CONF-13112--7

EXPERIENCE WITH A DIGITAL NOISE ANALYSIS SYSTEM IN SUBCRITICALITY MEASUREMENTS ON A MOCKUP OF THE FFTF*

V. K. Paré, R. C. Kryter, and J. T. Mihalcz
Oak Ridge National Laboratory
Oak Ridge, Tennessee 37830

Summary

A digital Fourier analyzer was programmed to perform reactor neutron noise analysis measurements and on-line processing of the data to obtain the steady-state reactivity. The system is suitable for recovering cross spectral density with low correlated-signal component and for repetitive measurements with efficient use of reactor time.

Introduction

A library of programs was prepared to adapt a commercial digital Fourier analyzer system for reactor neutron noise analysis. The system was tested and used in a series of measurements of reactivity at the ZPR-9 fast critical facility at Argonne National Laboratory. The measurements were part of a program to develop reactivity surveillance procedures for the Fast Flux Test Facility (FFTF), and the ZPR-9 was loaded to simulate the proposed FFTF core.

This library will be valuable to specialists in measurement of reactivity by neutron noise analysis. A description of the programs and operating procedures should also be more generally useful, however, since it illustrates the capabilities that can be obtained by adding additional programming to a commercial Fourier analyzer system. Such systems include the hardware and software needed for generation of averaged spectral densities and related quantities. In reactivity measurement these are intermediate, rather than final, results; they must be regrouped, corrected to remove the frequency response functions of the signal conditioning circuits, and fitted to a theoretical model to obtain parameters from which the value of the reactivity can be calculated. Presumably there are other noise analysis applications in which the spectral densities need to be processed by analogous procedures.

One of the primary reasons for employing the digital system, in place of an analog system previously used,¹ is its self-contained capability to process on-line the data and calculations necessary for reactor surveillance procedures. Also, the digital system is free from the nonideal characteristics, such as drift and feedthrough, that inevitably occur in analog systems, and it provides valuable versatility in data-taking sequences.

The data-taking sequences and processing programs were designed to achieve the following objectives: to (1) optimize utilization of reactor time; (2) accumulate $\sim 10^3$ to $\sim 10^5$ samples of spectra for ensemble averages; (3) accumulate, during part of the data-taking sequence, sums of squares of samples of spectra, so that standard deviations of the spectra can be estimated; (4) provide on-line processing and analysis with prompt printed results of reactivity calculations; (5) simplify commands, thereby reducing the probability of operator error and allowing the system to be run by persons not familiar with programming; and (6) record significant data so that the processing and analysis can be refined off-line.

*Research sponsored by the U. S. Atomic Energy Commission under contract with the Union Carbide Corporation.

Hardware

The hardware configuration of the digital Fourier analysis system² is shown in Fig. 1. All items shown were purchased from the manufacturer. The fast Fourier processor (FFP) stores data in blocks of N 16-bit words, with N variable from 64 to 2048 by powers of 2. Each block can store either a time sequence of N input data samples or a complex spectrum of $N/2$ frequency points plus a dc component. The data are stored in integer format with an attendant wide-range scale factor applicable to the entire block. Under control of microprograms loaded from the computer, the FFP does Hanning (time-window-shaping), Fourier transforms, block complex arithmetic, and other related operations. Multiple accumulators and hardware indexing and control reduce computing time. The FFP operates asynchronously from the computer, and data transfers are made through the computer's direct memory access channel (DMA).

The analog-to-digital converter (ADC) is a 200 kHz, 12-bit, 4-channel unit; two channels were used in the ZPR-9 experiments. Inputs could be obtained from any 2 of 15 detectors in the reactor. All signals were conditioned so that the signal voltage levels represented, within bandwidths adequate for the measurements, the neutron interaction rates in the corresponding detectors.

Organization of Software

The hierarchy of software in the system is illustrated in Fig. 2. The Fourier system and utility programs constitute the operating portion of the manufacturer's software. The Fourier system programs drive the ADC and FFP, buffer the ADC data through the computer's memory, and keep track of scale factors and other information for the data blocks in the FFP. The Fourier system is driven by commands from the control keyboard to execute FFP operations or to call user programs. The system also implements storage of keyboard commands in a program stack for later sequential execution. These keyboard programs are easily edited and can be recorded on perforated paper tape. Since they can call all other programs, they can serve as a versatile and convenient executive for the entire data-taking and processing sequence.

User programs can be written in assembly language or in Fortran; they can be called by manual keyboard commands or by keyboard programs, and they can call other user programs or Fourier system programs. Thus, they may be fully integrated into a system with almost unlimited flexibility.

The basic Fourier system, including space for the ADC buffer, uses about 12K words of core; thus in the present configuration about 12K are available for user programs with their required utilities.

Neutron Noise Analysis Programming

In the data-taking phase of operation samples of spectra are generated and accumulated; it consists mainly of FFP operations controlled by the keyboard program. In the processing phase, the averaged spectra are grouped, corrected, and fitted;

MASTER

then hard-copy outputs and a CRT display are generated. Most of the processing is done by user programs called by the keyboard program.

Data-Taking

The organization of the data-taking phase is affected by the consideration that the correlated components (which contain the reactivity information) of the two input noise signals can be quite small compared with the signals themselves. Consequently, the auto power spectral densities (PSD's) might not contain sufficient information to allow quantitative interpretation, and the cross power spectral density (CPSD) is of primary significance. Furthermore, ensemble averages of $\sim 10^3$ to $\sim 10^5$ samples of the CPSD must be obtained if the reactivity is to be calculated with adequate statistical precision. Such large ensembles pose a potential problem in a fixed-word-length digital system because the accumulating sum becomes much larger in magnitude than the samples that are being added to it. The sum is prevented from overflowing by adjustment, as necessary, of the block scale factor; however, the same scale factor must be applied to each sample before it can be added to the sum. As a result, bits must be dropped from the right, and eventually the most significant bit in the sample will represent a smaller value than the least significant bit in the sum; thenceforth, further samples will make no contribution to the sum at all. For this reason, 16-bit computer words were not adequate for the large ensembles required, and the manufacturer's software was supplemented by implementing double-precision multiplication operations so that the samples of the CPSD, as well as of the PSD's, could be calculated and accumulated in double (32-bit) precision. To accommodate this word length, the real and imaginary parts of the CPSD are accumulated in separate FFP data blocks.

Eight data blocks were required in the FFP for the calculations required during data-taking; thus, 1024-word blocks were used, yielding 512-point, double-precision spectra.

The breakfrequency of the reactor transfer function of the ZPR-9 varied from ~ 770 Hz at near critical to ~ 38 kHz at the lowest reactivity. The maximum spectral frequency, $F_{\max}$, was set to provide spectral data well above the expected breakfrequency and to allow for the requirement--in a digital analyzer--that low-pass input filters be used to prevent "aliasing" (i.e., contributions from frequencies above $F_{\max}$). Values of 10.24, 25.6, 51.2, or 100 kHz were selected according to reactivity level. The corresponding frequency intervals in the spectra were 20, 50, 100, or 195.3 Hz, respectively.

The structure of the data-taking program is indicated in Fig. 3. The prefix "s" indicates that the square of the spectrum sample is calculated and summed. On completion of the first outer loop, a user program employs these sums of squares, along with the corresponding linear sums, to calculate estimated standard deviations (as functions of frequency) of the PSD of channel A and of the real part of the CPSD. The results are held in the computer until the end of data-taking, and then they are placed in two blocks which were used during data-taking for the generation of Fourier transforms.

Usually, outer loop counts of $L_1 = 200$ and $L_2 = 800$ are used to obtain a relative standard deviation of $\sim 3\%$ for the individual frequency spectrum points of the PSD's and to allocate 20% of running time for accumulating statistical data. The inner loop count, I , which controls the number of samples taken for the CPSD, is varied to achieve a statistical precision comparable to that of the PSD's. (This variation is necessary

because the relative magnitude of the correlated component changes with reactivity.) The nested loop structure is used to intersperse the calculations of PSD's and CPSD throughout the run so that the coherence calculation is valid even if the reactivity drifts. After all looping is completed, the standard deviation values are loaded into two FFP blocks, and all summed spectra are normalized by dividing each sum by the number of samples taken. The standard deviations, calculated from 20% of the total numbers of samples, are renormalized so as to become estimates of the standard deviations of the final averaged spectra.

Processing

The complete data-taking and processing sequence is outlined in Fig. 4. All the segments shown are sequenced by the keyboard program. The first three comprise the data-taking phase and have been described; they are followed by output of the unprocessed spectra in binary code on paper tape.

To reduce the number of data points to a manageable level, a user program groups, by averaging (and renormalizing, in the case of the standard deviations), the 512 values in each spectrum into a set of 64. The new frequency points are nominally spaced at intervals of 7.8%, but the first 24 points are not grouped since doing so would result in larger intervals. The standard deviations are converted to relative values for convenient comparison with theoretical expectations; for the lower half of the frequency range the agreement was consistently good.

Prior to the ZPR-9 reactor experiments, the overall frequency response characteristic of each detector, with its associated signal conditioning system, was measured by obtaining a PSD with the detector activated in a nonmultiplying neutron source-moderator assembly. These PSD's were grouped as described previously and assembled on master tapes. As part of the processing of reactor data, a user program divides the grouped PSD's and CPSD by the appropriate correction functions obtained from the master tapes.

After the grouping and frequency response correction operations, the CPSD data are fitted to the point reactor model formula:

$$\text{Re}[\text{CPSD}(f)] = C_0 / [1 + (f/f_b)^2], \quad (1)$$

in which C_0 is a constant, f is the frequency, and "Re" designates the real part. A user program varies the parameters f_b (the breakfrequency) and C_0 in an iterative process to obtain the best nonlinear least-squares fit. The program then calculates and prints the reactivity, $\$$ (in dollars), using the formula

$$(1 - \$) = f_b / f_{bc}, \quad (2)$$

in which f_{bc} is the breakfrequency at critical. In the on-line processing, no correction was made for variation of the prompt-neutron lifetime with reactivity. This correction (which is contained in the factor f_{bc}) could easily have been made on-line if the required information had been available. A complete tabulation of the measured CPSD and the fitted curve is punched, since printing would consume excessive time. The program also generates a CRT display on which the measured CPSD and fitted curve are superimposed.

Processing is completed by calculating the square of the coherence, i.e.,

$$\gamma^2 = |\text{CPSD}|^2 / (\text{PSD}_A)(\text{PSD}_B), \quad (3)$$

and punching, in binary code, the corrected, grouped spectra plus the relative standard deviations and γ^2 .

Typical results of these operations are plotted in Fig. 5. The reactivity is calculated within 4 min after the end of data-taking, and the remainder of the processing is completed in another 3 min. The data-taking itself consumes 6 to 60 min, depending on the number of CPSD samples required for the desired statistical precision.

Prior to the reactor measurements and before the program library was put into final form, test runs were made using electronically simulated reactor noise signals. These tests served not only to check the mathematical validity of the programs, but also to obtain from the prospective operators many comments which were valuable in making the final version of the system more straightforward to use and less susceptible to error.

Evaluation

Reactivity measurement by reactor neutron noise analysis is an example of a case in which the PSD and CPSD spectra are only intermediate results; they must be further processed and analyzed before useful answers are obtained. The processing and analysis operations can be done on-line in a self-contained digital Fourier analysis system if the data-taking sequences can be programmed flexibly and user-written programs can be readily integrated with the Fourier system software. The authors' program system was designed to be controlled by simple operator commands, but it could have been made fully automatic.

Some consequences of the use of a digital system are:

1. For ensembles of less than $\sim 10^5$ samples, there is no significant loss of accuracy due to truncation if full double-precision arithmetic is implemented. Double-precision words in the FFP have 32 bits, including sign. The digital system is free from the drift and feedthrough problems inherent in the multipliers and filters of an analog system.
2. For the frequency ranges covered, the digital analyzer used is not fast enough to allow continuous sampling of data. In either segment of the data-taking program illustrated in Fig. 3, 100 msec is required to complete the computations associated with each sample of $\text{Re}(\text{CPSD})$. The actual time spent sampling data from the detectors is $512/F_{\text{max}}$ for block-size = 1024; the corresponding times are 50, 20, 10, or 5.12 msec for F_{max} of 10.24, 25.6, 51.2, or 100 kHz, respectively. Thus, in the measurements the efficiency of utilization of reactor data ranged downward from 50%. For the keyboard program illustrated in Fig. 3, 100% utilization (i.e., real-time analysis) would be achieved for F_{max} of 5.12 kHz or less.
3. As pointed out previously, the manufacturer's software is designed for convenience and versatility. It implements user-written programs entered from the keyboard and allows general-purpose processing programs, which can be written in Fortran, to be integrated fully into the system. Nevertheless, more than 1/2 man-year was required to build the complete software system. Most of this time was spent developing and testing user programs and data-taking sequences, but some work was required to detect and correct errors and deficiencies in the manufacturer's software. These difficulties presumably occurred

because both the FFP and the ADC were newly marketed units and required elaborate sets of software drivers.

References

1. R. C. Kryter, "Cross Spectral Density Analyzer for Sub-criticality Measurement in an LMFBR," Instrumentation and Controls Div. Ann. Progr. Rep. Sept. 1, 1971, ORNL-4734, p. 97.
2. Hewlett-Packard Model 5451A, with 2100A Computer and 5470A Fast Fourier Processor.

NOTICE

This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Atomic Energy Commission, 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.

Figure Captions:

Fig. 1. Configuration of digital Fourier analyzer. Direct memory access channels are designated by "DMA."

Fig. 2. Hierarchy of software for digital Fourier analyzer.

Fig. 3. Structure of data-taking program. Meanings of prefixes are: Re, real part; Im, imaginary part; σ , accumulation of squares of spectrum samples for estimation of standard deviations.

Fig. 4. Complete data-taking and processing sequence for reactor noise analysis. Each segment is labeled "K" or "U" to indicate whether it is carried out by a keyboard program or a user program.

Fig. 5. Graph of corrected grouped data and fitted curve obtained by digital Fourier analysis system from ZPR-9 reactor at critical. The PSD data have been depressed a factor of 10 for clarity.

Figure 1

Figure 2

Figure 3

Figure 4

Figure 5