Transactions of the Korean Nuclear Society Autumn Meeting
Gyeongju, Korea, October 27-28, 2016

Using Crossflow for Flow Measurements and Flow Analysis

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1. Introduction

Ultrasonic Cross Correlation Flow Measurements are based on a flow measurement method that is based on measuring the transport time of turbulent structures. This technology has several advantages over the more commonly used Transit Time ultrasonic flow measurement method, one of those advantages being its ability to detect flow characteristics other than fluid velocity.

The cross correlation flow meter CROSSFLOW is designed and manufactured by Advanced Measurement and Analysis Group Inc. (AMAG), and is used around the world for various flow measurements. Particularly, CROSSFLOW has been used for boiler feedwater flow measurements, including Measurement Uncertainty Recovery (MUR) reactor power uprate in 14 nuclear reactors in the United States and in Europe. More than 100 CROSSFLOW transducers are currently installed in CANDU reactors around the world, including Wolsung NPP in Korea, for flow verification in ShutDown System (SDS) channels.

Other CROSSFLOW applications include reactor coolant gross flow measurements, reactor channel flow measurements in all channels in CANDU reactors, boiler blowdown flow measurement, and service water flow measurement.

At AMAG, a mathematical model has been developed, describing the behavior of the CROSSFLOW for various flow conditions. Results predicted by the model were compared to laboratory test results from Utah State University Water Research Laboratory, Utah, USA and good agreement was observed. Laboratory flow analysis results were also compared to the plant data, accurately predicting plant flow characteristics.

2. Cross Correlation Flow Measurement

Non-intrusive ultrasonic methods of measuring flow rate in conduits or pipes have been gaining popularity since the 1970s. One of these methods, the cross correlation method, has been known for a long time [1], but it became practical only in recent decades, due to recent advances in computer power [2].

In the simplest design of the ultrasonic cross correlation flow meter, two ultrasonic waves, separated by a known axial distance, are transmitted diametrically through the pipe, as shown in Fig. 2.1.

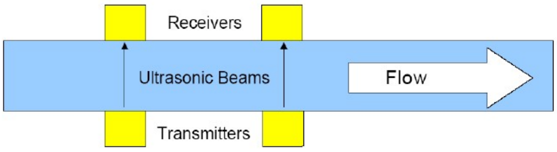

Fig. 2.1. Simplest cross correlation flow measurement set up.

Each wave is modulated by turbulent structures naturally present in the flow. Specifically, the phase of the ultrasonic waves is modulated by the turbulence velocity component along the direction of propagation of the ultrasonic waves. In single phase flow with constant temperature, this modulation is described by the following equation [2, 3]:

$$\phi(t) = \frac{f}{C^2}\int_0^D v_t(\varsigma, t)d\varsigma \tag{2.1}$$

In (2.1), f is the frequency of the ultrasonic waves, which is much higher than frequencies of the turbulent power spectrum. C is the speed of sound, v_t is the turbulence velocity component along the direction of the ultrasonic wave's propagation, ς is the spatial variable of integration along the direction of the ultrasonic wave's propagation, and t is time. If the signal, $\phi(t)$, is obtained in two flow cross-sections $z = z_1$ and $z = z_2$, the cross-correlation function of signals $\phi(z_1,t)$ and $\phi(z_2,t)$, over time T, can be calculated as follows:

$$R(\tau) = \int_0^T \phi(z_1,t)\cdot\phi(z_2,t+\tau)dt \tag{2.2}$$

If the distance between two ultrasonic waves, $l = z_2 - z_1$, is sufficiently small, the signals $\phi(z_1,t)$ and $\phi(z_2,t)$ maintain similarity to each other, but are shifted in time by a certain time delay, τ^*. This is because the turbulent structures deform while traveling from the upstream beam to the downstream beam, but remain recognizable. In such a case, the function $R(\tau)$ has a well defined maximum at $\tau = \tau^*$, and a measured flow velocity v_m can be introduced as:

$$v_m = \frac{l}{\tau^*} \qquad (2.3)$$

The value v_m is the average transport velocity of turbulent structures between the two ultrasonic beams over the time of measurement. Since there is a velocity gradient along the pipe cross section in pipe flow, v_m is not necessarily equal to the cross-sectional average axial flow velocity U. Understanding the relation between U and v_m is critically important ultrasonic flow measurement technology, not only for obtaining accurate results, but also in establishing traceability and uncertainty of flow measurements.

The underlying physical phenomena of ultrasonic cross correlation flow measurement are quite different from other conventional ultrasonic flow meters. As a result, the characteristics of the cross correlation flow meter are also quite different. The most important of these characteristics are given below.

2.1 Sensitivity to velocity distribution

Since CROSSFLOW measures the transport velocity of the ensemble of turbulent eddies along the pipe, it is not directly affected by radial and angular flow velocity components. Therefore its sensitivity to the velocity distribution in a pipe is smaller than that of transit time single-beam meters.

2.2 Sensitivity to beam orientation

Since CROSSFLOW is based on the effect of eddies on the ultrasonic beam, the effective flow sampling area is much wider than the beam size, and is instead defined by the size of the eddies detected by the meter. Consequently, sensitivity of the meter to the beam orientation around the pipe is significantly smaller than for other meters.

2.3 Magnitude of measured time delay

Measured time delay is defined by the velocity of the flow and has a magnitude in the order of milliseconds. In transit time ultrasonic meters, measured time delay is defined by the speed of sound, and its magnitude is in the order of microseconds. The longer magnitude of measured time in cross correlation flow measurement provides less stringent requirements for the cross correlation flow meter's electronics, hence making the meter even more robust.

2.4 Robustness to installation effects and temperature variation

With cross correlation flow measurement technology, the ultrasonic path is perpendicular to the pipe wall and to the wall-flow interfaces. Therefore, the acoustical path is very stable, and the meter is very robust to the installation affects and temperature variation in the flow and in the surrounding environment. This feature makes the meter particularly suitable for applications where high temperature or temperature variation can be observed, such as feedwater and reactor coolant flow measurements. In comparison, transit time ultrasonic flow meters (the most common flow meters on the market) send beams diagonal to the pipe wall. As a result, temperature changes can alter the path of the beam due to refraction, which makes accurate measurements more difficult.

2.5 Sampling time

As the CROSSFLOW is based on statistical processing of time signals, one of its uncertainty components depends on the data acquisition time. Therefore, CROSSFLOW may require longer sampling time than a transit time meter. However, due to other advantages described above, CROSSFLOW can measure the average flow with much better uncertainty than transit time clamp-on flow meters. For feedwater flow, CROSSFLOW has been demonstrated to achieve 0.5% uncertainty or better. Measurement uncertainty for other applications is similar but needs to be evaluated for each application separately.

2.6 Comparison of CROSSFLOW with transit time meters

Comparison of CROSSFLOW measurements with 5 transit time clamp-on meters is shown in Fig. 2.2. Measurements were performed in the National Institute of Standards and Technology (NIST) Hydraulic Laboratory and were compared to the reference flow measured with ±0.15% accuracy using a weighing tank [4]. CROSSFLOW results are designated as "E".

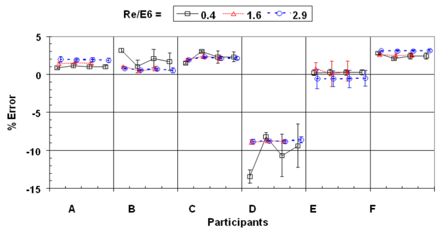

Fig. 2.2. Results of NIST evaluation of ultrasonic clamp-on meters. AMAG is participant E.

One can see that although scatter in CROSSFLOW measurements is slightly higher than in transit time meter measurements, the accuracy in the average flow is significantly better for the three Reynolds numbers that the comparison was done at.

2.7 Examples of CROSSFLOW measurements in CANDU reactors

In addition to feedwater flow measurements, one of the important applications of CROSSFLOW has been channel flow measurements in CANDU reactors. CROSSFLOW transducers have been permanently installed on over 100 SDS channels in most CANDU reactors around the world (from a few to 24 transducers per reactor). The challenges of this application are high temperature (>250ºC) and extremely high radiation fields. The demonstrated accuracy in this application is better than 1%.

3. Traceability

All flow measurements in industry, regardless of flow measurement technology, must be traceable to a laboratory setting, in order to ensure that the calculation of the flow measurement uncertainty is correct. To achieve such traceability, it is not sufficient to use a flow meter that performs well in a laboratory. A flow meter may achieve 0.5% uncertainty in a specific laboratory setting, but only be capable of achieving 2% uncertainty in an industrial condition where it is installed, due to differences between laboratory and field conditions.

For correct evaluation of flow measurement uncertainty in the field, the difference between laboratory conditions and field conditions must be quantified in terms of its effect on the flow meter, and must be included in the uncertainty calculation.

Since different flow measurement technologies are based on different operating principles, the method for determining whether laboratory conditions are representative of field conditions depends on the type of flow meter used.

Since CROSSFLOW is based on measuring the transport velocity of turbulent structures, the space-time development of turbulent structures in the laboratory must be representative of the space-time development of turbulent structures in the field. To achieve this, a mathematical model of cross correlation flow measurement was developed in AMAG. This allows one to compare flow conditions in the laboratory and in the field, and quantify the effects of flow condition on cross correlation flow measurement. The model can be used for predicting CROSSFLOW behavior in different flow conditions, and to optimize laboratory testing in order to ensure laboratory conditions are representative of field conditions.

Through such modeling, one can ensure that flow measurements in the field are traceable to a laboratory setting. As a result, differences in flow condition between the laboratory and the field can be identified, and accounted for in uncertainty calculation. Below are results of mathematical modeling of cross correlation flow measurement, and their comparison to laboratory test results.

4. Mathematical Modeling

A mathematical model of cross correlation flow measurement was developed, and the results of were compared with results of laboratory tests. Laboratory testing and mathematical modeling were conducted on a pipe flow for different distances downstream of a 90-degree elbow. The modeling included the following steps:

- Generation of inlet turbulent velocity field at pipe cross-section $z = z_1$.
- Numerical simulation of time-average velocity profile using $k - \varepsilon$ model.
- Calculation of turbulence velocity field in cross-section $z = z_2$ using local Taylor approximation.
- Calculation of measured flow velocity v_m using equations (2.1), (2.2), and (2.3).

The spectrum of signal $\phi(t)$ from equation (2.1), measured by the CROSSFLOW in laboratory tests, was used in the model to generate the inlet turbulent velocity field. The ratio of the cross-section average flow velocity U, to average measured velocity v_m, was obtained by the mathematical model. The same ratio was obtained in laboratory testing, using the cross correlation flow meter CROSSFLOW to obtain v_m, and using laboratory weigh tank instrumentation to obtain U. The two ratios, one from the model and the other from laboratory results, were compared to validate the model.

A schematic of the tests set-up is shown in Fig. 4.1. The laboratory test was conducted at the Utah Water Research Laboratory in Utah State University, Utah, USA.

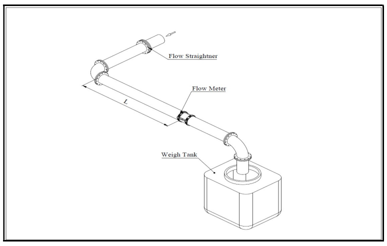

Fig. 4.1. Schematics of the Test Setup. Test Section consists of 12-inch plastic pipe with carbon steel 90-degree elbow and flow conditioner.

Good agreement between laboratory test results and modeling results were observed, not only in the trend of the ratio U / v_m , but in its absolute value as well. These results are presented in Fig. 4.2, where the ratio is plotted as a function of distance between measurement location (or simulation location), and an upstream elbow. Distance from the upstream elbow is normalized to pipe diameter. No adjustments of the modeling parameters were made in the mathematical model of the CROSSFLOW.

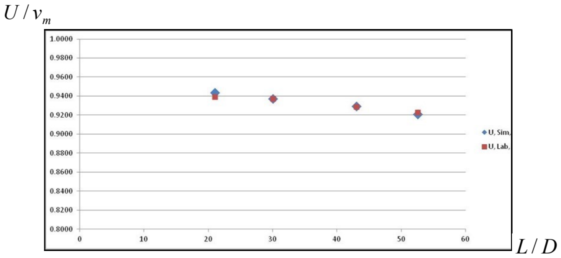

Fig. 4.2. Comparison of the ratio U / v_m predicted by mathematical modeling (blue diamonds) and obtained in laboratory testing (red squares). The ratio is along the vertical axis. Distance from upstream elbow (L) normalized to pipe diameter (D), is along the horizontal axis.

5. Flow Analysis

Existing experimental data and mathematical modeling show that cross correlation flow measurement technology can be used to classify or detect changes to flow conditions which may affect the ratio U / v_m , and consequently flow measurement results.

A method of flow analysis developed at AMAG allows a quantitative characterization of the flow conditions at the CROSSFLOW location, and therefore allows for comparison of flow conditions present in laboratory testing and in the field. This method was validated using laboratory testing and mathematical modeling described above. The results in Fig. 5.1 plot a *flow characterization factor*, derived from flow analysis methods, versus distance from an upstream disturbance. By applying such analysis to laboratory data and to plant data, one may compare flow conditions present in the laboratory and in the plant at measurement locations.

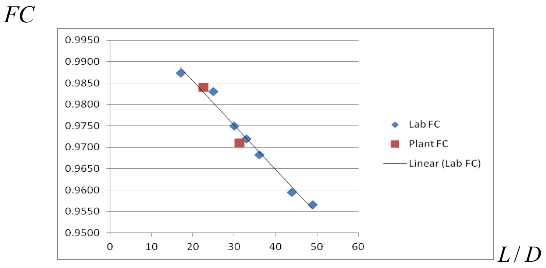

Fig. 5.1. Comparison of the flow characterization factor (FC) observed through laboratory testing (blue diamonds), and plant data (red squares). Figure shows dependence of FC on distance from an upstream disturbance in units of L/D.

6. Conclusions

Cross correlation flow measurement is a robust ultrasonic flow measurement tool used in nuclear power plants around the world for various applications. Mathematical modeling of the CROSSFLOW agrees well with laboratory test results and can be used as a tool in determining the effect of flow conditions on CROSSFLOW output and on designing and optimizing laboratory testing, in order to ensure traceability of field flow measurements to laboratory testing within desirable uncertainty.

REFERENCES

[1] M.S. Beck and A. Plaskowski, “Cross Correlation Flowmeters – Their Design and Applications”, Adam Hilger, Bristol, 1987.

[2] P.D. Lysak, D.M. Jenkins, D.E. Capone, and W.L. Brown, “Analytical Model of an Ultrasonic Cross-Correlation Flow Meter, Part 2”, Flow Measurement and Instrumentation, Vol. 19, 2008, pp. 41-46.

[3] Y. Gurevich, A. Lopez, R. Flemons, and D. Zobin, “Theory and Application of Non-Invasive Ultrasonic Cross-Correlation Flow Meter in Harsh Environment”, Proceedings of FLOMEKO 98, Lund, Sweden, 1998.

[4] G. Mattingly and T.T. Yeh, "NIST's Ultrasonic Technology Assessment Program to Improve Flow Measurements",