THE ANALYSIS OF THERMAL FLUCTUATIONS IN THE SEMISCALE
TESTS TO DETERMINE FLOW TRANSIT DELAY TIMES USING
A TRANSFER FUNCTION CROSS-CORRELATION TECHNIQUE

by

A. C. Raptis and G. F. Popper
Components Technology Division

MASTER

U of C-AUA-USERDA

BASE TECHNOLOGY

August 1977

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

The facilities of Argonne National Laboratory are owned by the United States Government. Under the terms of a contract (W-31-109-Eng-38) between the U. S. Energy Research and Development Administration, Argonne Universities Association and The University of Chicago, the University employs the staff and operates the Laboratory in accordance with policies and programs formulated, approved and reviewed by the Association.

MEMBERS OF ARGONNE UNIVERSITIES ASSOCIATION

The University of Arizona	Kansas State University	The Ohio State University
Carnegie-Mellon University	The University of Kansas	Ohio University
Case Western Reserve University	Loyola University	The Pennsylvania State University
The University of Chicago	Marquette University	Purdue University
University of Cincinnati	Michigan State University	Saint Louis University
Illinois Institute of Technology	The University of Michigan	Southern Illinois University
University of Illinois	University of Minnesota	The University of Texas at Austin
Indiana University	University of Missouri	Washington University
Iowa State University	Northwestern University	Wayne State University
The University of Iowa	University of Notre Dame	The University of Wisconsin

NOTICE

This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Energy Research and Development Administration, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately-owned rights. Mention of commercial products, their manufacturers, or their suppliers in this publication does not imply or connote approval or disapproval of the product by Argonne National Laboratory or the U. S. Energy Research and Development Administration.

THE ANALYSIS OF THERMAL FLUCTUATIONS IN THE SEMISCALE
TESTS TO DETERMINE FLOW TRANSIT DELAY TIMES USING
A TRANSFER FUNCTION CROSS-CORRELATION TECHNIQUE

by

A. C. Raptis and G. F. Popper
Components Technology Division

U of C-AUA-USERDA

NOTICE

This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Energy Research and Development Administration, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights.

BASE TECHNOLOGY

August 1977

TABLE OF CONTENTS

	<u>Page</u>
ABSTRACT	iii
1.0 INTRODUCTION	1
2.0 THEORY	2
3.0 DATA ANALYSIS	4
4.0 EVALUATION OF RESULTS	6
5.0 CONCLUSIONS	7
6.0 REFERENCES	8

THE ANALYSIS OF THERMAL FLUCTUATIONS IN THE SEMISCALE
TESTS TO DETERMINE FLOW TRANSIT DELAY TIMES USING
A TRANSFER FUNCTION CROSS-CORRELATION TECHNIQUE

by

A. C. Raptis and G. F. Popper

ABSTRACT

On April 14, 1976, EG&G performed the Semiscale Blowdown 29-1 experiment to try to establish the feasibility of using a transit time flowmeter (TTF) to measure transient blowdown two-phase flow rates. The recorded signals from that experiment were made available to and analyzed by the Argonne National Laboratory using the transfer function cross-correlation technique. The theoretical background for the transfer function method of analysis and the results of the data analysis are presented. Histograms of transit time during the blowdown are shown and topics for further investigation are identified.

1.0 INTRODUCTION

The transit time flowmeter (TTF) is based upon the principle of measuring the delay time, τ , of a disturbance in the fluid between two sensors separated by a distance, d . This technique has received considerable attention and development for measuring sodium flow rates.^(1,2,3) EG&G examined the feasibility of using this technique for measuring water flow rates by utilizing the thermal fluctuations between two thermocouples spaced some distance apart. The ultimate objective was to use this method to measure two-phase flow rates. In 1975, EG&G performed a steady state experiment at the Westinghouse Canada Ltd. (WCL) water loop to try to verify the performance of the TTF for this application.⁽⁴⁾ The recorded signals from the steady state experiment were made available to the Argonne National Laboratory (ANL) Instrumentation and Control (I&C) Section of the Component Technology (CT) Division. The WCL steady state signals were processed by using the ANL transfer function method and the results indicated that strong correlation peaks were apparent in certain portions of the data. The results were reported in reference 5.

On April 14, 1976, EG&G performed the Semiscale Blowdown 29-1 (B29-1) experiment and the recorded transient signals were also made available to ANL. The semiscale system is a non-nuclear model of a nuclear reactor and its primary use is for loss-of-coolant experiments where the fluid is hot water (325°C) that flashes into steam during blowdown. The B29-1 signals were processed at ANL using the transfer function method to determine delay times. The signals were processed by choosing consecutive data block sizes of 1024 or 512 and sampling rates, Δt , equal to 1 ms or 2 ms. The choice of the data block size was arbitrary and not based on any specific scientific procedure. The above choice of block size and sampling rate yields correlation functions at every 0.512, 1.024 or 2.048 seconds. In processing the B29-1 signals, no averaging was performed. Strong correlation peaks were found, but the transit delay times determined cannot be verified since no other data are available for comparison. In this report, the theoretical background for the transfer function method of analysis and the results of the data analysis are presented.

2.0 THEORY

The theoretical background of the transfer function method was presented in an earlier report,⁽⁵⁾ but for completeness will be repeated here. Correlation,

as it applies to waveforms, is a method of time-domain analysis that is particularly useful for detecting periodic signals buried in noise, for establishing coherence between random signals, and for establishing the sources of signals and their transmission times. In essence, correlation is a measure of the similarity between two waveforms. In general, there are two distinct quantities desired when correlation is applied to a problem. Consider the generalized measurement situation shown in Fig. 1, where there are two accessible observation points X and Y where measurements can be made. The system signals x and y are related through some linear impulse response, h and y is perturbed by some uncorrelated noise source, n . Usually the main interest lies in the nature of the transmission path and, in particular, what this path does to the signal. In some applications, an excitation is applied to the system and the interest is in the form and strength of the response. These two approaches are measurements of relationship and causality, respectively, and both are implied in the word "correlation".

Mathematically, the cross-correlation of two signals $y(t)$ and $x(t)$ over a period of time, τ , is given by:

$$R_{yx}(\tau) = \int_0^T y(t) x(t + \tau) dt, \quad (1)$$

where $R_{yx}(\tau)$ is simply the averaged product of $y(t)$ delayed with respect to $x(t)$. When the value of $R_{yx}(\tau)$ is high for some delay τ , it can be said that x and y are similar, in some sense, at this delay value. The problem with this type of analysis lies in the interpretation of the given value of the cross-correlation function $R_{yx}(\tau)$. This interpretation is not easy or clear. The use of the normalized cross-correlation function, for some particular cases, makes the interpretation easier. The normalized cross-correlation function is given by:

$$\rho_{yx}(\tau) = \frac{R_{yx}(\tau)}{\sqrt{R_{xx}(0) R_{yy}(0)}}; \quad -1 \leq \rho_{yx}(\tau) \leq 1, \quad (2)$$

where $R_{xx}(0)$ and $R_{yy}(0)$ are the auto-correlation functions for $x(t)$ and $y(t)$ for zero delay respectively. In the special case where the value of $\rho_{yx}(\tau)$ is equal to +1, it can be said that the correlation is clear, and we can interpret the delay as the true one, which indicates that the transmission

path, as shown in Fig. 1, is lossless and there is no noise contamination. Physical situations, like the one under consideration however, do not exhibit the above ideal characteristics. Usually transmission path losses exist and noise contamination is present. These considerations will yield a normalized cross-correlation somewhere between zero and one. The result of such a measurement is difficult to interpret, because two situations can occur. First, the transmission path has a gain less than unity, or second, the contaminating noise has reduced the degree of causality between signals $x(t)$ and $y(t)$. The distinction between the two cases is not clear, and therefore some other method of obtaining the cross-correlation function must be implemented.

Consider the time varying signals $x(t)$ and $y(t)$ generated at two points along the flow channel as shown in Fig. 2. The portion of the channel between these two signals can be characterized by determining the transfer function. The transfer function is obtained by considering frequency domain techniques. The theory to be developed here can be found in textbooks on communications and data processing but will be presented for completeness.

The Fourier Transforms of the input and output signals are given by:

$$\begin{aligned} F_x(\omega) &= F\{x(t)\} \quad \text{and,} \\ F_y(\omega) &= F\{y(t)\}. \end{aligned} \tag{3}$$

Using Eqs. (3), the power spectra are:

$$G_{xx}(\omega) = F_x(\omega) F_x^*(\omega) \tag{4}$$

$$G_{yy}(\omega) = F_y(\omega) F_y^*(\omega) \tag{5}$$

$$G_{yx}(\omega) = F_y(\omega) F_x^*(\omega) \tag{6}$$

Where $G_{xx}(\omega)$, $G_{yy}(\omega)$ and $G_{yx}(\omega)$ are the input, output and cross-power spectra of input - output and where $*$ indicates the conjugate of the quantity. The output is related to the input through the following relationship.

$$y(t) = h(t) \Delta x(t) + n(t) \tag{7}$$

where Δ indicates convolution. In the frequency domain, Eq. (7) becomes:

$$F_y(\omega) = H(\omega) F_x(\omega) + F_n(\omega) \tag{8}$$

$H(\omega)$ is the Fourier transform of $h(t)$ or the transfer function of the system and $F_n(\omega)$ is the Fourier transform of the additive uncorrelated noise, $n(t)$. If it is assumed that $F_n(\omega)$ is small or $G_{yx}(\omega)$ is smoothed enough to make the cross power of the input, $x(t)$, and the noise, $n(t)$, negligible, then

$$G_{yx}(\omega) = H(\omega) G_{xx}(\omega) \quad (9)$$

or

$$H(\omega) = \frac{G_{yx}(\omega)}{G_{xx}(\omega)} \quad (10)$$

Since $G_{yx}(\omega)$ and $G_{xx}(\omega)$ can be determined from the input and output signals, Eq. (10) gives the system transfer function.

The inverse transform of Eq. (9) yields

$$R_{yx}(\tau) = h(\tau) \Delta R_{xx}(\tau) \quad (11)$$

where $R_{xx}(\tau)$ is the auto-correlation of $x(t)$ and $R_{yx}(\tau)$ is the cross-correlation of $x(t)$ and $y(t)$. Equation (11) is obtained by making use of the fact that correlation and power spectra form a transform pair, and that multiplication in the frequency domain implies convolution in the time domain. Equation (11) will yield the cross-correlation function.

3.0 DATA ANALYSIS

The signals used were recorded by EG&G during the B29-1 experiment. The experimental transit time flowmeter was located in a spool piece in the semi-scale system. The spool piece with the thermocouple assembly is shown in Fig. 2. Specific details about the semiscale system and the experiment are presented in reference 6. The signals were recorded on channels 2, 4, 6, 8 and 10 of an FM tape recorder, which correspond to thermocouples 1, 2, 3, 4 and 5 respectively. The distances between thermocouples 1-2, 1-3, 1-4 and 1-5 are 29.74, 30.15, 31.93 and 38.89 cm, ± 0.013 cm respectively. While monitoring the signals, it was observed that overloading occurred frequently, but did not appear to take place at blowdown except for a second or two.

The signals recorded before blowdown were considered steady-state while the signals during blowdown were considered transient since the flow changes

with time. The normal way to process the steady-state signals would be to use a hardwired correlator and directly obtain the cross-correlation function. This process requires a rather long averaging time for meaningful peaks to appear. These hardwired correlators yield meaningful results only when the available signals are relatively clean with respect to the contaminating noise and the delays are clearly identifiable and appear with certain regularity. The available signals from this experiment do not present these clear cut characteristics. Therefore, instead of direct correlation, the method discussed in Section 2 of this report was used. The transient signals recorded during blowdown, if processed with a hard-wired correlator, will yield a transit time delay every averaging time. The impulse response method will yield a transit delay every 1.024 sec or .512 sec and hence give a better history of the blowdown.

The equipment used for processing the data were an HP5451A 4 channel Fourier Analyzer, which includes an A/D converter, a display unit, an HP-2116C digital processor, and a data storage disc capability. A Honeywell-7600 tape deck was used in playing back the tape. An X-Y plotter was used to record the data from the display unit of the analyzer.

Based on Eqs. (3) through (11) a program was written for the HP-5451A Fourier Analyzer. A block diagram of this program is shown in Fig. 3. The first step of this process is the A/D conversion of the signals under consideration. The signals were digitized two channels at a time and placed on a disk in consecutive blocks of size 256, 512 or 1024. The choice of the block size is arbitrary and not based on any scientific method. The second step calculates the Fourier Transforms of the given signals, while step three calculates the power spectrum of the given signals as well as the cross-power spectrum of the signals under consideration. The results of step three are shown in Figs. 4 and 5. Figures 4 and 5 indicate that the frequency range of the input signals is between 1 and 5 Hz. Frequency contribution below 1 Hz might have been attenuated because of the limitations of the instrumentation used. Step four performs the evaluation of Eqs. (9) and (10) where the transfer function $H(\omega)$ of the system is evaluated, while step five takes the inverse Fourier Transform of the transfer function $H(\omega)$, which yields the impulse response of the system $h(t)$. Step six convolves the auto-correlation function of the input signal with the impulse response of the system. The result is the cross-correlation function $R_{yx}(\tau)$. The auto-correlation, the impulse response and the cross-correlation functions of a representative pair of signals are given in Fig. 6. If the system represented a pure delay operation,

the impulse response would have been a delta function at a time equal to the actual delay of the system, which would have required white noise as its frequency response. As is obvious from Fig. 6, the system is more complicated and this is the main reason that direct cross-correlation is difficult. The peak of this function, as would be expected from a physical system, has a certain width which is directly related to the width of the peak of the cross-correlation function. Figure 7 displays the coherence function, which is a measure of similarity between the two signals on channels 2 and 4. If the coherence function is equal to one, it indicates that the signals are fully similar. In calculating the coherence function, it is important to realize that the power spectra and the cross-power spectrum of the processed signals must be obtained under identical conditions, such as filter bandwidth, record length etc., otherwise gross errors in coherence estimation will be obtained. From Fig. 7, it is seen that the signals are fully coherent up to about 40 Hz.

4.0 EVALUATION OF RESULTS

Portions of the available signals, starting at approximately 7 seconds before blowdown, were processed in block sizes of 512 and 1024 without any averaging. The signals recorded on channels 2 and 4 that correspond to thermocouples 1 and 2, were the first to be processed. The results showed no correlation between the signals from the thermocouples in the steady state condition. The absence of correlation between the two signals was to be expected since the thermocouples were 29.74 cm apart. This observation is based on the fact that as the distance between two thermocouples is increased while the flow remains constant, the coherence between two thermocouple signals decreases drastically to the point that the signals become completely incoherent. The coherence between two signals increases as the distance becomes smaller and therefore, the data recorded on channels 4 and 8, that corresponds to thermocouples 2 and 4 were processed next. About 22 seconds of the signals were processed in consecutive block sizes of 1024 and at a sampling rate, Δt , equal to 1 ms. The value of the coherence function was approximately equal to one, which is the maximum value a coherence can attain. Figures 8 through 15 give some representative cross-correlation, auto-correlation and impulse response functions for the data starting at about 7 sec before blowdown to 13 sec after blowdown. Each figure represents the auto-correlation function at some time τ before or after blowdown. The signals were processed with a digital low pass filter with a high frequency cutoff of 10 Hz except for the results in Fig. 11 where no filtering was

used. Each cross-correlation function yields a transit delay, τ , which then can be translated to flow since the distance between thermocouples is known. Figure 16 gives a plot of transit delay, τ , as the time of the experiment is progressing. The time of the experiment in Fig. 16 is approximate since the time code of the experiment could not be read correctly. From Fig. 16, it is observed that some points indicate a negative transit delay, τ . This observation cannot be attributed, at least with the available information, to the experiment. It is speculated that the negative delay is due to the response of the thermocouples which might be slow with respect to the flow rate of the medium.

The same segment of the signals were processed with data block sizes of 512 which yields a transit delay every 0.512 seconds. The results follow the trend of those obtained with the 1024 block sizes. Representative cross-correlation functions before and during blowdown are shown in Fig. 17. From Fig. 16, it is seen that at about 1 second after the blowdown begins, the value of τ increases drastically, which means that the flow decreases. This event cannot be explained, but can only be speculated that is due to back pressure. The differences between the curves of Fig. 16 cannot be explained in a precise theoretical or practical way and therefore these differences warrant further investigation for a better understanding.

The signals recorded on channels 8 and 10, which correspond to thermocouples 4 and 5, were processed next. Thermocouples 4 and 5 are placed 7.96 cm apart. About 90 seconds of the signals were processed with a block size of 1024 and a sampling rate, Δt , equal to 2 milliseconds. Such an arrangement yields a transit delay approximately every 2 seconds. Representative cross-correlation functions for the signals are shown in Fig. 18. The transit delays for thermocouples 4 and 5 during the time of the test are plotted in Fig. 19. From Fig. 19 it is observed that, except for one point, the negative transit delays were not present. From the same figure, it is observed that another disturbance occurs where the transit delay increases drastically in the time span of 30 to 50 seconds after blowdown. This increase in time delay, actually means a decrease in flow rate and cannot be explained from the available information. This increase in flow does not appear in Fig. 16 since the signal processing was terminated at about 13 seconds after blowdown.

5.0 CONCLUSIONS

The TTF is applicable to measuring two-phase transient flow, if the relationship

between the transit delay and the flow variations is determined, which means that the thermal fluctuations that are detected by the thermocouples must be related in some way to the flow conditions. High flows require that the thermocouples be placed further apart, while lower flows require that the thermocouples be placed closer together. The spacing of the thermocouples should be studied further, since proper spacing will eliminate some of the problems of coherence and therefore correlation. In processing the data, the accuracy of the transit delay will also depend upon these factors:

- record length
- filter bandwidth
- filter shape
- averaging time
- extraneous noise
- sampling rate

The most important of these are record length and filter bandwidth. These factors must be investigated and the results must be related to the transient transit delay times.

6.0 REFERENCES

1. Raptis, A.C. and Forster, G.A. "A Signal Analysis Method Using The Cross-correlation of Turbulence Flow Signals to Determine Calibration of Permanent Magnet Sodium Flowmeters", ANL-CT-76-8 (July 1975).
2. Randall, R.L., Pehrul, P.J. and Grayban, G.R. "Development of Noise Analysis Techniques for Measuring Reactor Coolant Velocities", NAA-SR-11193 (March 25, 1966).
3. Bentley, P.G. and Dawson, G.G. "Fluid Flow Measurements by Transit Time Analysis of Temperature Fluctuations", TRG-R-115 (Feb. 1966).
4. Lassahn, G.D. "Thermocouple Correlation Transit Time Flowmeter Tests at WCL", TREE-NUREG-1007 (Nov. 1976).
5. Raptis, A.C., Forster, G.A. and Popper, G.F. "The Analysis of Thermal Fluctuations in the Westinghouse Canada Water Loop to Determine Flow Transit Delay Times Using a Transfer Function Cross-correlation Technique", ANL-CT-76-39 (July 1976).
6. Lassahn, G.D. "Feasibility Study of Thermocouple Correlation Type Transit Time Flowmeter in Transient Steam-Water Flow", TREE-NUREG-1011 (March 1977).

Fig. 1 Generalized system representation.

Fig. 2 Experimental setup for the transit time flowmeter.

Fig. 3 Block diagram representation of the transfer function method.

Fig. 4 Representative power spectra of the input $G_{xx}(\omega)$, and the output $G_{yy}(\omega)$

Fig. 5 Representative cross-power spectam $G_{xy}(\omega)$

Fig. 6 Representative auto-correlation, impulse response and cross-correlation functions.

Fig. 7 Representative coherence function.

Fig. 8 Auto-correlation, impulse response, and cross-correlation functions at -6.14 sec. before blowdown.

Fig. 9 Auto-correlation, impulse response, and cross-correlation functions at -5.12 sec. before blowdown.

Fig. 10 Auto-correlation, impulse response, and cross-correlation functions at -4.09 sec. before blowdown.

Fig. 11 Auto-correlation and cross-correlation functions at 0.0 sec. blowdown begins.

Fig. 12 Auto-correlation, impulse response and cross-correlation functions at 1.02 sec. after blowdown.

Fig. 13 Auto-correlation, impulse response and cross-correlation functions at 4.09 ms after blowdown.

Fig. 14 Cross-correlation functions at 4.09, 5.12 and 7.16 sec. after blowdown.

Fig. 15 Cross-correlation functions at 11.26, 12.28 and 13.92 sec. after blowdown.

Fig. 16 Transit delay variation with time during blowdown.

Fig. 17 Cross-correlation functions at -2.55, 1.024 and 3.57 ms during blowdown.

Fig. 18 Representative cross-correlation functions during blowdown.
Blocksize 1024, $\Delta t = 2$ ms.

Fig. 19 Transit delay variation with time during blowdown.

EXTERNAL DISTRIBUTION LIST FOR ANL-CT-77-17

cc:	A. E. Arave	(10)	EGG
	R. D. Wesley		EGG
	G. O. Lassahn		EGG
	T. E. Murley		NRC
	R. M. Scroggins		NRC
	Y. Y. Hsu		NRC
	G. O. McPherson		NRC
	R. E. Feit		NRC
	L. S. Tong		NRC
	N. Zuber		NRC
	F. C. Legler		ERDA
	S. J. Sims		COO, RPD
	M. Levenson		EPRI
	W. Loewenstein	(2)	EPRI
	P. A. Lottes		ANL
	R. Henry		ANL
	E. Redden		ERDA/RSRC