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Impulse-Response Measurement Techniques to Determine
Optimum Input-Signal Characteristics

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I. Introduction

Previous work by J. D. Balcomb⁽¹⁾ has shown that the use of cross-correlation methods with a pseudo-random input signal of small, fixed amplitude and pulse-like character can be used to determine the impulse response of a linear system in a brief time even in the presence of substantial system noise. The work reported here represents a preliminary effort at gaining familiarity with the cross-correlation technique of impulse-response measurement in preparation for use of the technique to make system transfer function measurements during the NRX-A2 test series⁽²⁾.

Of particular interest in this initial effort was the study of the relation between the parameters of the pseudo-random signal produced by a feedback shift register^(2, 3) and the accuracy of the resulting impulse-response computation for a specified system. The input-signal parameters of interest are:

1. the basic pulse interval, Δt ;
2. the number of basic pulse intervals per sequence, N ;
3. the sequence length or period, $L = N \Delta t$; and
4. the amplitude of the pulses, A .

Also of interest in the study was the effectiveness of the cross-correlation technique to eliminate or greatly reduce the effects of system noise on the calculated impulse response. Indeed, this is one of the principal virtues

of the method, inasmuch as it permits the use of small signal amplitudes with correspondingly small perturbations of the system variables⁽¹⁾.

The specific objectives of the analog-computer study were:

1. to determine what combination of parameters for the pseudo-random input signal are required for the optimum determination of the impulse response of a given system in the absence of background noise, and
2. to use this signal to determine how well the impulse response for a system can be computed when noise is present in that system, and to determine whether the presence of noise requires a new optimization of the input-signal parameters.

In this study, a series of runs were made using feedback-shift-register-generated signals with different parameter values as inputs to a simple second-order system mocked up on the analog computer. An analog cross-correlation circuit was used to determine the system impulse response from the input and the measured output of the system. By varying Δt , and maintaining N constant, the effect of varying the sequence length L upon the accuracy of the impulse-response calculation was determined.

A number of similar runs was also made with a gaussian noise signal inserted either at the input or the output of the test system. These measurements were performed to evaluate the effectiveness of noise discrimination in the

impulse-response determination, as a function of the ratio of the rms signal amplitude to the rms noise level.

II. Theory

Consider a simple linear system whose unit impulse response is $h(t)$. Assume that the input and output functions for this system are $F(t)$ and $C(t)$ respectively.

The cross-correlation function for this system $\phi_{io}(\tau)$ is defined as the time integral of the product of the input and output functions $[F(t)$ and $C(t)]$, where one of these [in this case, $C(t)$] is shifted in time by the variable amount τ .

$$\phi_{io}(\tau) = \lim_{T \rightarrow \infty} \frac{1}{2T} \int_{-T}^{+T} C(t + \tau) F(t) dt. \quad (1)$$

The output function $C(t)$ can be written as the convolution of the input and the unit impulse response. Thus,

$$C(t) = F(t) * h(t) \equiv \int_0^{\infty} F(t - \lambda) h(\lambda) d\lambda, \quad (2)$$

or, for mathematical convenience,

$$C(t + \tau) = F(t + \tau) * h(t) \quad (3)$$

$$C(t + \tau) = \int_0^{\infty} F[(t + \tau) - \lambda] h(\lambda) d\lambda. \quad (4)$$

When equation (4) is substituted into equation (1), one obtains,

$$\phi_{iO}(\tau) = \lim_{T \rightarrow \infty} \frac{1}{2T} \int_{-T}^{+T} \int_0^{\infty} h(\lambda) F[(t + \tau) - \lambda] d\lambda F(t) dt \quad (5)$$

$$= \int_0^{\infty} h(\lambda) \left[\lim_{T \rightarrow \infty} \frac{1}{2T} \int_{-T}^{+T} F(t) F[(t + \tau) - \lambda] dt \right] d\lambda. \quad (6)$$

The expression in brackets is defined to be the autocorrelation function, $\phi_{ii}(\tau - \lambda)$ for $F(t)$; thus,

$$\phi_{ii}(\tau - \lambda) = \lim_{T \rightarrow \infty} \frac{1}{2T} \int_{-T}^{+T} (F(t) F[t + (\tau - \lambda)]) dt. \quad (7)$$

It can be shown that for any function $F(t)$ which is purely random, the autocorrelation function is an impulse; i.e.,

$$\phi_{ii}(\tau - \lambda) = K \delta(\tau - \lambda) \quad (8)$$

where K is a scale factor and $\delta(t)$ represents the unit impulse function.

If one combines equations (6), (7), and (8), (assuming of course that $F(t)$ is a purely random function) one obtains

$$\phi_{iO}(t) = K \int_0^{\infty} h(\lambda) \delta(\tau - \lambda) d\lambda. \quad (9)$$

It can be seen that equation (9) has the exact form of the convolution integral; i.e., it represents the convolution of the impulse-response function for our system with the unit impulse. The result is nothing more than the system unit impulse response. Thus, in the case where the input $F(t)$ is a random function,

$$\phi_{iO}(\tau) = K h(\tau)$$

Therefore, if one can calculate the cross-correlation function of a system when that system is perturbed by a purely random input signal, the impulse response of the system can be obtained.

III. Apparatus and Procedure

The signal used to perturb the system is a two-valued signal, with the time interval between switching from one value to the other being randomized in a predetermined manner. The signal also has a finite sequence length such that, after a given period of time, the sequence repeats itself. The sequence length was generally chosen to be very long compared to the shortest allowed switching interval (i.e., the basic pulse interval).

The signal described above was generated by a shift-register generator connected with appropriate feedback paths. The feedback paths provide the basis for the generation of the cyclic pattern described above^(2, 3), and were so chosen as to produce so-called maximum-length sequences (i.e., sequences of the longest possible length for the given number of shift-register stages).

The output signal from the shift-register generator was fed into a test system consisting of a second order system with a break frequency $f_n = 1$ CPS and a damping factor $\zeta = 0.5$, wired up on the analog computer. The response of the system to the input was multiplied by a signal identical to the input signal, but delayed in time by a preselected length of time. This product was then integrated by means of an analog integrator for a time equal to an integral number of sequence lengths in order to yield the value of the cross-correlation function evaluated at the given delay time.

The delayed input signal was generated by means of a second shift-register generator identical to the first but triggered by a controllable delayed pulse.

Figure 1 is a schematic diagram illustrating the test setup. The test procedure was as follows: With the integrator initially set to zero and the switch set to the "ground" position, the feedback-shift-register generator #1 was started. The output of the generator, consisting of a predetermined, pseudo-random, dual-level signal, was applied as input to the test system. During this time, the output from feedback-shift-register generator #2 was zero.

After a certain interval of time which was initially set on the preset counter, two things happened simultaneously: (1) feedback-shift-register generator #2 was turned on and began to generate a signal identical to that of #1 but delayed in time with respect to #1, and (2) a relay threw the switch at the integrator input, from "ground" to the multiplier output terminal. The integrator then began to integrate the multiplier output.

When feedback-shift-register generator #2 completed one sequence length and was ready to repeat itself, the switch at the integrator input was automatically thrown to the "ground" side. This caused the integrator to hold that voltage which it had on its output the instant before the switch was thrown. This voltage was read from a voltmeter and was recorded, completing one run.

A number of such runs were made, each with a different delay time for feedback-shift-register generator #2. The integrator voltages read were then

FIGURE 1

Schematic Diagram Illustrating the Test Setup Used

plotted vs. the delay time, yielding a curve for the impulse response of the system as a function of time.

Figure 2 shows a recording of a portion of one of the binary pseudo-random signals used as an input to the second order test system, along with the response signal of the system.

The frequency spectra of two of the pseudo-random signals are shown in Figures 3 and 4. These spectra apply to the two sequences $N = 63$ and $N = 127$ and were determined by straight-forward Fourier analysis. In general, the amplitude spectra for the different sequences have the same shape, with a null at the N th harmonic of the frequency corresponding to the sequence length, and a decrease in the spacing of the discrete frequency components with increasing value of N (bits per sequence).

For some of the runs, an external noise signal was inserted into the system. This signal was generated by an H. H. Scott, Inc. Type 1812, 1 cps-5 Kcps Random Noise Source. The noise signal was inserted either at the input of the second order system or at the output. An RMS voltmeter was used to measure the effective amplitude of both the noise signal and the pseudo-random signal. In all the "with noise" runs, the rms amplitudes of the noise signal and the pseudo-random signal were adjusted to be equal at the output of the second order system.

FIGURE 2

Recording of the Pseudo-Random Signal and the Corresponding
Second Order System Response

FIGURE 3

Amplitudes of the Harmonics of a Maximum Length Shift Register
Sequence of the Length $2^6 - 1 = 63$ bits with Output Levels of $+1$ and -1

FIGURE 4

Amplitude of the Harmonics of a Maximum Length Shift Register Sequence of the Length $2^7 - 1 = 127$ bits with Output Levels $+1$ and -1

IV. Results

After a few exploratory runs in which different values for the pseudo-random signal parameters were tried, some good impulse-response results were obtained for certain sets of parameter values. One set, the results of which are illustrated in Figure 5, was chosen as a reference run. (For comparison, the theoretical impulse response is given in Figure 6.) Separate, individual variations of signal parameters from those of this run were then made, and the results were compared to those for the reference run in order to evaluate the effects of these parameter variations.

A careful comparison of Figures 5 and 6 shows very close agreement at almost all points of both curves. However, the experimentally obtained curve (Figure 5) is shifted downward slightly compared to the ideal curve. This shift is explainable in terms of the properties of the input pseudo-random signal and can be corrected for⁽¹⁾. However, in addition, the peak of the curve in Figure 5 is approximately 5% lower than that in the exact or ideal curve. No effort was made in the present study to determine the precise reason for this small amplitude decrease, although a number of small deficiencies in the experimental setup are recognized which may have played a role. These include the following: (1) the input signal was not precisely balanced to give zero average value, (2) the shift register generator power supply was somewhat noisy, and (3) inaccuracies may have been introduced as a result of the reduced accuracy of the analog multiplier at low signal amplitude levels. In any event, the results given in

FIGURE 5

Unit Impulse Response for a Second Order System ($\zeta = 0.5$, $f_n = 1 \text{ cps}$).
Data Obtained by Cross-Correlation.

FIGURE 6

Theoretical Unit Impulse Response for a Second Order System
 ($\zeta = 0.5$, $f_n = 1$ cps)

Figure 5 would be sufficiently accurate for most applications, and certainly for the purposes of the present study.

A. Minimum Acceptable Ratio of Sequence Length, L, to Settling Time, T

Four runs were made to determine how the impulse-response results are affected by reducing the sequence length, L. The reference case, Figure 5, was run with a 10.23-second sequence length. By comparison, the settling time of the second order system was approximately 1.8 to 2 seconds, as indicated in Figure 6.

Figure 7 shows the impulse response obtained with the sequence length reduced to 8.084 seconds. This sequence length was obtained by decreasing the clock period ΔT from 0.01 seconds to 0.008 seconds. Although more points should have been taken around the 1.0 second point, the data taken does agree very well with the reference case.

With a further decrease in the input signal clock period ΔT to 0.005 seconds, a sequence length of 5.115 seconds was obtained. The resulting impulse response is shown in Figure 8. In this figure, one can see a tendency for the amplitude of the impulse response to increase and a general shift of the response below the amplitude axis.

When a clock period ΔT of 0.002 seconds was used, the sequence length decreased to 2.046 seconds. Figure 9 shows the resulting impulse response. The

FIGURE 7

Unit Impulse Response for a Second Order System ($\zeta = 0.5$, $f_n = 1 \text{ cps}$).
 Data Obtained by Cross-Correlation.

FIGURE 8

Unit Impulse Response for a Second Order System ($\zeta = 0.5$, $f_n = 1$ cps).
 Data Obtained by Cross-Correlation.

FIGURE 9
Unit Impulse Response for a Second Order System ($\zeta = 0.5$, $f_n = 1$ cps).
Data Obtained by Cross-Correlation.

tendency toward a further amplitude increase and a further off-set from the zero amplitude axis can be seen.

From these results, the need for a sequence length of at least twice the system settling time is evident.

B. Results with Different Sequences

All of the runs described in Section A were made with a maximum length sequence of $N = 1023$. Most other runs in the test series covered in this report were run with $N = 1023$ or higher. However, one run was made with a sequence $N = 127$. Figure 10 shows the resulting response. It can be seen that this response curve compares well with the reference run, Figure 5. However, it should be pointed out that the spacing between the data points is 0.1 seconds (corresponding to the clock period or basic pulse interval, Δt used). This 0.1 second time interval between data points is the smallest interval obtainable with this particular sequence N , and sequence length L , and with the particular correlator used. If shorter data intervals are desired with the same approximate sequence length ($L \approx 10$ seconds), either a sequence with a larger number, N of pulse intervals must be used (with correspondingly shorter clock periods, ΔT), or else a correlator must be used which has the capability of providing correlation time shifts which are smaller than ΔT . The correlator used to obtain all the results in this report was capable of shifting the two signals being correlated only by an integral number of ΔT 's. Thus, with this correlator, the maximum number of data points available corresponds to N , and the minimum data point spacing is equal to ΔT .

FIGURE 10
Unit Impulse Response for a Second Order System ($\zeta = 0.5$, $f_n = 1 \text{ cps}$).
Data Obtained by Cross-Correlation.

The above discussion would seem to indicate that if a correlator is used which imposes no great restriction on the minimum spacing of data points, as with the use of available digital correlation codes, there is no need to limit the choice of ΔT . However, this is not true.

J. D. Balcomb has shown⁽¹⁾ that the autocorrelation of the pseudo-random signal is an isosceles triangle of elevation N and base $2\Delta T$. Now when L is fixed and ΔT is made larger, N decreases. The effect of this is to decrease the height of the triangle and to increase its width at the base. Such a change makes the autocorrelation function a poorer approximation to a true impulse. As a result, the cross-correlation function no longer can be considered to be equal to the response to an impulse.

Thus, if the impulse response of a test system is desired, some upper limit must be imposed on the length of ΔT . This limit is dependent on (1) the degree to which the autocorrelation function may differ from a true impulse function without causing measurable distortion of the response from a true impulse response function, and (2) the "speed" of the test system (or the highest frequency of interest in the test system). These two items are obviously related because what may be considered to be a very good approximation of a true impulse for one test system may appear to be a very poor impulse for a second, much faster system.

In Figure 10, the "speed" of the test system or highest frequency of interest is approximately one cycle per second. The value of $\Delta T = 0.1$ sec. used here is

exactly 10 times greater than the $\Delta T = 0.01$ sec. used for the reference case (Figure 5). The value of N (127) used in Figure 10 is roughly $1/10$ the value of N (1023) used in the reference case. Thus, the "impulse", to which the test system responded in Figure 10, is only $1/10$ the height and 10 times wider at the base than the "impulse" to which the same system responded in Figure 5. In comparison, however, Figures 5 and 10 agree very closely. Therefore, the "impulse", to which the test system responded in Figure 10, appears to be an adequate representation of a true impulse for this test system. The value of ΔT related to the highest frequency of interest in this test system is $\Delta T = \frac{1}{10}(\frac{1}{f})$.

Presumably, if data had been taken for the same test system with pseudo-random input signal parameters of $N = 63$, $\Delta T = 0.2$, and $N = 31$, $\Delta T = 0.4$, the cross-correlation response functions would have been increasingly distorted from the reference case.

On the basis of the results obtained in the work reported here, a good rule of thumb for choosing ΔT appears to be $\Delta T \leq \frac{1}{10}(\frac{1}{f})$ where f is the highest frequency of interest in the test system.

C. Effects of System Noise

Three runs were made to determine how well the impulse response of a second order system ($f_n = 1$ cps, $\rho = 0.5$) can be determined in the presence of a noise signal.

All of these runs were made with a pseudo-random signal identical to that used in the reference case. Thus, all three "with noise" runs may be compared with the reference run.

The first run was made with a 1 cps to 5 Kcps random noise signal inserted at the output of the second order system. The RMS value of the noise signal was adjusted to equal the RMS value of the system's response to the pseudo-random input signal. Figure 11 shows the resulting impulse response. Examination of this curve shows that it is almost identical to the reference case, Figure 5.

The second run, Figure 12, was made with the noise source inserted at the input to the second order system. The noise source amplitude was adjusted so that the RMS value of the second order system's response to the noise, at the system's output, was equal to the RMS value of the system's response to the pseudo-random input signal. Considerable scattering of the data can be observed. For easier comparison purposes, the curve for the reference case was drawn in over this data.

FIGURE 11

Unit Impulse Response for a Second Order System ($\zeta = 0.5$, $f_n = 1 \text{ cps}$).
 Data Obtained by Cross-Correlation.
 Correlation Interval = 1 Sequence Length or 10.23 Seconds.

FIGURE 12

Unit Impulse Response for a Second Order System ($\zeta = 0.5$, $f_n = 1$ cps).
 Data Obtained by Cross-Correlation.
 Correlation Interval = 1 Sequence Length or 10.23 Seconds.

Theoretically, the above scattering in the data can be reduced by calculating the cross-correlation function over a longer time interval. All runs reported up to this point were made with a cross-correlation time interval corresponding to one full sequence length. The theory indicates the cross-correlation should be calculated over an infinite length interval. However, it has already been shown that good results can be obtained with an entirely reasonable integration time.

In an effort to show how "scattering" could be diminished through use of a longer integration time, a run was made with all conditions identical to the previous run except that, the cross-correlation was calculated over a 5 sequence length time period. Figure 13 shows the results. Again, the curve drawn corresponds to the reference case. The results do show a reduction in the "scattering" although there are still a few "wild" points.

These three curves illustrate that:

1. Noise generally outside the frequency range of the test system seems to cause very little error (Figure 11).
2. Noise within the frequency range of the test system and of amplitude equal to the pseudo-random signal will cause some "scattering" of data.
3. Longer correlation time tends to reduce the scattering.

FIGURE 13

Unit Impulse Response for a Second Order System ($\zeta = 0.5$, $f_n = 1$ cps).
 Data Obtained by Cross-Correlation.
 Correlation Interval = 5 Sequence Lengths or 5×10.23 Seconds.

D. Application of the Cross-Correlation Impulse Response Measurement Technique to the Analog Computer Model of the Feedsystem

Since our eventual goal is to apply the above technique to some complex system, illustrative studies were also performed using a model of the Test Cell A feedsysteem set up on the analog computer⁽⁴⁾. All the control loops were closed and the system was brought to steady-state operation at 33 lb/sec total flow and 90°R temperature in the mixing chamber.

A small impulse was inserted into the PCV-50 valve position signal, and the resulting response of liquid flow at FE-7 was plotted on a strip chart recorder. This trace is shown in Figure 14.

A pseudo-random signal ($N = 2047$, $\Delta T = 0.01$ seconds, $L = 20.47$ seconds) was then inserted at the same location of the system (valve PCV-50 position). This signal was cross-correlated with the measured liquid flow signal at FE-7. The resulting impulse response curve is shown in Figure 15. The amplitude scale gives the flow rate response (lb/sec) to a unit impulse in the position of PCV-50 (1 inch second).

The pseudo-random signal amplitude used in this run corresponds to a ± 0.003 inch stem displacement for valve PCV-50.

A comparison of the FE-7 liquid flow impulse response curves of Figure 14 (obtained directly) and Figure 15 (obtained by cross-correlation) shows that qualitatively a great deal of similarity exists between the two response curves.

FIGURE 14

Feedsystem Response to an Impulse in Turbine Inlet Valve (PCV-50) Position

FIGURE 15

Response of the Liquid Flow Rate at FE-7 of the Test Cell A Feedsystem to a Unit Impulse at the Turbine Inlet Valve. Data Obtained by Cross-Correlation on an Analog Computer Model of the System.

V. Conclusions

1. The pseudo-random input signal should have a sequence length of at least twice the test system settling time.
2. The basic pulse interval ΔT of the pseudo-random signal should be no greater than about $\frac{1}{10}$ of the period of the highest natural frequency component of the test system.
3. System noise is most likely to cause inaccuracy in the impulse response results when the noise is within the frequency pass band of the test system.

VI. Planned Future Work

Future work is planned to determine:

1. What modifications must be made to this impulse-response measurement technique so that transfer functions can be determined simultaneously with respect to several different system inputs?
2. If an isolated portion of the test system is non-linear, how badly will this non-linearity affect impulse response measurements for other linear parts of the system?
3. What input signal amplitude levels are to be considered practical in the NRX test series? This question will be answered both on real parts of the NRX facility and on analog computer models for each NRX test reactor and the facility⁽²⁾.

VII. References

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