A MICROPROCESSOR-CONTROLLED SCANNING DENSITOMETER SYSTEM

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ABSTRACT

An Automated Scanning Densitometer System has been developed at the Idaho National Engineering Laboratory (INEL) by uniting a microprocessor with a low energy X-ray densitometer system. The microprocessor controls the detector movement, provides self-calibration, compensates raw readings to provide time-linear output, controls both data storage and the host computer interface, and provides measurement output in engineering units for immediate reading. The densitometer, when used in a scanning mode, is a precision reference instrument that provides chordal average density measurements over the cross section of a pipe under steady-state flow conditions.

Results have shown an improvement over the original densitometer in reliability and repeatability of the system, and a factor-of-five improvement in accuracy.

1. INTRODUCTION

Introduction of the microcomputer into traditional instrument design is enhancing cost effectiveness of testing, and yielding more useful transducer data. EG&G Idaho is using microprocessor-based technology to improve their instrumentation and develop new designs related to the rapidly advancing energy field. One such area of interest to both the nuclear and non-nuclear fields is flow transducer development. There is an increasing need to improve the capabilities of these devices to meet the demands of the rapidly advancing energy technology. One reference instrument useful in environmental testing of transducers--and other devices as well--is the densitometer. This paper describes the development and automation of the scanning densitometer, a low energy, X-ray system that has seen considerable improvement by the application of a microprocessor. The theory of densitometry is presented first, a description of the earlier scanning densitometer system next, and an explanation of the modifications which have expanded the system in hardware and software last. The improvements provided by the microprocessor can be summarized as follows: (a) control of the scanning hardware, (b) simplicity of use, (c) automatic self-test and calibration, (d) display of scanner position, (e) verification of scanner locations, (f) data reduction, (g) compensation of raw readings to provide a time-linear output, (h) measurements output in engineering units for immediate readings, (i) bulk data storage, and (j) host computer interface.

2. Densitometer Theory

Low energy, X-ray attenuation densitometers are systems which measure the attenuation of one or several radiation beams used to infer the density of the attenuating material. A simple densitometer system (Figure 1) consists of a radiation source, detector, and shielding material that defines the beam geometry. A source which emits photons of only one energy level-of-interest (X-ray band) is used, and the emitted photons are absorbed and scattered by whatever material occupies the path between the source and the

Figure 1. Single beam measurement elements.

detector. Charged pulses generated in the detector by photo electric absorption of incident X-rays are integrated and amplified. The measured pulse heights of the pulses are proportional to the photon energy deposited in the detector; thus, the density of a material along the beam path is inversely proportional to the count rate of a predetermined pulse height (Reference¹).

The primary application of the densitometer at the INEL has been to gas-liquid mixtures flowing through pipes. The configuration for this type of densitometer can have one or more fixed-position radiation sources on the side of the pipe opposite one or more fixed-position, or movable radiation, detectors. Successive detector positioning, covering the entire flow area and giving a sufficient number of data points, can indicate steady chordal average density distributions, or density of a beam path from the source to the detector. From this, the cross-sectional average density, or the density of a complete cross-section of the flow in the pipe, can accurately be obtained. The major advantage of using radiation as a tool for measuring the density of a material is that the measurement does not disturb the material, nor need the integrity of the materials container be compromised by mechanical penetrations. This paper covers only the scanning densitometer that allows the use of only one detector and one source to cover the complete cross section of a pipe. The application is limited to steady-state flow conditions.

3. SCANNING DENSITOMETER DESCRIPTION

The scanning densitometer arrangement is shown in Figure 2. The traversing detector is rotated or scanned around the pipe in a circular arc about the source, to measure various chordal densities over the full cross section of the pipe. Depending on the flow diameter, 25 to 50 azimuthal positions will provide full coverage. The hardware, coupled with electronics, traversing motor, and controller, forms the scanning densitometer system. This system has been used for steam-water, steady-state loops in Canada and Karlsruhe, Germany, and presently is

Figure 2. Scanning densitometer arrangement, showing X-ray source, cross section of piping spool piece, and angle which defines the location of the traversing detector.

installed in the Semiscale air-water loop facility at the INEL (shown in Figure 3).

Figure 4 shows the system configuration before the upgraded modifications. Pulses were counted for the selected preset time as set on the dual counter/timer. At the end of the preset time, the number of pulses counted was transferred by the printout control to the teletype. Upon completion of printout, the counter was reset to zero and counting was automatically restarted. Also, at the end of the preset time, a control signal was sent from the counter/timer to the preset indexer to start the detector traversing motor and move the detector to the next position. When the preset number of steps had been accomplished, power to the motor was turned off. The speed of the stepping motor was adjusted so that the detector was moved to its next position in slightly less time than was used by the teletype for data printout.

Thus, a traverse was started by moving the detector to its initial position. The X-ray pulses were counted for 10 s (or 20 s), and the number counted was typed on the teletype. While the typing proceeded, the detector was moved by the stepping motor to position two. The counter was reset and counting restarted at the new position. This procedure was repeated automatically for the specified number of azimuthal detector positions, at which time the operator stopped the process and returned the detector to its initial position for the next data run. References 2 through 5 contain additional information on the system.

This system was subject to many operator errors: the controller was manually controlled; no position verification was available; all data was manually manipulated or typed into another computer to be processed and analyzed; and no quick-look scheme was available to determine if the system was operating properly.

Figure 3. Photograph of a scanning densitometer.

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Figure 4. Block diagram of the original electronics for the scanning densitometer.

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Figure 5. Expanded block diagram of the scanning densitometer.

4. MODIFIED SCANNING DENSITOMETER DESCRIPTION

To overcome the deficiencies of the system, the scanning densitometer was modified to provide densitometer control and data acquisition and analysis--all performed and controlled by a microprocessor. Figure 5 shows the expanded block diagram, and Table 1 lists the major components and model numbers. The detector electronics, shown in Figure 4, have remained the same, up to the Single Channel Analyzer.

The heart of the system is a Multibus, single board computer BLC80/204 (see Table 1); an additional memory board is used to provide a total memory capacity of 8K RAM and 16K EPROM. The Multibus was chosen for the system bus standard as it defines the interconnection and communication signals between different modules of the system. The CAMAC standard was chosen for instrumentation packaging as it covers all communication from the component level up to the systems level. The Multibus cards are mounted in a rack chassis, and the instrumentation modules are mounted in a CAMAC crate. The single board computer controls the actions performed by the CAMAC instrumentation modules. Both standards offer significant advancement in increasing flexibility, reducing special hardware and software efforts, and minimizing system obsolescence. A number of manufacturers offer boards that are compatible with the two systems.

The remaining hardware can be divided into three functional areas: (a) control of the scanning hardware, (b) acquiring and storage of data, and (c) data analysis. The system is completely keyboard controlled; all commands, operating mode selection, and entering of test parameters are done from the keyboard. A 16-digit alphanumeric display mounted in the keyboard enclosure is used to guide the operator through setup procedures by displaying prompts; the information is typed at the keyboard. The hardware chosen overcomes the system deficiencies and is explained in the following sections.

TABLE 1. MAJOR COMPONENTS OF THE SYSTEM

Component	Model	Comments
Main Processor	National BLC 80/204	8080 Single Board Computer with 4K RAM 8K EPROM and 48 I/O ports.
Memory Board	Monolithic System Corp. MSC 8001	4K RAM 8K EPROM.
Keyboard	George Risk Ind. Model 756	Full ASCII keyboard with heavy-gauge all-steel enclosure.
Alphanumeric Display	Litronix DL-1416	There are four digits per unit, and four units. Displays are 41 mm high, and are mounted in keyboard enclosure.
Printer	Axiom EX-820	Printer with graphics capability. Uses 125-mm electrosensitive paper.
Multibus to CAMAC Card	Monolithic System Corp. MSC 8204	General purpose interface card, I/O mapped.
CAMAC Crate Controller	Kinetic Systems #3408-ZIA	Controls the crate
Stopping Motor Controller	Kinetic Systems #3361-EIA	Controls the movement of the stepping motor.
Quad Counter	Kinetic Systems #3640-LIA	Counter used for encoder, stepping motor, and X-ray counts.
CAMAC Crate	Kinetic Systems #1500-PIB	Crate and power supply.
Encoder	Litton #70-LD2000-1-4-0	Optical incremental encoder used to verify the position of the scanning densitometer.
Display Interface Card	Monolithic System Corp, MSC 8204	General purpose interface card for inclinometer display and position display I/O mapped.
A/D Board	Burr-Brown MP8418	12-bit converter for the inclinometer.

TABLE 1. (Continued)

Component	Model	Comments
Inclinometer	Schaevitz LSOC-450-0994	Used to verify position of scanning hardware, and to obtain the angle reading.
Math Processor	Advanced Micro Computer, AMC 95/6011	Performs the mathematical calculations. Uses the LSI Am9511 processor chip.
Cassette Interface Card	Interdyne #IB4100	Contains the interface logic and software to drive unit.
Cassette Tape Drive	Interdyne #IC25000	Cassette tape drive.
Clock Module	Digital Pathways, Inc. TCU-410	Provides year, month, day, hour, minute, and second for tagging data.

5. BASIC SYSTEM OPERATION

The effective control of the scanning hardware is based upon the control of the stepper motor. Therefore, the stepper motor is completely microprocessor controlled; with several means available to verify the actual position of the scanning densitometer. Depending on the program mode of system operation, an inclinometer, which measures horizontal angles of the detector in reference to gravity, or a shaft-position encoder, which measures the rotation of the stepping motor, can be used to provide positional feedback information. On finding positional errors, the system is self-correcting to provide accurate and repeatable data. Displays are available that provide the operator with visual positional information, allowing the status to be known during test operation.

Count rate, the basic unit of data, was acquired in previous densitometer systems by use of a rate meter. In the present configuration, data are acquired by counting the pulses out of the detector electronics for the period of time selected, with an improvement by a factor of five in accuracy. Two units of the quad counter are cascaded to form a 32-bit counter. Each scan point is organized as part of a complete scan, which is printed out and labeled for future reference. The printer provides a hard copy of the data and all information relating to the scan. This includes a title assigned to the scan and the particular parameters about the scan. The clock module provides date and time information for tagging the data. The operator has the additional options of plotting the data for a quick look, and of transferring the data to a cassette tape unit for storage.

The data collected from a test scan will fall within the range of values obtained for scans of all-dry-air to all-water. Densitometer calibration is accomplished by obtaining reference scan data for known density conditions of the two end points. These data are stored into memory for mathematical calculations, and also plotted alongside the current scan for quick look plots.

The calculations performed for data analysis are the conversion of the data into engineering units for printouts, calculations of the chordal average density for each scan position, and the calculation of the cross-sectional density for the whole pipe. This is automatically done for each scan, along with printing out the calculated values. If further data analysis is required, the options to store all data on the cassette unit and transfer the data to the host computer may be used.

6. SOFTWARE DESCRIPTION

The software is written in a modular, structural form, using PL/M for ease of design, implementation, debugging, and documentation. Enough utility software is built-in to allow a semi-skilled person to operate the system. The combination of prompts included in the software and the software support package for the alphanumeric display and keyboard is what has made the system versatile, yet simple to operate. The software support package consists of three procedures, DISPLAY, KEYBOARD, and LINE\$EDIT. The DISPLAY procedure places the prompts on the alphanumeric readout, which guides the operator through operational setup procedures and allows verification of the entered parameters.

The keyboard service procedure is written to allow special function keys and line editing capabilities. The keyboard is interrupt driven, which allows special keys to be used, such as restart of scan, termination of the program, and stopping and starting of the execution of the program. A one-character Queue is used to store characters as they are typed. If the Queue is full, the character is ignored. A LINE\$EDIT procedure is used to extract characters as needed from the Queue and place them into a buffer, as well as display them on the alphanumeric display. Characters from the buffer and display can be deleted and re-entered if needed. The whole buffer is passed to the calling procedure upon typing a carriage return.

The software flow of the main procedure is depicted in Figure 6. At power-up, the system is initialized and a memory check is performed. Home or reference position is determined by one of two means, manually moving the scanning densitometer to the desired location, or using the inclinometer to automatically move the scanning densitometer to the level position. Once home position is established, an Input Command Loop is entered. There are six possible commands to be executed, each being a separate procedure: MODE\$0, MODE\$1, MODE\$2, MODE\$3, MODE\$4, and TRANSFER\$DATA. The different modes are described below.

MODE\$0

This mode provides repeated scans of the pipe, with the angular position around the pipe specified by steps of the stepping motor, and verification of position determined by the use of the encoder.

The number of positions, number of steps per position, the start position, and the time interval are programmed in at the keyboard.

When MODE\$0 is executed the following take place:

1. The controller steps the scanning densitometer through the programmed number of positions
2. Values obtained during the scan are printed out
3. All-water and all-dry-air reference data values are saved in memory for mathematical calculations
4. Chordal average density is calculated for each position
5. A plot of the scan data versus position with an overlay of the reference data is provided for each scan

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Figure 6. Block diagram of the software of the MAIN procedure.

6. Cross-sectional density is calculated for each scan
7. Data are stored on cassette tape for retrieval.

MODE \$1

This mode allows special locations to be stored in memory, and upon execution the detector is moved sequentially to each of these positions. The time interval and up to ten positions can be programmed. Positions are specified by the number of steps referenced from the home position, with verification performed by the encoder. The programmed positions can be repeated, or new positions typed in. No calculation or storage of data takes place. When MODE\$1 is executed the following happens:

1. The controller steps through all programmed locations
2. Count rates and positions are printed out on the printer.

MODE \$2

This mode provides manual operation of the scanning densitometer from the keyboard. Two basic operations can be programmed: (a) move to specific location, or (b) acquire a data point. When a data sample is taken, the value is printed.

MODE \$3

This mode provides repeated scans of the pipe, with positions around the pipe specified by degrees, and verification of position determined by the use of the inclinometer.

The number of positions, the start angle, the delta angle, and the time interval are programmed in at the keyboard. When MODE\$3 is executed, the following take place:

1. The controller steps the scanning densitometer through the programmed number of positions
2. Values are printed out during a scan
3. All-dry-air and all-water reference data values are saved in memory for mathematical calculations
4. Chordal average density is calculated for each position
5. A plot of the scan data versus angular position, with an overlay of the reference data, is provided for each scan
6. Cross-sectional density is calculated for each scan
7. Data are stored on cassette tape for later retrieval.

MODE \$4

This mode allows special locations to be stored in memory, and upon execution the detector is moved sequentially to each of these positions. The time interval and up to ten positions can be programmed. All positions are specified by an angle referenced from the home position, with verification performed by the inclinometer. The programmed positions can be repeated, or new positions typed in, with no calculation or storage of data taking place. When executed the following occur:

1. The controller steps through all preprogrammed locations
2. Count rates and positions are printed out on the printer.

TRANSFER\$DATA

This is a command that will cause data stored on the cassette tape to be transferred to a host computer. Two options are available to the user: (a) the header block that contains the information stored on the cassette tape being examined is transmitted to the printer for reference; or (b) data stored on the cassette recorder are transmitted to a RS-232C port. The latter option allows further computations to be performed by the host computer.

For each of the six modes of operation discussed above, verification of the entered parameters is performed before execution of the input command is actually started. This is accomplished in several ways: (a) as the parameters are entered, visual feedback is provided, (b) the operator easily recalls all parameters and makes changes without affecting other entered values, and (c) all parameters are printed out and the user is asked if the information is correct. Once parameters are entered and verified, the program is executed as outlined under the explanations of the different mode, with E typed on the keyboard to start the process. An additional feature of MODE\$1 and MODE\$3 allows a test heading to be entered for each scan to help identify data at a later time.

The modular structure of the software allows separate procedures to exist that handle the functions of the different hardware. The input command procedure calls upon the various hardware procedures to accomplish the objectives as outlined. The system functions are described in the following paragraphs.

The math processor, as controlled by the software, calculates the angle from the inclinometer voltage reading. The voltage is converted to a digital word by the 12-bit A/D converter, and then converted to a BCD number. This number is displayed and printed out. The resolution, as limited by the A/D board, is 0.0198 degrees (2.441 mV). The limitation of the scanning hardware is ± 45 degrees (± 5.0 V).

The pulses from the encoder are counted to determine the position of the scanning densitometer. The counter is an up-down counter and must be reset when home position is determined. The detector location is determined by both the encoder and inclinometer. The results are compared, and if any difference exists an error flag is set. Once the flag is set, one of the two outputs is used as the official position, and the detector position adjusted to correct errors. The instrument used as the official unit depends on the mode of operation selected.

The stepper motor is controlled by loading into a register the number of steps and the direction of travel. The controller then moves the motor the requested number of steps and sets a bit in the status register to signify that the move is completed. Two extra outputs are provided on the controller, allowing an up-down counter to be connected. The counter is used to verify the correct number of pulses sent to the stepper-motor and the location of the scanning densitometer in reference to the home position. The controller has two inputs connected to limit switches. When a switch is triggered it prevents further travel, thus preventing overtravel of the mechanism.

The count rate is obtained by enabling the counters in the Quad counter for the selected time. The time is governed by using two of the timers found in the interval timing chip (8253) located on the processor board. The value entered is loaded into the register and counted down to zero, at which time an interrupt is given to the processor to signify the time is completed. The keyboard interrupt is disabled during this time period to prevent any interruptions. The range for the time period as set by the software is 1 to 100 s.

The printer is an Axiom model that can mix high resolution graphics with full ASCII alphanumerics. By software control, three different character sizes and up to 128 dots per inch for horizontal dot resolution can be obtained on the 5 in. wide electrosensitive paper. For each scan point, the position, count rate, angle in degrees, and chordal average

density are printed out. For each scan, the cross-sectional density is also printed out. The graphic capability will be used to plot the count rate versus angle of each scan. This will be plotted along side the reference scans count rate for comparison. The user can immediately make the decision to repeat the scan or continue with the test series.

The front panel displays available to the user are the inclinometer voltage reading (+5.000 V), inclinometer angle reading (+45.00 degrees), and the scan position (99). The last two are updated by the processor after the scanning densitometer has moved to a new position.

The date and time are available from the Timing Control Unit for recording the data. This information is acquired once per scan. Battery backup power keeps the current time valid for three months.

The data analysis is performed by using the Arithmetic Processor, which saves on memory requirements and execution time. The calculation performed and sequence storage of data uses a 32-bit floating point format. Radian is used for the angle unit calculations, but degree unit is used for display and printout. The calculations performed are as follows: the angle is calculated from the voltage reading of the inclinometer Equation (1); chordal average density is calculated for every scan point by Equation (2); the count rate and chordal average density for each scan point are used to calculate the cross-sectional density for the complete scan, Equation (3).

Inclinometer angle calculation:

$$\theta = \sin^{-1} \left(\frac{V_o}{7.078} \right) \quad (1)$$

where

θ = traverse angle in radians

V_0 = Inclinator output voltage.

Chordal average density:

$$\rho_c(\theta) = \rho_f - (\rho_f - \rho_g) \frac{\ln \frac{I_f(\theta)}{I_g(\theta)}}{\ln \frac{I_f(\theta)}{I_g(\theta)}} \quad (2)$$

Cross-sectional average fluid density:

$$\bar{\rho} = \frac{\sum_{i=p_1}^{p_2} \left[\rho_c(\theta_i) 0.5 (D_o + D_s) (\cos \theta_i) x_f(\theta_i) \Delta\theta \right]}{\sum_{i=p_1}^{p_2} \left[0.5 (D_o + D_s) (\cos \theta_i) x_f(\theta_i) \Delta\theta \right]} \quad (3)$$

where

$I_f(\theta)$ = count rates for all water

$I_g(\theta)$ = count rates for all dry air

ρ_f = the density of the subcooled water giving rise to traverse count rates $I_f(\theta)$

- ρ_g = the air density yielding count rates $I_g(\theta)$
 ρ_c = the chordal average density determined from the two-phase fluid count rates $I(\theta)$
 D_o = plexiglass pipe segment outer diameter
 $\bar{\rho}$ = cross-sectional average fluid density
 D_s = twice the distance from source center to nearest outer surface of the plexiglass pipe segment
 θ = traverse angle in radians
 x_f = fluid chordal path length

$$= [D_i^2 - (D_o + D_s)^2 \sin^2 \theta]^{1/2}$$

 D_i = plexiglass pipe segment inner diameter
 P_1 = start position
 P_2 = end position.

As data are acquired during a scan, the information is stored into a 1K block of memory. The information stored are test heading, setup parameters, date/time, count rates, calculated density values, and constants used for calculation. When the scan is completed, and if the mass storage option is specified, the information is passed to the cassette for storage; otherwise the information stored in memory is lost. The data on the cassette tape are organized as 1K blocks, with each block representing one scan of the pipe. The first block on the tape is called the header block, and contains the information about where and what reference data to use,

and how many data blocks are stored on the tape. The software is written to allow a complete test series to be stored on one tape, even though the test might last several days. The cassette driver software (1K EPROM) is located on the Interface card, and controls all functions of the cassette unit. The TRANSFER\$DATA command allows the user to examine the header block, or transfer the contents of the tape to a host computer.

Error checks are performed throughout the complete operation of the system. During setup procedures, the user is asked to repeat any step containing an error. Operational errors that will not affect the results will be noted on the printer, and the program will continue on. An example of this is if the encoder and inclinometer readings do not agree. Some operational errors will cause the system to wait until action is taken to correct the situation (no cassette tape in place). Others will cause the system to stop all operations and return to the command loop (stepping motor controller failure). All errors will either be noted on the alpha-numeric display or on the printer.

7. CONCLUSION

The scanning densitometer has seen considerable improvement with application of the microprocessor, expanding the original system to meet testing requirements. The scanning hardware is completely automatic, performing self-test calibration and verification of scanning positions. Readouts and a printer have been added for monitoring the current status of the system. For increased versatility, five different modes of operation have been incorporated. This sophisticated operating system minimizes the operator's interaction with the hardware, allowing a semi-skilled person to use the system.

Data handling capabilities have been expanded by providing mathematical calculations and recording data on the printer in engineering units for immediate observation. Each data scan is documented by recording all specified parameters, including date and time; available options are quick

look plots and mass storage of essential data. Results have proven this system to be more reliable and accurate than the original densitometer. The principles used can be applied to increase the performance of a wide range of instrumentation systems in both nuclear and non-nuclear fields.

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