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NUCLEAR REACTOR CONTROL WITH STEPPING MOTOR ACTUATORS*

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ABSTRACT

A control rod actuator system capable of reproducing the position of rotary control rods to 0.01° has been developed for the Phoebus-2 Zepo critical assembly (a zero power neutronic mockup for the Rover reactor, Phoebus-2). The heart of the actuator is an electric stepping motor whose output shaft rotates 1.8° for each input electrical pulse. Each step is accurate to $\pm 5\%$, and the rotational error is non-cumulative. Steps of 0.01° are obtained by means of a 180:1 gear reduction, combined with a spring load on the output shaft to eliminate backlash. Control rod position information is obtained by simply counting algebraically the number of electrical pulses which step the motor. The safety philosophy is based on limiting the pulse rate, which limits the rate of increase of reactivity. In addition, a fail-safe scram system is provided in the form of an electrically-operated clutch, which decouples a control rod from its gear train and allows a spring to scram the rod. The system also includes a power level control loop which uses either one or two control rods as the control elements. The electronic controls for the stepping motors consist of highly reliable transistor circuits which operate in switching fashion; that is, the transistors are completely on or off.

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INTRODUCTION

The Phoebus-2 Zepo critical assembly (a zero power neutronic mockup of the Rover propulsion reactor, Phoebus-2) recently underwent a major modification. In April 1966 the reflector assembly was converted to the reflector configura-

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tion which will be used on the Phoebus-2 propulsion reactor. The reflector assembly contains the control rods in an annulus of beryllium which surrounds the core. Prior to the modification, the control rods were rectilinearly operated. A few of these were constructed to simulate rotary control rods so that measurements pertinent to rotary control rods could be made. The new reflector assembly contains 18 identical rotary rods, each having an operating span of 180° . Rotation of the rods toward or away from the core provides control of the reactor by decreasing or increasing the fraction of leakage neutrons reflected back into the core, thus controlling the reactivity. The rod position for minimum reactivity is defined as 0° and the maximum as 180° . An illustration of the Phoebus-2 Zepo critical assembly is shown in Fig. 1. The core is shown in the lowered position; for operations it is raised into the reflector with a hydraulically operated ram.

This paper describes the electric stepping motor actuator system developed for the Phoebus-2 Zepo critical assembly. The system features control rod settings to 0.01° , operating ease which minimizes the time and effort required to execute experiments, a safety philosophy based on limiting the rate of increase of reactivity, and a fail-safe scram.

A similar application of the stepping motor was reported by E. F. Grob and C. E. Cohn of the Argonne National Laboratory¹. They developed a stepping motor actuator for the Argonne Advanced Research Reactor critical experiment. Reliability, compactness, and simplicity were the prime considerations in their design.

In January 1966 Atomics International, a division of North American Aviation, Inc., successfully completed one year unattended operation of their FS-3 power system (identical to the SNAP-10 system)². The SNAP-10A is the power system which was launched in April 1965 and functioned successfully in orbit for 43 days³. The SNAP system uses stepping motor control rod actuators developed by Atomics International. These are capable of operating continuously for 10,000 hours in a high temperature, nuclear

environment, high vacuum for extended periods as demonstrated by the above two tests⁴. This dramatically illustrates the reliability potential of the electric stepping motor actuator, which is essential for nuclear reactor applications.

DESCRIPTION OF ACTUATORS

In order to provide versatility and safety, two types of actuator were developed. The two differ primarily in the maximum speed capabilities and angular resolution. The first type, called "control rod actuator", is used to accurately position 16 of the control rods in a deliberately slow fashion for safety reasons. Steps of 0.01° are produced and the rate is limited to $0.7^\circ/\text{sec}$. The second type, called "period rod actuator", is used to make rapid changes in reactivity as required during fast period measurements. The two period rod actuators are geared to produce 0.2° steps and are limited to $45^\circ/\text{sec}$. They are also the actuators used in the power control loop discussed later in the paper.

A cross-sectional view of a control rod actuator is shown in Fig. 2. The heart of the actuator is an electric stepping motor* which is constructed to produce 200 steps per revolution or $1.8^\circ \pm 5\%$ per step; the error is non-cumulative. The stepping motor drives into a 180:1 harmonic drive gear reduction which reduces the motor steps of $1.8^\circ/\text{step}$ to $0.01^\circ/\text{step}^{**}$.

This gear reduction is a simple inexpensive method of obtaining high gear reductions using a minimum of space. The three basic components of the harmonic drive are shown in Fig. 3. The circular spline is a rigid fixed internal gear which has 360 teeth. Mating with the circular spline is a flexible external gear called "flex spline" which has two teeth less than the circular spline. The wave generator is an elliptical ball bearing

* A bifilar "SLO-SYN" model SS250-1004 is used in the control rod actuators, model SS400-1006 in the period rod actuators (Superior Electric Co., 383 Middle Street, Bristol, Connecticut).

** Made by the Harmonic Drive Division, United Shoe Machinery, Beverly, Massachusetts.

which fits inside the flex spline. It produces gear contact between the flex spline and circular spline at two points 180° apart. Rotation of the wave generator walks the flex spline around in the opposite direction of rotation to the wave generator input. The gear reduction can be calculated by the following formula and for our case the reduction is 180:1.

$$N = \frac{\text{number of teeth on circular spline} - \text{number of teeth on flex spline}}{\text{number of teeth on circular spline}}$$

Also shown in Fig. 3 is the 9:1 planetary gear reducer used in the period rod actuators. Its output reduces the stepping motor rotation to 0.2°/step.

The output of the gear reducer is coupled to the actuator output shaft through an electrically energized clutch. Connected to the output shaft is a clock spring wound to 40 inch pounds at 0° and approximately 44 inch pounds at 90°. The spring serves to remove the backlash from the gear trains. The spring and electric clutch provide the fail-safe scram feature. When the clutch is de-energized, the spring rotates the control rod to the 0° position. Plots of control rod position vs time for a scram shutdown from the 90° and 180° rod positions are shown in Fig. 4. The de-energizing time for the clutch introduces a 20 millisecond delay following initiation of a scram.

If a control rod is scrambled from the 180° position, it reaches a maximum velocity of approximately 900°/sec. The inertia load (0.6 lb-in-sec²) rotating at this velocity has approximately 74 inch pounds of kinetic energy. This energy is absorbed during the last 15° of travel by a hydraulic dashpot. The dashpot consists of a piston sealed in an oil filled barrel. The barrel bore is 1.000 inches inside diameter and the piston has 0.005 inches diametral clearance. The slowdown arm on the actuator output shaft hits the piston and forces it down the barrel. The kinetic energy is dissipated in the oil as it is forced past the piston. A small spring inside the barrel resets the piston when the actuator is rotated away from 0°.

Limit switches are provided for indication at the 0° and 180° rod positions. A potentiometer geared to the output shaft provides a reliable but

coarse control rods position indication. The voltage from the potentiometer operates a meter on each control module in the control room.

An exploded view of a control rod actuator is shown in Fig. 5. The assembled actuator is shown in Fig. 6. The period rod actuator looks identical except the stepping motor is slightly longer. The bottom view in Fig. 6 shows the slowdown arm attached to the output shaft, the hydraulic dashpot, the position potentiometer, the linear variable differential transformer, and the limit switches. The 180° stop is shown near the bottom. The actuator is rotated to the 0° position.

CONTROL CONSOLE

The Phoebus-2 Zepo control console was designed to provide versatility in positioning the control rods with individual as well as group positioning capabilities. Redundant rod position information is provided for each control rod, one being an accurate digital reading and the other an analog meter reading. A picture of the control console is shown in Fig. 7. It is housed in two standard 19-inch racks. The main operating console is located on the right, while the left rack houses the 16 control modules which contain the actuator control circuits. One is provided for each "control rod actuator". The control module is shown in Fig. 8. The modular construction enables quick troubleshooting by complete replacement of a malfunctioning module. In addition, the transistor circuits are fabricated on printed circuit cards which simplifies troubleshooting by card replacement. Some of the printed circuit cards are shown in Fig. 9.

The bottom chassis of the main operating console contains the pulse generators used for positioning the control rods. The desired pulse rate is produced by rotating the control handles. (CW rotates the rods "out" to 180°, and CCW rotates them "in" to 0°). The handles, which are spring loaded, return to the zero-rate position when released. Also included with these three variable-rate pulse generators is a keyed audio oscillator which gives the operator an audio indication of the pulse rate. The pulse generator on the right is called the "common pulse generator" and is used for positioning

groups of control rods. Its rate is limited to 70 pps in order to limit the rod rates to $0.7^\circ/\text{sec}$ if all 18 control rods are being operated together. The other two pulse generators are used to position the two period rods. Their rate is normally limited to 50 pps ($10^\circ/\text{sec}$ for the period rods since they step $0.2^\circ/\text{pulse}$) but can be increased to 225 pps ($45^\circ/\text{sec}$) by pushing the button above the pulse generator control handle.

A fixed-rate (150 pps) pulse generator is provided for individual operation of the 16 control rod actuators. Each control module contains a "single-common" switch used for selecting the pulse source. If the switch is in the "common" position then the common pulse generator will position that particular control rod or rods. If the switch is in "single", then that rod is controlled from the push buttons on the control module (see Fig. 8). The two push buttons on the bottom left position the control rod from the fixed 150 pps generator. The two push buttons on the right are single-shot pulse generators which are used to step the control rod one step at a time, providing vernier adjustment for the control rod.

ACTUATOR CONTROL CIRCUITS

The control circuits for each actuator are housed in the control modules. The two period rod control modules are located above the period rod electronic counters as shown in Fig. 7. As mentioned before, the 16 control modules for the control rod actuators are grouped together in the left console. A block diagram of the actuator control circuit is shown in Fig. 10. The major components contained in the control modules are stepping motor pulse logic circuits, zero reference amplifier circuit, rod position meter, stepping motor pulse counter (not included in period rod control modules), single-common toggle switch, and push buttons for positioning the control rod while in the single position.

The stepping motor is basically a synchronous induction motor with a two-phase stator winding and a permanent magnet rotor⁵. Stepping of the motor is achieved by exciting the two-phase stator windings with d-c current

and alternately reversing current in the windings. One step occurs when the current of one stator winding is reversed, which is equivalent to completing 1/4 cycle of a sine wave if the motor is operating in two-phase synchronous fashion from a sinusoidal supply.

The electronic circuits employed for switching the d-c current are simplified if bifilar field windings are used. Instead of reversing the current in a winding, current of the same polarity is switched to a winding which is identical except for being wound in the opposite direction. In Fig. 11, the bifilar windings of field A are labeled 1 and 3; field B, 4 and 5. During static conditions, one winding of each field is energized. Stepping occurs when the current of one winding is turned off and the other turned on. The switching sequence required to step the motor CW and CCW is shown in Table 1.

TABLE 1
Switching Sequence for Stepping Motor

Step	Energized Windings			
	CW Rotation		CCW Rotation	
1	1	4	1	4
2	3	4	1	5
3	3	5	3	5
4	1	5	3	4
5	1	4	1	4

The logic circuit used to produce the switching sequence of Table 1 is shown in Fig. 11. Each input pulse to the single-shots results in changing the state of one flip-flop determined by the NAND gate logic. The output of each flip-flop controls the switching for one field (FF1 for field A, FF2 for field B); therefore, only one of the bifilar windings of each field will be energized at a time. The flip-flop outputs operate the power driver which does the heavy field current switching (0.65 amps/windings for model SS250-1004 motor, 0.85 amps/winding for model

SS400-1006 motor). The power driver circuit is shown in Fig. 12.

The 16 stepping motors for the control rod actuators are all powered from one voltage-regulated power supply. The two period rods each have individual current-regulated power supplies (1.7 ampere regulation, 0.85 amps/winding) which are used to provide greater torques at their higher stepping rates, 225 pps. If the stepping motors are powered from a voltage-regulated supply their field current decreases with increasing stepping rate, thus reducing the output torque. However, if a current-regulated supply is used, the field current can be maintained at the maximum rating resulting in maximum torque for all stepping rates. For our application, the current was maintained at maximum rating within the limits of the current-regulated supply used. This was sufficient to allow reversing directions at 260 steps/second without skipping steps. The maximum stepping rate of the same motor and load configuration (period rod actuator with 9:1 gear reduction and control rod load inertia of 0.6 lb-in-sec^2) operating from a voltage regulated supply (21.2 volts DC) was 180 pps.

PULSE COUNTERS

Control rod position information is obtained by simply counting algebraically the number of electrical pulses which step the motors. Two types of pulse counters are used: an electronic bi-directional counter* and a stepping motor pulse counter. Three electronic bi-directional counters are used to count the pulses from the three variable pulse generators. They are located directly above each pulse generator control handle (see Fig. 7). The electronic counter for the common pulse generator has five digits, the least significant figure being 0.01° . It is used to determine the position of the control rods operated as a group from the common pulse generator. The other two electronic counters are used to determine the positions of the two period rods. Incorporated with each of these two

* Made by Anadex Instruments, Inc., Van Nuys, California.

counters is a pulse-doubling circuit which causes the counter to count twice for each pulse to the actuator. This is required in order to have direct read-out in degrees since the period rod actuator steps $0.2^\circ/\text{pulse}$. These counters have only four digits, which is sufficient accuracy for the period rod positions.

In addition to pulse counting, the electronic counters provide an output signal when the counter reaches a preset level. This signal is used to stop the pulses when the preset level is reached. This feature is useful for quickly reproducing previous rod settings and is used in making fast period measurements.

The second type of pulse counter is a stepping motor pulse counter which is capable of counting in either direction at rates to 275 pps. Figure 13 shows the stepping motor pulse counter. It consists of a small stepping motor whose output advances $45^\circ/\text{step}$ and a 12.5:1 gear train. This gives an input motion of $3.6^\circ/\text{step}$ to the mechanical digital counter. The unit wheel of the digital counter is divided into 100 divisions, thus providing a 0.01° indication for each step. The control module for each control rod actuator contains one of these stepping motor counters. They utilize the same pulse logic circuit which is used for the actuator stepping motors. The two flip-flops simply drive two sets of power drivers in parallel: one for the actuator stepping motor and one for the stepping motor counter.

The stepping motor pulse counters are automatically reset to the zero position upon shutdown by allowing the pulses from the 150 pps generator to step the counter to the zero position. The counter is stopped at the zero position by a mechanical stop in the counter. A small slip clutch allows the motor to slip. The pulses are turned off by sensing the zero position of the digital counter with a photodiode. A small hole was drilled through the digital wheels and a light bulb shines through the hole when all wheels are at the zero position. The photodiode operates a relay to stop the pulses.

The accuracy of the angular location of any rod depends on the accuracy of its zero position as well as the number of input pulses to it. The zero count reference for the two period rods is simply the 0° stop.

The situation is more complicated for the 16 control rod actuators. They utilize a linear variable differential transformer (LVDT) for a zero reference. This was necessary because the flex spline member of the harmonic drive gear reducer acts like a flexible coupling between the motor and the gear reducer output. Before the harmonic drive will transmit any output torque, the input torque must balance the output spring torque. This is called windup and results in having to step the motor several steps before the output actually begins to move. The number of windup steps is not consistent with each startup or from one actuator to another; therefore, the 0° stop could not be used as a zero reference for starting the pulse counter. The LVDT was introduced to eliminate this difficulty. It is located beside the 0° limit switch (see Fig. 6). The LVDT slug is spring loaded so it pushes against the slowdown arm when the arm is near the 0° stop. The LVDT output is zero when the slowdown is at the 0° stop and increases as the arm rotates away from the stop. The LVDT output is detected with a level sensing amplifier which is set to allow pulse counting to begin after the actuator has moved 0.05° from the mechanical 0° . When groups of control rods are being operated from the common pulse generator, a logic circuit holds rods at the LVDT zero reference position until all rods have reached this zero reference. At this time, all rods start moving out, and the common pulse electronic counter and the individual step motor counters begin counting. Thus obtaining the zero reference is done automatically, which saves considerable time for the operators. The output of each LVDT can be selected for observation on the zero reference chassis located at the top right of the main control console.

POWER CONTROL LOOP

A power control loop was included in the Phoebus Zepo control system in order to simplify experiments such as core flux distribution measurements.

Using a power control loop, a given power level can be achieved quickly and held constant during the flux mapping process.

A block diagram of the Phoebus Zepo power control loop is shown in Fig. 14. The power controller consists of a summer amplifier, a divider circuit, and a voltage-to-pulse converter. The output of the controller goes to either one or both of the period rod actuators which are the only control rods used in the power loop. The power control chassis is directly above the two period rod control modules as shown in Fig. 7. The control panel includes a power demand potentiometer, a power control ON/OFF switch, and meters for demanded power and measured power. The amplifiers are Philbrick model PP45 transistorized operational amplifiers. They are mounted on a printed circuit card, shown in the center of the top row of cards in Fig. 9.

The purpose of the power controller is to algebraically sum the power demand and power measured signals, amplify their difference (power error), and convert the power error signal to pulses which step the control rods "in" or "out" according to the sign of the power error signal. An amplification of 200 was required for stiff loop operation using one control rod. The amplified power error signal is converted to pulses by the pulse generator shown in Fig. 15. It produces pulses whose rate is proportional to the magnitude of the power error signal. The input circuit of the pulse generator has a deadband of about 0.4 volts and accepts only positive inputs. This feature is utilized for sense detection. An inverter amplifier is used to provide positive voltage when the power error signal is negative. The power error signal and the inverter output are fed into two separate pulse generators. One is used to step the control rods in the "out" direction, the other to step them in the "in" direction, depending on which has a positive input signal.

The transfer function from reactivity to power in a nuclear reactor includes a term in the numerator which is proportional to power. Therefore,

a control loop which includes a reactor will have an open loop gain which varies with the power level. A power control loop with level dependency results in a drastic change of performance if operating over a wide power range. However, this problem can be eliminated if the loop gain is divided by the power level, thus removing the level dependency. In the Phoebus Zepo power control loop, the power demand signal is generated from a potentiometer on the control panel; therefore, a circuit which divides by power demand is easily implemented. Figure 16 shows the circuit diagram of the divider. The power demand potentiometer is mechanically ganged to a second potentiometer which is used as the input resistance (in series with a 1K resistor) of the operational amplifier, and is equal to the feedback resistor (100K). The potentiometer is connected so that 100% power demand results in a gain of one, and 0% power demand results in a gain of 100.

This amount of gain correction is more than sufficient for the Phoebus Zepo control system because the nuclear instrumentation automatically changes range each decade of power. Therefore, the divider need only correct for power changes which vary a factor of 10. Dividing by power demand rather than measured power results in the correct steady-state loop gain but will not give correct gain during transients. However, the effect of the loop performance is negligible.

SUMMARY

The electric stepping motor characteristics are favorable for driving nuclear reactor control rod actuators when precision positioning capabilities and high reliability are desirable. The stepping motor output moves in discrete steps from electrical input pulses, which allows utilization of digital computer circuitry for control and logic decisions. Accurate control rod position information is obtained by simply counting algebraically the number of electrical pulses which step the motor. Controlling the rate at which the control rods rotate is easily accomplished by controlling the pulse rate to the stepping motors, thus providing a reliable reactivity rate control.

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FIGURE 1, PHOEBUS-2 ZEPO CRITICAL ASSEMBLY

FIGURE 2, STEPPING MOTOR ACTUATOR

FIGURE 3, ACTUATOR GEAR REDUCERS

FIGURE 4, SCRAM RESPONSE OF STEPPING MOTOR ACTUATOR

FIGURE 5, ACTUATOR COMPONENTS

FIGURE 6, ZEPO CONTROL ROD ACTUATOR

FIGURE 7, CONTROL CONSOLE

FIGURE 8, ACTUATOR CONTROL MODULE

FIGURE 9, ACTUATOR CONTROL CIRCUIT CARDS

FIGURE 10, ACTUATOR CONTROL CIRCUIT

FIGURE II, STEPPING MOTOR PULSE LOGIC CIRCUIT

FIGURE 12, STEPPING MOTOR POWER DRIVER

FIGURE 13, STEPPING MOTOR PULSE COUNTER

FIGURE 14, POWER CONTROL LOOP

FIGURE 15, PULSE GENERATOR

FIGURE 16, POWER CONTROLLER DIVIDER CIRCUIT