ and σ_s^2 can be found. The dependencies permitting the determination of these two parameters of the power spectrum have the following form:

$$\overline{\omega}=\overline{\omega}_c; \quad \sigma_s=0.654\,\Delta_{1/2\omega_c}, \tag{2}$$

where $\overline{\omega}_c$ is the mean value of the instantaneous frequencies and $\Delta_{1/2\omega_c}$ is the distribution width of $p(\omega_c)$ at half its height.

From dependencies (1) and (2) an additional conclusion follows, that, if they are valid, knowing the whole distribution $p(\omega_c)$, the only information on the power spectrum of this signal which can be determined, from $p(\omega_c)$, are the values of $\overline{\omega}$ and σ_s, i.e. the mean value and the standard deviation of the power spectrum. In turn, the shape of the power spectrum is not directly related to that of the distribution $p(\omega_c)$.

Dependence (1) was given in [1] without assumptions restricting its validity range. However, a previous publication by ANGELSEN [2] contained dependencies resembling formula (1), obtained for narrow-band signals, i.e. on the assumption that the ratio $\sigma_s/\overline{\omega}$ tended to zero.

A further part of this paper gives a system permitting the measurement of the instantaneous frequency of a signal and comparison between the theoretical dependencies given above and the measured results.

2. Construction principles of the system

Fig. 1 shows a schematic diagram of an impulse flowmeter where a phase loop system (*PLL*) was used to measure the instantaneous frequency of a Doppler signal.

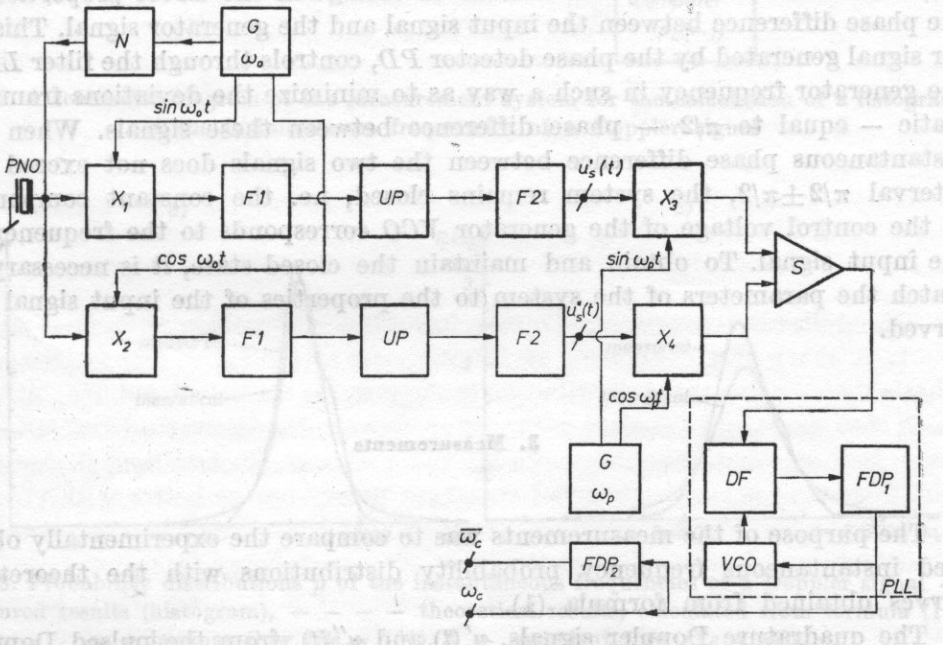

Fig. 1. A simplified schematic diagram of the impulse flowmeter with a (*PLL*) phase loop system for the measurement of the instantaneous and mean frequencies of the Doppler signal. X_1, X_2 – multiplying systems, S – summator, N – transmitter, F_1 – low-pass filter after demodulation, F_2 – low – pass filter after sampling, $G\omega_0$ – carrier frequency generator, $G\omega_p$ – generator of the centre frequency of the system *VCO*, *UP* – sampling and hold units, *PD* – phase detector, LPF_1 – low-pass filter in the *PLL* system, LPF_2 – filter averaging the instantaneous frequency, *VCO* – voltage controlled oscillator $u_s'(t)$, $u_s''(t)$ – quadrature Doppler signals, ω_c – instantaneous frequency of Doppler signal, $\overline{\omega_c}$ – mean frequency of Doppler signal

The classical pulsed Doppler flowmeter demodulates, samples and filters the high-frequency signal detected in two independent channels shifted in phase by +90°, or −90°, depending on the flow direction. The two low-frequency signals thus obtained, $u_s'(t)$ and $u_s''(t)$, called quadrature signals, are fed to the detector of instantaneous frequencies through a single side band modulation system, consisting of the multiplying units X_3 and X_4, and the sumator S. The task of this system is to shift the spectrum of the Doppler signal described by $u_s'(t)$ and $u_s''(t)$ towards higher frequencies, while retaining information on the flow direction. The new carrier frequency ω_p corresponds to the frequency of the generator *VCO* at zero control voltage.

The phase loop system itself consists of three functional units: the phase detector *PD*, the low-pass filter LPF_1 and the voltage controled oscillator *VCO* with its frequency depending on the control voltage. The principle of the operation of the system is also such control of the frequency of the generator *VCO* so that the phase difference between the input and the generated signals would be constant. To that end, use is made of voltage in the direct proportion to the phase difference between the input signal and the generator signal. This error signal generated by the phase detector *PD*, controls through the filter LDF_1 the generator frequency in such a way as to minimize the deviations from the static — equal to $\pi/2$ — phase difference between these signals. When the instantaneous phase difference between the two signals does not exceed the interval $\pi/2 \pm \pi/2$, the system remains closed, i.e. the constant component of the control voltage of the generator *VCO* corresponds to the frequency of the input signal. To obtain and maintain the closed state, it is necessary to match the parameters of the system to the properties of the input signal observed.

3. Measurements

The purpose of the measurements was to compare the experimentally obtained instantaneous frequency probability distributions with the theoretical curves obtained from formula (1).

The quadrature Doppler signals, $u_s'(t)$ and $u_s''(t)$, from the pulsed Doppler flowmeter manufactured at the CNRS ER 248 Laboratory were recorded on magnetic tape. The measurements were carried out for two stationary flows in a rigid pipe with 16 mm internal diameter. The transducer diameter was 16 mm, the sample volume was set on the flow axis. One of the flows investigated was laminar with the Reynolds number $Re = 700$, and the other was turbulent $Re = 5000$.

Fig. 2 shows a schematic diagram of the measurement system used to determine the probability distributions of the instantaneous frequency of the signal. The quadrature Doppler signals, $u_s'(t)$ and $u_s''(t)$, were fed to the instantaneous frequency detector, based on a *PLL* system. The voltages occurring at the output ω_c (Fig. 1) of this system were sampled by the *A/D* convertor at a frequency of 50 kHz and introduced to the computer memory.

Further signal processing was carried out in a software manner. The programme elaborated by the authors analyzed successively the input data in order to produce a histogram from them. Points on the instaneous frequency axis, ω_c, correspond to the discrete voltages fed to the computer (Fig. 3). The y-axis describes the number of times the given voltage, representing the respective instantaneous frequency, occurred in the signal recorded. Each of these values is divided by the total number of the samples analyzed so as to normalize the distributions obtained. The histograms thus obtained were smoothed by local averaging, i.e. each value of the original histogram was replaced by the arithmetic mean of five values — the one currently calculated and the two adjacent ones on both sides.

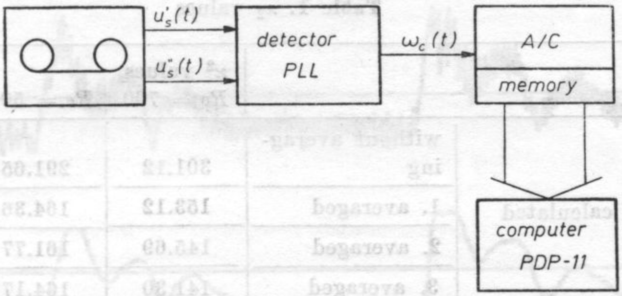

Fig. 2. A schematic diagram of the measurement system for the calculation of a listogram of the instantaneous frequencies of a Doppler signal

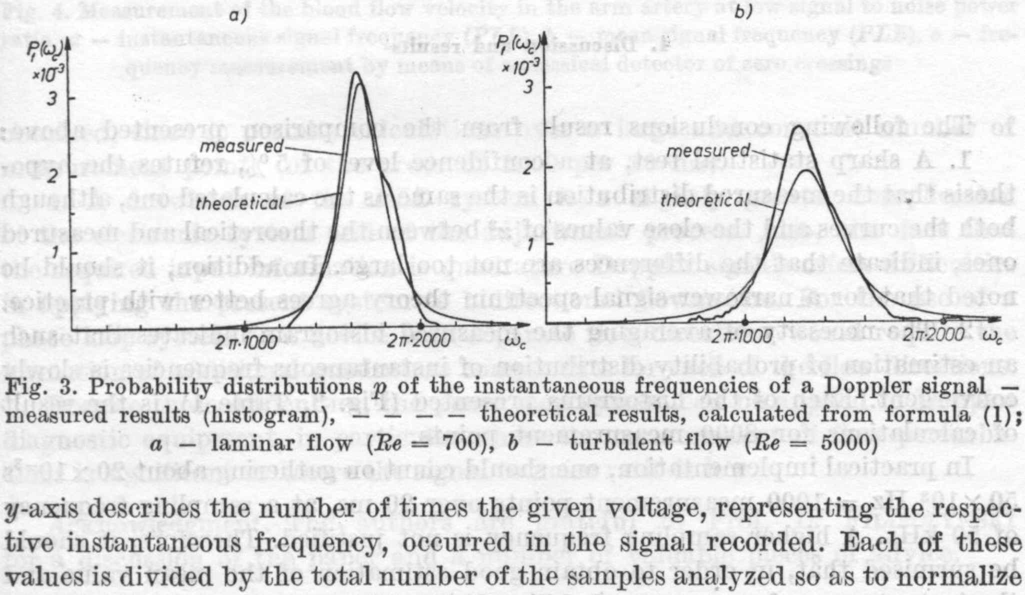

Fig. 3. Probability distributions p of the instantaneous frequencies of a Doppler signal — measured results (histogram), — — — — theoretical results, calculated from formula (1); a — laminar flow (Re = 700), b — turbulent flow (Re = 5000)

The measured curves shown in Fig. 3 were smoothed by using the method presented above, three times in succession. In order to compare the theoretical and measured curves, the $\varkappa^2$ statistical test was used. When the value of $\varkappa^2$, calculated as a function of the difference between the theoretical and measured curves, is less than a specific constant value, it can be accepted that the theoretical curve represents a correct description of the phenomenon, the observation of which was the basis for determining the measurement curve.

Table 1 represents a comparison of the calculated and theoretical $\varkappa^2$ values.

Table 1. $\varkappa_2$ values

		$\varkappa^2$ values $Re = 700$	 $Re = 5000$
$\varkappa^2$ calculated	without averaging	301.12	291.65
	1. averaged	153.12	164.36
	2. averaged	145.69	161.77
	3. averaged	141.30	164.17
$\varkappa^2$ theoretical	$\varkappa^2$ at 5% confidence level	101.67	101.67

4. Discussion and results

The following conclusions result from the comparison presented above:

1. A sharp statistical test, at a confidence level of 5%, refutes the hypothesis that the measured distribution is the same as the calculated one, although both the curves and the close values of $\varkappa^2$ between the theoretical and measured ones, indicate that the differences are not too large. In addition, it should be noted that for a narrower signal spectrum theory agrees better with practice.

2. The necessity of averaging the measured histogram indicates that such an estimation of probability distribution of instantaneous frequencies is slowly convergent. Each of the histograms presented (Fig. 3, Table 1), is the result of calculations for 8000 measurement points.

In practical implementation, one should count on gathering about $20 \times 10^{-3}\,\mathrm{s}$ $50 \times 10^{3}\,\mathrm{Hz} = 1000$ measurement points over 20 ms, at a sampling frequency of 50 kHz. A higher sampling frequency is not justified. Therefore, it should be surmised that, in order to obtain good estimation of the mean value and the instantaneous frequency probability distribution width, it would be necessary to average results over a few cardiac cycles. The $\varkappa^2$ test results shown in Table 1 show that it is very interesting to use local histogram averaging. Perhaps, this operation can to a large extent replace averaging results for successive cardiac cycles, although the lack of theoretical elaborations makes it difficult to draw motivated conclusions here.

3. By comparing the features of the phase loop system with a classical detector of zero crossings, it is indicated that it has the following advantages:

— better performance at low signal to noise ratios, as illustrated by Fig. 4;

— when applied to the analysis of the flow nature, the phase loop permits the measurement of the parameters of the signal which are related directly to its spectrum by relations (1) and (2), and ensures greater stability of the results obtained, since it permits calculations over a large and constant number of measurement points (of the order of 1000 per 20 ms).

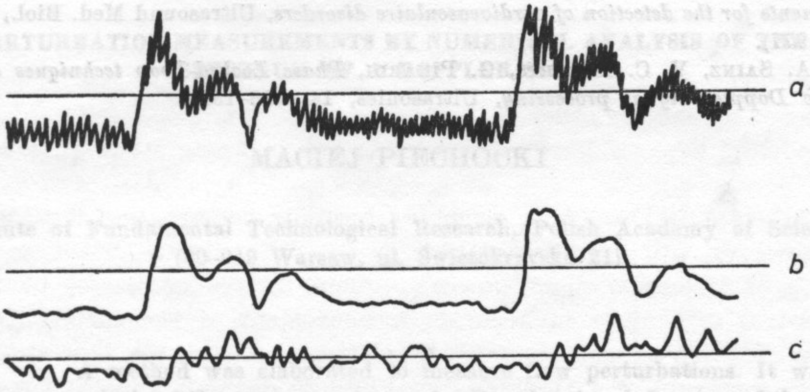

Fig. 4. Measurement of the blood flow velocity in the arm artery at low signal to noise power ratio. *a* — instantaneous signal frequency (*PLL*), *b* — mean signal frequency (*PLL*), *c* — frequency measurement by means of a classical detector of zero crossings

4. A drawback of the *PLL* system is a slightly greater complication of the electronic system and of the adjustment process. Also, the fact that the required input information is quadrature Doppler signals offers difficulties in applying the present system to bidirectional flowmeters. For the use of a phase loop system to a device with separate flow directions would require the formation of additional quadrature components for each of the flow directions.

Despite these difficulties, the phase loop system can be applied in Doppler diagnostic equipment, in particular where the measurement of flow perturbations is significant or where the signal to noise ratio is low.

Acknowledgment. The authors are grateful to Prof. L. FILIPCZYŃSKI for a discussion of the paper and a number of valuable pieces of advice.

References

[1] B. A. J. ANGELSEN, *Instantaneous frequency, mean frequency and variance of mean frequency estimators for ultrasonic blood velocity Doppler signals*, IEEE Trans. on Biomed. Enging., **28**, 11 (1981).

[2] B. A. J. ANGELSEN, *Spectral estimation of a narrow-band gaussian process from the distribution of the distances between adjacent zeros*, IEEE, Trans. Biom. Enging., **27** (1980).

[3] W. R. Brody, I. D. Meindel, *Theoretical analysis of the C. W. Doppler ultrasonic flowmeter*, IEEE, Trans. Biom. Enging., **21**, 3, 183–192 (1974).

[4] P. M. Brown, K. W. Johnston, M. Kossam, R. S. Cobbold, *A critical study of ultrasound Doppler spectral analysis for detecting carotid disease*, Ultrasound in Med. Biol., **8**, 5, 515–523 (1982).

[5] F. K. Forster, *The applications and limitations of Doppler spectral broadening measurements for the detection of cardiovasculaire disorders*, Ultrasound Med. Biol., **38**, 1223–1226 (1977).

[6] A. Sainz, V. C. Roberts, G. Pinardi, *Phase Locked-Loop techniques applied to ultrasonic Doppler signal processing*, Ultrasonics, **14**, 128–132.