THEORY AND APPLICATION OF A NON-INVASIVE ULTRASONIC CROSS-CORRELATION FLOWMETER

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Ultrasonic cross-correlation flow measurement technique was developed in the early seventies. Although this technique has certain advantages over the more conventional transit time approach, cross-correlation meters did not gain acceptance due to the complex data processing algorithm required and to the poor understanding of the physical mechanism that the technique is based on. In the last few years there has been a concentrated effort to develop fundamental understanding of the cross-correlation principle. This effort resulted in a more accurate and reliable flow meter capable of continuous operation at temperatures of up to 320°C.

In this paper, a theoretical treatment of the interaction between turbulent flow and ultrasonic waves is outlined. This approach provides a closed form relationship between ultrasonically measured fluid velocity and the average flow velocity. The relationship has been verified by a number of calibration measurements carried out for different temperatures, flows and different pipe sizes. Examples of the use of the improved ultrasonic cross-correlation flow meter (CROSSFLOW™) in nuclear power plants are also given.

I. Introduction

Operation of any ultrasonic cross-correlation flow meter is based on the fact that when an ultrasonic beam travels across a pipe it is affected by random fluctuation present in the flow. When the affected signal is processed, a random signal $Xa(t)$, which is a signature of turbulence fluctuations in the flow, can be obtained. If a second ultrasonic beam is transmitted a certain distance L downstream of the first beam it will produce another random signal $Xb(t)$. If distance L is sufficiently short then $Xa(t)$ will be approximately equal to $Xb(t+\tau^*)$, where $\tau^*=L/Vm$ and Vm is the measured fluid velocity in the pipe [1].

The advantages of the cross-correlation approach over the more conventional transit time approach are related to the following features of the cross-correlation flow meter:

- ultrasonic beams are transmitted perpendicular to the pipe surface so that there is no beam refraction, and the flow velocity is measured directly by measuring time of travel of the fluid between the two beams
- typical value of τ^* is of the order of 100 ms, in contrast to transit time meters, where a typical difference in transit times is of the order of 1 ms
- measurement results are independent of the speed of sound: this makes meter performance independent of temperature and of the pipe material
- measured flow velocity is determined only by the axial velocity in the pipe and is not sensitive to the radial velocity component

As a result of these features meter accuracy is independent of temperature, and, in principle, it can be used for measuring multiphase and mixed flows. However, in practice, the cross-correlation technique was used only for specific applications such as water - sand or water -coal mixture, where the use of other instruments was not feasible. Two major reasons prevented wider acceptance and further development of the cross-correlation meters for pure liquids.

1) Calculation of the cross-correlation function could be done only by bulky and expensive analog equipment. At present, this problem is easily resolved by using personal computers and modern data acquisition software.

2) Physical interpretation of the measured velocity in terms of the average flow velocity is significantly more difficult than for transit time meters.

One of the examples of successful application of the cross-correlation technique is associated with the non-invasive ultrasonic cross-correlation flow meter for pure liquids developed by Canadian General Electric for Ontario Hydro [2]. The meter was calibrated at the Ontario Hydro calibration facility capable of producing flows at high temperatures (up to 200°C) and high velocities (up to 5 m/s) in pipes of 35-40 cm in diameter.. Calibration results and the use of the meter in Ontario Hydro nuclear power plants confirmed its high accuracy and its temperature stability [3].

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understanding of the measured velocity Vm requires better quantitative analysis of the effect of flow perturbations on the ultrasonic wave.

B. Effect of flow turbulence in a pipe on an ultrasonic wave in pure liquid

Normally the amplitude of velocity and pressure fluctuations in ultrasonic wave is very small, and the flow velocity field (including turbulent velocity fluctuation), is not affected by ultrasonic waves. The total velocity field in the flow in the presence of ultrasonic waves, U*(r,t), can be described as a superposition of the unperturbed turbulent velocity field Uo (r,t) and a perturbation U due to an ultrasonic wave

$$U^* = Uo + U \qquad (4)$$

An ultrasonic wave in a turbulent flow can be described approximately by a linear wave equation with coefficients which are functions of time and coordinates and are determined by the known turbulent velocity distribution Uo and by its derivatives [5]. The maximum frequency of turbulent flow pulsation in a pipe is estimated as Uo / λ_k, where λ_k is the Kolmogorov scale [6]. This frequency for typical pipe flow is of the order of 1 kHz, and is much smaller then a typical frequency of the ultrasonic wave. In this case, an ultrasonic wave can be represented in the form of a high frequency periodic function with low frequency perturbed amplitude A and phase φ:

$$U(r,t) = A(r,t)\cos(\omega \cdot t + k \cdot r + \varphi) \quad (6)$$

Analysis of the wave equation for an ultrasonic wave in a turbulent flow shows that in equation (6) amplitude A is found from a solution to a complex differential equation. Coefficients in this equation are determined by the turbulent velocity field Uo. In contrast, phase φ has a simple physical interpretation. If an ultrasonic wave is induced by an ultrasonic source at r = 0, then at r = D

$$\varphi(t) = \varphi_0 + (\omega / C^2)\int_0^D U_{0r}(r,t)dr \quad (7)$$

where Uor is the radial component of the velocity Uo (projection of the velocity vector Uo onto the direction of the ultrasonic beam), C is speed of sound in the liquid, φ_0 is a constant.

Thus, if signals Xa (t) and Xb(t) represent phase changes of the ultrasonic wave then they are determined by expression (7) and can be interpreted in terms of turbulent parameters of the flow. A more rigorous analysis can be performed to obtain Vm as a function of statistical characteristics of turbulence in the flow. The main problem in such an analysis is that these statistical characteristics are not very well known even for long straight pipes. However simple approximate estimation of Vm can be made.

C. Estimation of the Measured Velocity for a Straight Pipe.

The integral in equation (7) is approximately proportional to the product of the intensity of turbulent velocity pulsations, u_t, and of the scale of turbulence, λ_t:

$$u_t \lambda_t \sim \int_0^D U_{0r}(r,t)dr \qquad (8)$$

and is therefore proportional to the turbulent viscosity, since $\mu_t \sim u_t \cdot \lambda_t$ [6].

The turbulent viscosity μ_t is widely used in many turbulence models and can be calculated for a number of different pipe configurations. A typical shape of the distribution of μ_t in a pipe is shown on Figure 2. This shape, according to the Nikuradze data [7] is independent of the Reynolds number.

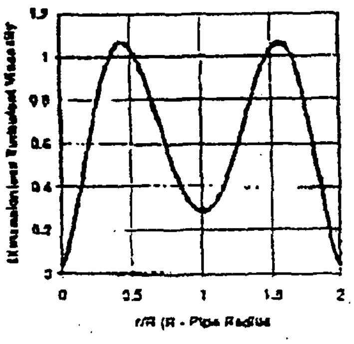

Figure 2. Qualitative Distribution of the Effective Turbulent Viscosity in a Pipe. [7]

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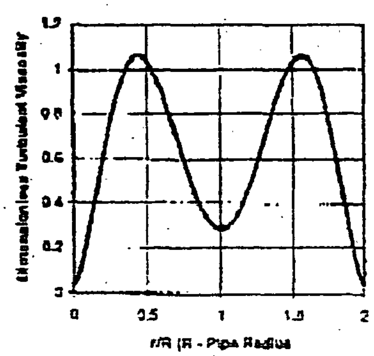

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A typical trend of the boiler feedwater flow for different plant power levels is shown in Figure 4. The flow rate is proportional to the power level, which dropped from 100% of the full power value to 90% and increased again to 98% percent.

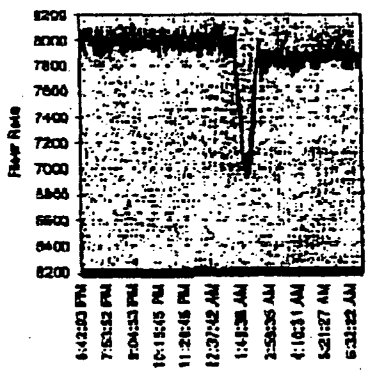

Figure 4. Typical Feedwater Flow Trend Obtained Using CROSSFLOW in a Nuclear Power Plant. Reactor Power was at 100%, 90%, and 98% of full power.

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