THE ANALYSIS OF THERMAL FLUCTUATIONS IN THE
WESTINGHOUSE CANADA WATER LOOP TO DETERMINE
FLOW TRANSIT DELAY TIMES USING A
TRANSFER FUNCTION CROSS-CORRELATION TECHNIQUE

by

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Base Technology

July 15, 1976

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ABSTRACT

Aerojet Nuclear Company performed an experiment at the Westinghouse Canada Ltd. water loop to try to verify the performance of a Transit Time Flowmeter to ultimately measure two-phase flow rates. The recorded data from that experiment was made available and analyzed by the Argonne National Laboratory using a transfer function cross-correlation technique. The theoretical background for the transfer function method of analysis and the results of the data analysis are presented. Strong correlation peaks, which are very close to the expected delay times, were found in certain portions of the data.

1. 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) The Aerojet Nuclear Company (ANC) 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. ANC performed an experiment at the Westinghouse Canada Ltd. (WCL) water loop to try to verify the performance of the TTF for this application. The recorded data from that experiment was made available to the Argonne National Laboratory (ANL) Instrumentation and Control (IC) Section of the Components Technology (CT) Division. The WCL data was processed by using the ANL transfer function method and the results were very encouraging. Strong correlation peaks, which are very close to expected delay times, were found in certain portions of the data. In this memorandum, the theoretical background for the transfer function method of analysis and the results of the data analysis are presented.

2. THEORY

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, in general, 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. However, physical situations, like the one under consideration, 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 measuring of such a result 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 as a system with input $x(t)$ and output $y(t)$ as shown in Fig. (1). With the input and output of this system known, the system can be completely 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 here 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 $y(t)$.

Eq. (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. Eq. (11) will yield the cross-correlation function.

3. EXPERIMENT

The experimental set-up at the WCL is shown in Fig. (2). The data from the four thermocouples were recorded on an FM tape recorder. The filters or other instruments that were used for data recording, as well as experiment details, were not available to ANL. This information was not necessary since ANL was concerned only with the data that was recorded. Each run was about 2 minutes long. Runs 293 through 324 did not present any thermal fluctuations, and, as will be shown later, do not yield any valuable information. Reasons for these results might be experimental conditions or instrument malfunctions. For the remainder of the runs, the data seems to be better and the results more meaningful.

4. DATA PROCESSING

The normal way to process the thermocouple signals obtained from the

WCL experiment would be to use a hard-wired correlator and directly obtain the correlation. These hard-wired correlators yield meaningful results when the available signals are relatively clean with respect to 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. It can be seen from Fig. (4), where samples of the signals from Run 325 are shown, that no identifiable trends exist between the two signals. This suggests that either there is no correlation between the two signals or, if correlation exists, it is not easily extractable. The method discussed in Section 2 of this report will make use of these signals in order to characterize the medium between the two thermocouples.

The transfer function $H(\omega)$ completely characterizes the system as far as the frequency content is concerned and the impulse response $h(t)$ gives the time domain characteristics. Based on Eqs. (3) through (11) a program was written for the HP-5451 Fourier analyzer. A flow 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. Samples of such signals are shown in Fig. (4). The second step is to obtain the Fourier Transforms of the given signals as indicated by Eq. (5). The output of this operation is shown in Fig. (5). It can be seen that the frequency range of these signals is between 0.1 and 5 Hz. Also, small contributions are present for frequencies above 5 Hz. The contribution between zero and 0.1 Hz must have been filtered while recording the data. Fig. (6) represents the same Fourier transform, but all frequencies above 4.88 were digitally filtered. This filtering was necessary in order to clean up the signals from higher frequency contributions that will contaminate the final cross-correlation waveform. Step three calculates the power spectrum of the filtered signals as well as the cross-power spectrum of the two signals under consideration. The results of this step are shown in Fig. (7). Step four performs the evaluation of Eqs. (9) and (10) where the transfer function of the system is evaluated. The result of this operation is shown in Fig. (8). Step five takes the inverse Fourier Transform of the transfer function $H(\omega)$ which yields the impulse response of the system $h(t)$. This function is displayed in Fig. (9). When no filtering is used, the impulse response $h(t)$ is very noisy, and it is impossible to determine its

characteristics. If the system represented a pure delay operation, the transfer function would have been a delta function at a time equal to the actual delay of the system. As is obvious from Fig. (9), the system is more complicated and this is the main reason that direct correlation does not work. Also, the peak of this function, as it 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 functions. 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 $R_{yx}(\tau)$ and is displayed on Fig. (11). Fig. (10) displays the auto-correlation function of the input signal.

5. EVALUATION OF RESULTS AND CONCLUSIONS

The available data can be divided into three groups defined as Runs 293 to 324, Runs 325 to 328, and Runs 329 to 334. In the first group, by just looking at the data, one can see that nothing of any significance is happening. All of the runs look identical, and the analysis indicates the same thing. Several functions such as auto-correlations, cross-correlations, impulse responses, power spectra and Fourier Transforms, for Runs 299, 300, 301, 304, 305, 312, 327 are displayed in Figs. (12) through (20). The majority of them indicate a strong correlation peak at zero, which is the same for both the cross-correlation and auto-correlation functions. This is to be expected since the impulse response also has a strong peak at $t = 0$. This indicates that either there was no flow, or both thermocouples detected an external event having nothing to do with flow and completely independent with respect to time. Figs. (14), (15) and (16) demonstrate the effect of filtering, where the impulse response and cross-correlation functions are very much contaminated with noise and therefore unreadable before filtering. The impulse response and cross-correlation functions in Fig. (20) indicate a delay of 440 ms which cannot be explained from the information given by ANC. The only possible reason for this correlation is that for the first time a slow movement of the fluid was detected or instrumentation problems were corrected.

The auto-correlation, impulse response, and cross-correlation functions for Runs 325, 326 and 327 are displayed in Figs. (21), (22) and (23). These

functions indicate high correlation peaks and delays can be determined. Digital filtering of the data was done during processing. Anything above 4.88 Hz was filtered out. The functions are very clean and show a high degree of correlation. The delays observed were 85 ms for Run 325, 90 ms for Run 326, and 220 ms for Run 327. These runs were processed several times with excellent reproducibility.

Figs. (24), (25), and (26) display the cross-correlation functions for Runs 328, 329 and 331. The velocity of the fluid was greater for these runs and therefore much shorter delay times were obtained. For display purposes, Runs 328, 329 and 331 were expanded in scale. Run 328 has a delay of 10 ms, 329 has a delay of 9 ms, and Run 331 has a delay of 4 ms. The data were processed by using records of 1024 samples with a sampling rate (Δt) of 0.002 seconds. For uncorrelated noise cancellation, 20 records were used for averaging. It is desirable to use records of 2048 samples or possibly (if computer capabilities allow) 4096 samples, and a greater number of records for averaging. This was not possible with the short 2 minute recordings available for each run. Based on the results presented here, it can be seen that the WCL data is low frequency (0-5 Hz), but for the data recorded on channels two and three, a band-pass filter with a low frequency cut-off of 1.0 Hz was used. This filtering resulted in the loss of useful information that, if included, could improve the accuracy of the final results.

In conclusion and based on the results presented in this report, correlations exist, and therefore, the transit time flowmeter is feasible. For more confidence in the validity of this analysis, it is suggested that the experiment, if possible, be performed again with special attention to filtering and recording techniques. It is also recommended that a filter with a low cut-off frequency as close as possible to zero be used. Also, if possible, recordings of longer duration should be taken. These two improvements will greatly facilitate the data processing effort and improve the results.

6. REFERENCES

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3. Bentley, P.G. and Dawson, G.G. "Fluid Flow Measurements by Transit Time Analysis of Temperature Fluctuations", TRG-R-115 (Feb. 1966).

FIG. (1) Generalized System Representation

WCL TEST FLOWMETER THERMOCOUPLE MOUNTING PLATE, SIDE VIEW

FIG. (2) WCL Test Flowmeter.

FIG. (3) Block Diagram Representation of the Transfer Function Method.

FIG. (4) Actual Experimental Signals, Run 325

FIG. (5) Run 325, Fourier Transforms of Input Signals

FIG. (6) Run 325, Fourier Transforms of Input Signals, Digitally Filtered.

FIG. (7) Run 325, Power Spectrum of Input $G_{xx}(\omega)$, and Cross-Power Spectrum $G_{xy}(\omega)$.

FIG. (8) Run 325, Transfer Function of the System

FIG. (9) Run 325, Impulse Response of the System

FIG. (10) Run 325, Auto-correlation Function of Input Signal.

FIG. (11) Run 325, Cross-correlation Function.

Relative Amplitude

FIG. (12) Run 299, Auto-correlation, Impulse Response and Cross-correlation Functions.

FIG. (13) Run 300, Auto-correlation, Impulse Response and Cross-correlation Functions.

FIG. (14) Run 301, Unfiltered Fourier Transforms of Input Signals

FIG. (15) Run 301, Unfiltered Impulse Response

FIG. (16) Run 301, Unfiltered Cross-correlation Function.

FIG. (17) Run 304, Auto-correlation, Impulse Response and Cross-correlation Functions.

FIG. (18) Run 305, Auto-correlation Impulse Response and Cross-correlation Functions

FIG. (19) Run 312, Auto-correlation, Impulse Response and Cross-correlation Functions.

FIG. (20) Run 321, Auto-correlation, Impulse Response and Cross-correlation Functions.

FIG. (21) Run 325, Auto-correlation, Impulse Response and Cross-correlation Functions.

FIG. (22) Run 326, Auto-correlation, Impulse Response and Cross-correlation Functions.

FIG. (23) Run 327, Auto-correlation, Impulse Response and Cross-correlation Functions.

FIG. (24) Run 328, Cross-correlation Function.

FIG. (25) Run 329, Auto-correlation, Impulse Response and Cross-correlation Functions.

FIG. (26) Run 331, Cross-correlation Function.