THE PENNSYLVANIA STATE UNIVERSITY

COLLEGE OF ENGINEERING

SYSTEMS AND CONTROLS LABORATORY

RESEARCH REPORT NO. 2 UNIVERSITY PARK, PA OCTOBER, 1965

THE SYSTEMS AND CONTROLS LABORATORY

The Systems and Controls Laboratory was started in 1964 to encourage graduate research and development on engineering systems, with emphasis on improving the understanding of basic elements and devices and bridging the gap between theory and practice. The experimental equipment and facilities of this laboratory have been provided for carrying out experimental investigations on devices and systems involving many of the different engineering disciplines. Several graduate assistants are now working on projects and thesis topics of vital interest to engineers concerned with the advanced design and development of new engineering systems.

Much of the work involves mathematical and computer modeling and analysis as well as the experimental investigation of breadboard and prototype systems or devices. A major goal of this work is to accomplish a useful synthesis of analytical and experimental methods in research and development of advanced engineering systems for effective use by engineers and scientists working on future aerospace systems.

Financial support for this program is derived from the University, The National Aeronautics and Space Administration, The United Aircraft Corporation, The Bendix Corporation, and the Ordnance Research Lab. A major share of the projects in the Systems and Controls Laboratory are carried out by Graduate Assistants and junior staff members under the supervision of Dr. J.L. Shearer, Rockwell Professor of Engineering, and other members of the graduate faculty.

CONTENTS

SIGNAL NOISE IN FLUID AMPLIFIERS

J. C. Tamulis, IBM Fellow

In some applications, working pure fluid amplifiers have been hindered by the presence of noise. The term "noise" is used here to refer to that part of a signal which is present at the output ports and is considered undesirable. This noise will be referred to as signal noise in order to delineate it from the audible noise that is produced by the amplifier and is radiated into the surrounding atmosphere.

Project Objectives

The objectives of the project are:

(1) To determine and describe the basic mechanisms by which signal noise is generated and transmitted.

(2) To formulate the results where possible into a form that will be directly applicable to the design of fluid amplifiers. The scope of this representation encompasses forms such as equivalent circuits, normalized curves and computer programs.

Research Plan

As described in Semi-Annual Report No. 1 (April 1965), the approach to the problem of signal noise is broken into two major sections, one experimental and one theoretical. What follows will be an extension of the discussion presented in the report referred to above.

I. Experimental

A. Large Scale Fluid Amplifier

The large scale fluid amplifier is being instrumented as shown schematically in Fig. 1.

All pressure transducers are of the strain gage type, and all five are supplied with a common D.C. voltage. All circuitry and associated electronic gear have been completely shielded to minimize electrical noise. A photograph of the apparatus is shown in Fig. 2. Within the enclosing aluminum housing are arranged, as shown in Fig. 3, four differential amplifiers for driving recording equipment, two differential amplifiers for necessary isolation, and one summing operational amplifier. The isolation and summing circuitry is included to obtain a differential signal from pickups such as left and right noise transducers. The nature of the problem requires these transducers (and others) to be connected to the fluid amplifier with the shortest possible coupling.

B. Free Jet Apparatus

The free jet apparatus mentioned in the previous report has been built and installed as shown in Fig.4.

The jet has been designed so that its aspect ratio (height-to-width ratio of nozzle) can be varied from 1:1 to 4:1. Three pressure transducers monitor the supply and receiver pressures. The transducers are similar to those used on the large scale fluid amplifier and are powered from the same D.C. supply voltage.

Two of the transducers are used for measurement of pressures at the end of the interchangeable receiver ducts of different lengths. One transducer monitors the jet supply pressure. An overhead railing provides ease in positioning the receiver ducts and positioning the hot wire anemometer probes.

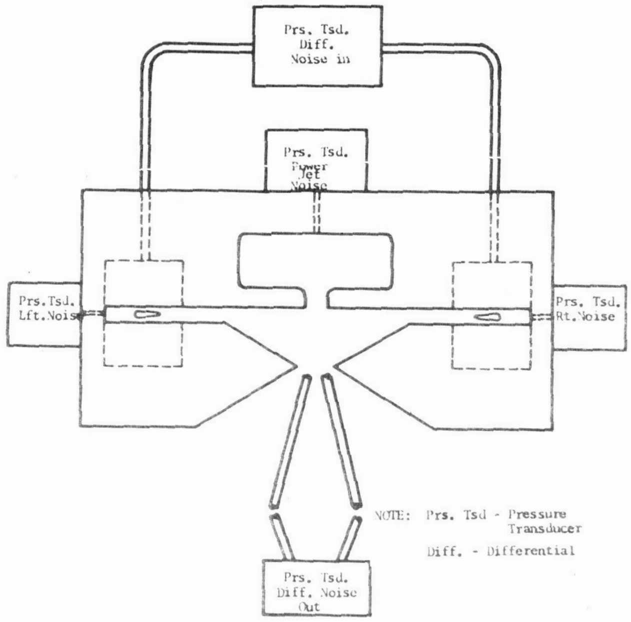

Fig. 1 Schematic Diagram of Large Scale Fluid Amplifier with Transducers

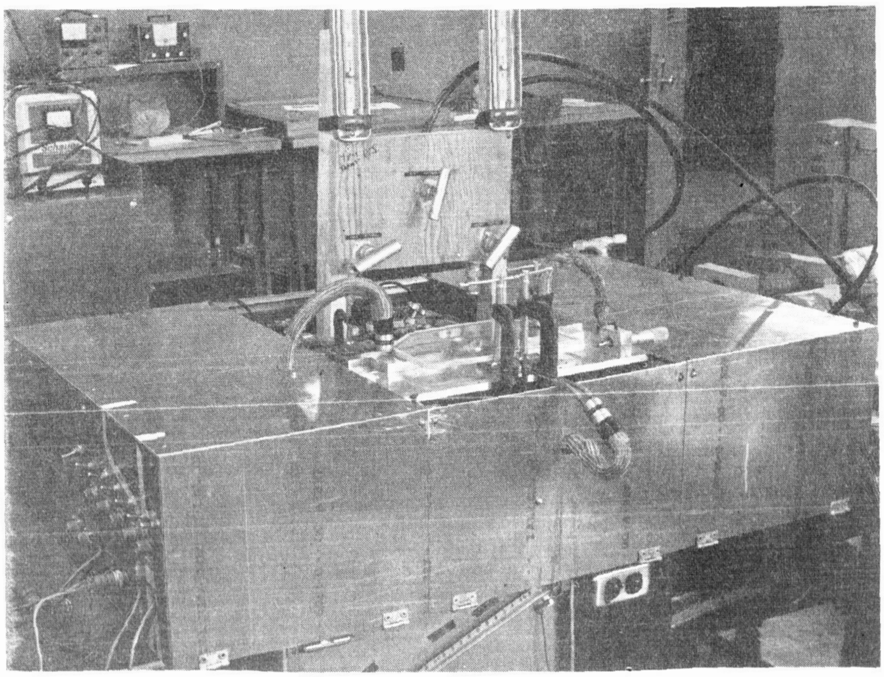

Fig. 2 Photograph of Exterior of Instrumented Large Scale Fluid Amplifier Model

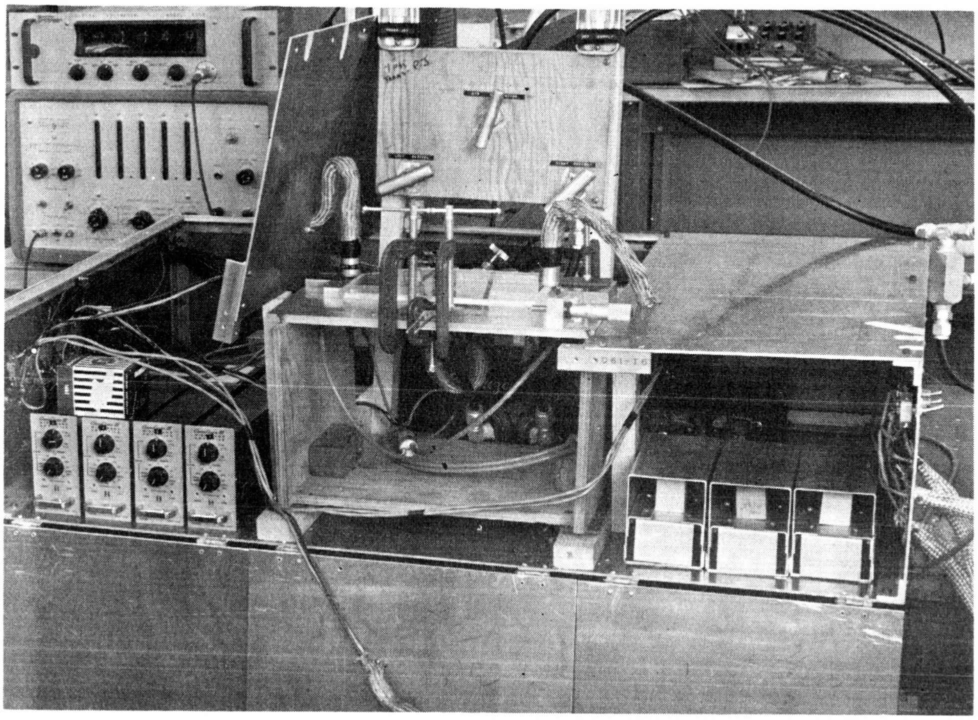

Fig. 3 Photograph of Interior of Housing
Showing Electronic Amplifiers

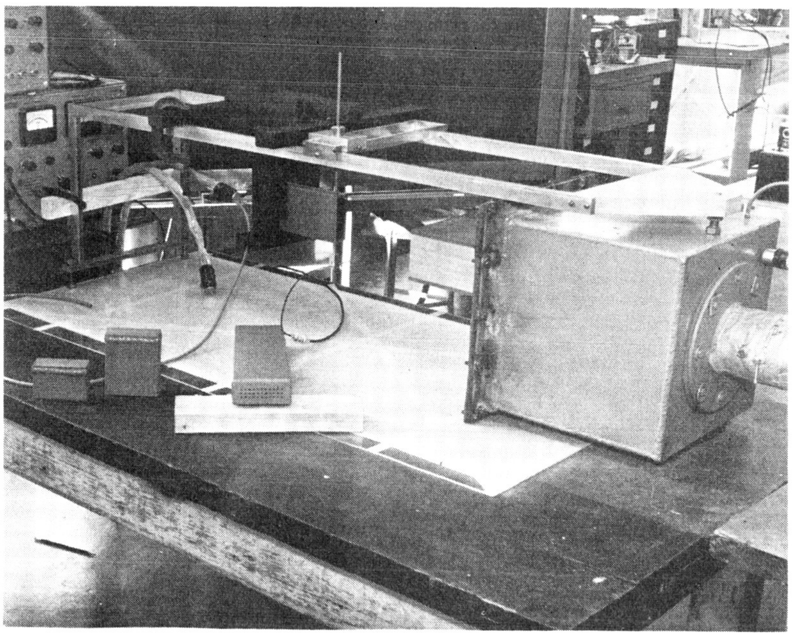

Fig. 4 Photograph of Experimental Apparatus for Studies
of Free Jets and Receiver Ducts of Various Lengths

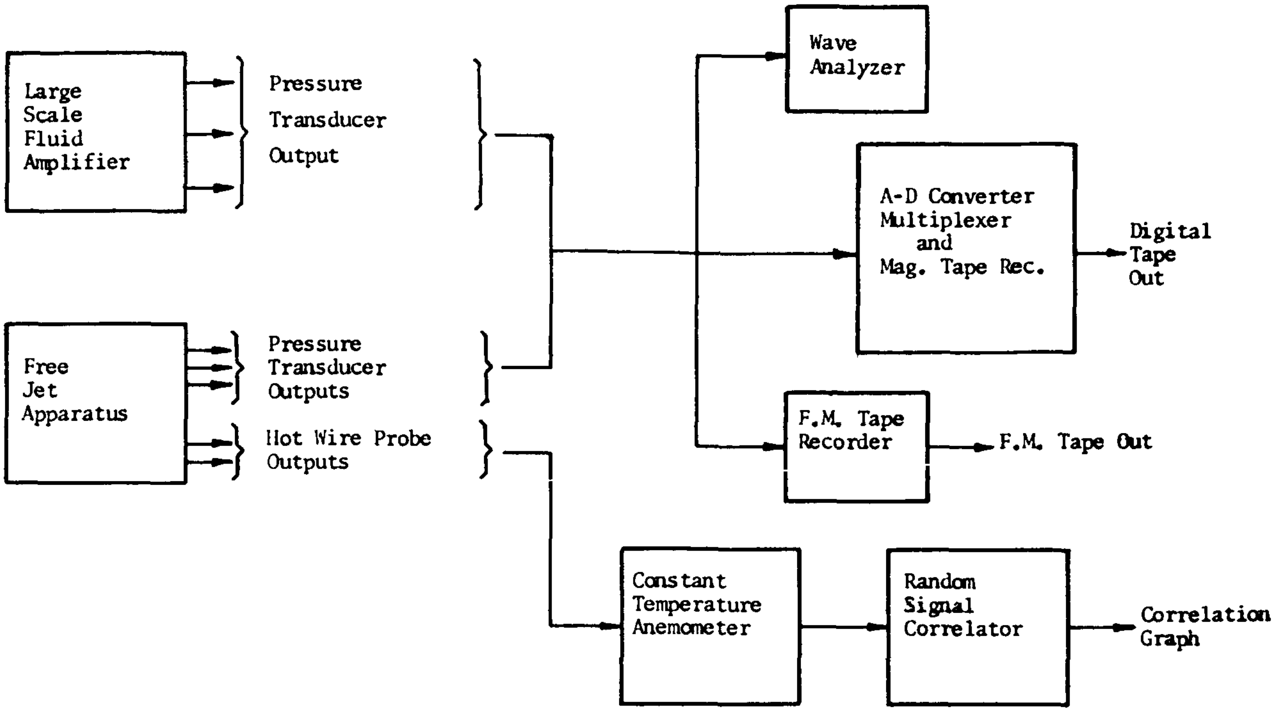

Fig. 5 Comprehensive Block Diagram Showing Various Measuring and Recording Devices

C. Associated Measuring and Recording Devices

Shown in Fig. 5 is a comprehensive block diagram showing all of the significant measuring and recording equipment which is planned for use on this project. Presently available in the Systems and Controls Laboratory are:

1. Two constant temperature anemometers (DISA)
2. One random signal correlator (DISA)
3. One 2% wave analyzer (B & K)

Planned for the near future are:

1. F.M. Tape recorder (Honeywell)
2. A/D converter, multiplexer, and magnetic tape recorder (SEL)

The binary-coded decimal readout will be on a seven track gapless magnetic tape, five characters per word, with a packing density of eight hundred characters per inch. A special computer program is being developed to allow the gapless tape to be processed by an available IBM 7074 computer. Arrangements have been made through the IBM Corp. to have the F.M. tapes digitized and gapped in Owego, N.Y.

II. Analytical and Theoretical Considerations

The present study is being limited to proportional pure fluid pressure amplifiers. The initial phase of experimentation will be concerned with attempting to identify an internal noise source or sources within the amplifier. To gain insight into internally generated noise, the free jet apparatus will be studied. As outlined in the previous report, the receiver duct will be viewed as a wave guide with turbulent conditions at one boundary. Pressure measurements at the far end of the duct will be made to try and detect the presence of spatial pressure variations at that end. In addition, the A/D converter with digital tape readout will be used to obtain information with respect to the power spectrum of the noise. The wave analyzer will be used to determine the effective upper frequency limit of the noise and the F.M. tape recorder will be introduced into the experimentation for time expansion as needed. The A/D converter is to convert up to twelve thousand words/sec using five characters per word. When multiplexing is introduced, the higher frequency noise may exceed a safe sampling rate criteria. Time expansion will then be used. Future work on much smaller devices and/or work at higher Reynolds numbers is also expected to increase the upper frequency limit.

Information obtained from the power spectrum and measurement made on the jet at the duct entrance with the anemometer equipment will then be used in an effort to obtain a basic noise generator model together with its transmission characteristics (1,2...6)* This basic model will then be expanded in order to relate it to actual fluid amplifier characteristics such as geometry and power jet velocity. Also, work will be done to investigate the inter-related effects of noise in the receiver ports, signal amplitude and power jet turbulence (7,8,9).

This work is being supported partly by a fellowship from the IBM Corp. and partly by NASA Grant NGR 39-009-023.

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* Numbers in parentheses denote references at end

PNEUMATIC STEPPING MOTOR

R. P. Martin, Research Assistant

Initial development tests of a prototype pneumatic stepping motor (PSM) designed and fabricated at the Systems and Controls Laboratory have been conducted. These tests have demonstrated that the fluid stepping motor is one new type of component which should be considered and developed for future use in advanced fluid control systems. These tests have furnished valuable information about a particular concept and design, and they have indicated important factors which will affect the design of other fluid stepping motors as well.

The prototype operates by converting input pressure pulses to oscillating mechanical movement. The oscillating motion is then converted to output steps. The coding of the input signal pulses determines the direction of the oscillation which in turn controls the output step direction. The PSM operates with the signal form shown in Figs. 6 and 7. The motor is not sensitive to the exact shape of the pressure pulse, but maximum input energy is supplied by a square wave, so pulses most closely approaching this ideal will permit development of the highest output power.

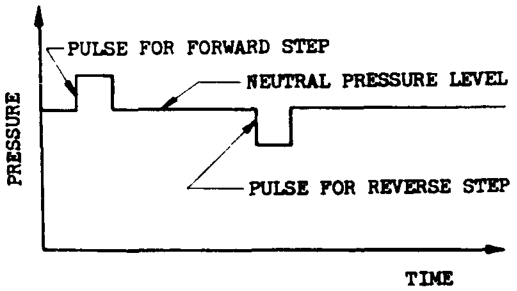

Fig. 6 Coded Single Pulse Signal Form

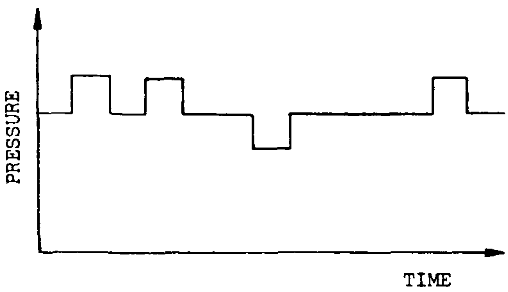

Fig. 7 Coded Single Pulse Signal Train

Two forward pulses at maximum rate followed by single reverse and forward pulses with different delay intervals between pulses.

The prototype PSM built and tested is partially shown in Figs. 8, 9, and 10. The air spring air bag (shown on the left in Fig. 8) is charged so that the swing plate is centered as shown when the neutral level pressure is applied to the signal port. Application of each forward pressure pulse causes the swing plate to move to the left and then return to the centered position. The motion of the swing plate and the attached pawl-carrier causes the right pawl (shown in Fig. 10) to engage a forward ratchet wheel tooth, while the left pawl is lifted clear. Then the detent is overcome and an output step is made. The detent controls the step size and uniformity. The worm shaft drives the output shaft through a worm and gear (not shown). The worm and gear are employed to provide reduced output speed and to prevent load torque from overcoming the detent.

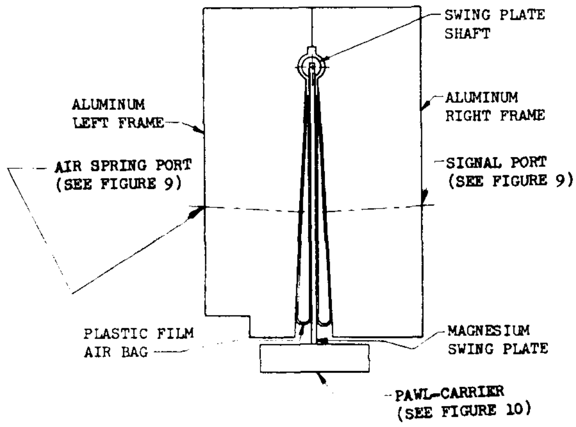

Fig. 8 Prototype PSM Design Configuration

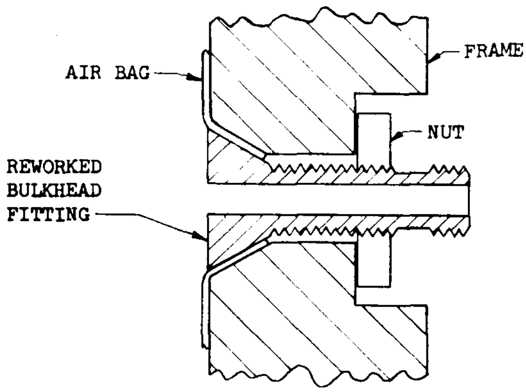

Fig. 9 Air Bag Installation

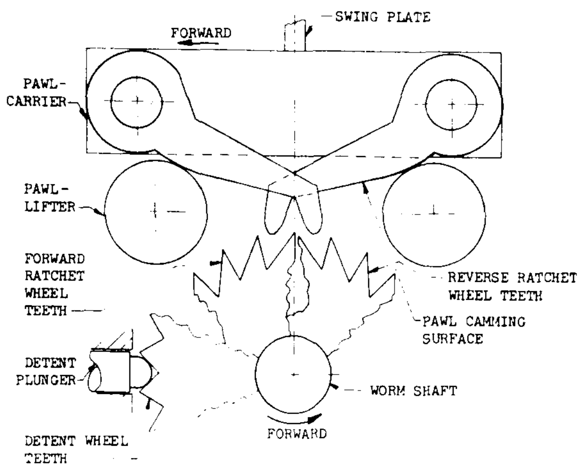

Fig. 10 Pulse and Ratchet Mechanism

Operation for a reverse step is similar except that each reverse input pulse moves the swing plate to the right, thus causing the left pawl to drive the worm shaft in the opposite (reverse) direction.

Tests were conducted with the pneumatic pulse generator shown in Figs. 11 and 12. As the signal wheel is rotated, the distribution manifold is connected either to one of the applied pressure ports or to the exhaust port. Holes in the signal wheel are arranged to sequence the pressure applied so that the desired input signal pressure pulses are transmitted to the PSM.

The operating and performance information, conclusions, and suggestions which follow are the most important results of the design and development test program conducted with the prototype PSM. The first group of statements pertains to fluid stepping motors in general.

1. Fluid stepping motors are feasible and are promising for future development as components in both aerospace and industrial fluid control systems.

2. Although additional work must be accomplished to realize the full potential of fluid stepping motors as components, the ultimate influence of fluid stepping motors on the design of fluid control systems will be highly dependent on the success achieved in generating and transmitting suitable, highly uniform pulse-type signals.

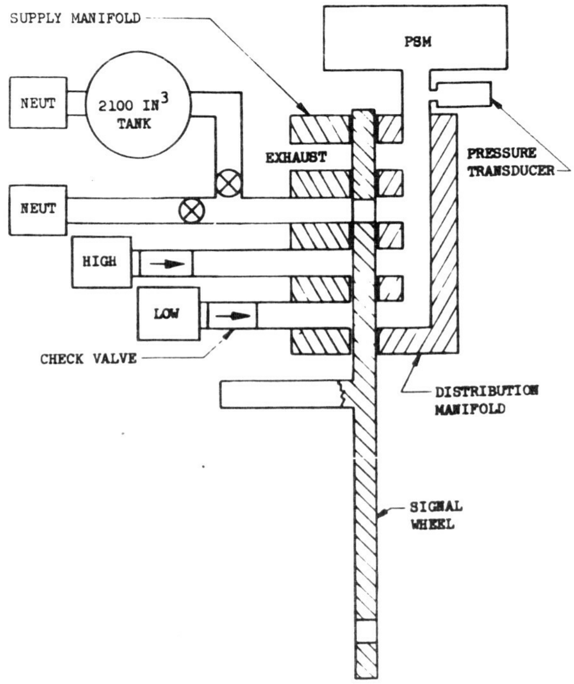

Fig. 11 Pulse Generator Schematic

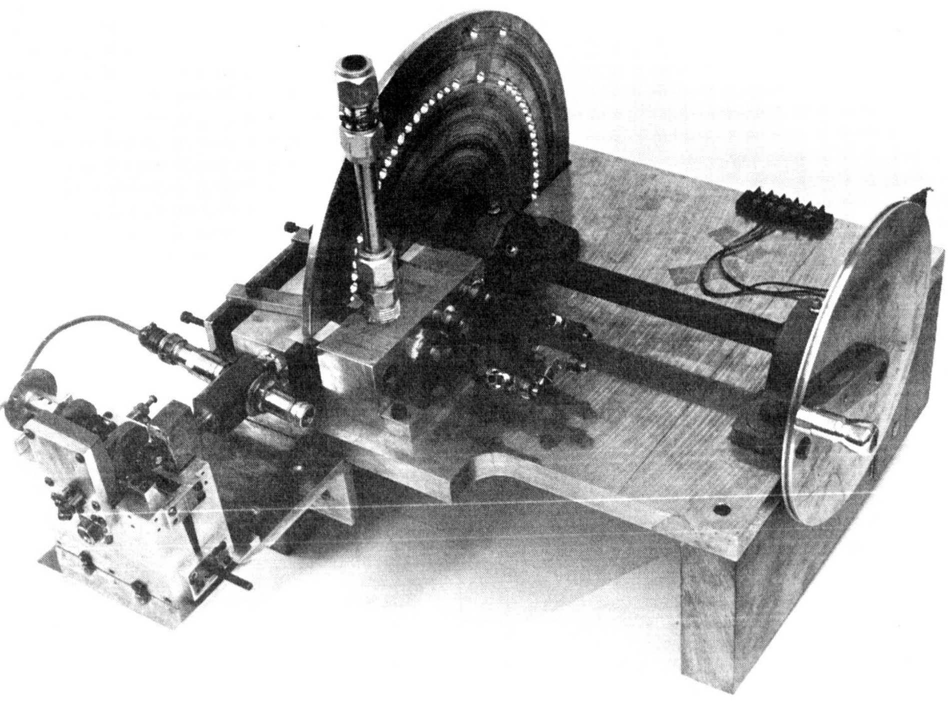

Fig. 12 Pulse Generator and PSM

3. Fluid stepping motors employing separate signal, power, and fluid exhaust connections instead of the combined power-signal input employed for the PSM should be considered for future development especially for less restrictive applications.

The next group of statements refers primarily to the prototype PSM.

1. The basic design concept and approach proved to be sound. Future refinements can be expected to produce worthwhile improvements.

2. The use of flexible air bags instead of a spring and bellows for accomplishing the conversion of pressure pulses to movement of the pawl-carrier is a key to the success of the design. Only moderate success was achieved with the relatively crude manually-heat-sealed plastic film used, but development of a more sophisticated single piece air bag design permitting reliable use at pressures up to 100 psig would result in realization of the many advantages of this basic approach. Success with the prototype design also suggests investigation of a different type of high force, short-stroke fluid motor analogous to the so-called electrical torque motor used in servovalves.

3. Special care must be taken to achieve suitable positioning of the pivot axes of the swing plate and pawls and the centerlines of the worm shaft and the pawl lifters in order to obtain satisfactory operation of this design, especially with the pawl camming-surface shape used in this model. The shape employed here was selected with emphasis on ease of fabrication. Computer studies should be used to analyze and optimize dynamics of the basic reversible double ratchet-pawl design used for the prototype to provide a basis for determining and controlling the critical dimensions and shapes. Quality control techniques to assure establishment and maintenance of proper adjustments are also essential.

4. Conceptually and practically, one of the least attractive features of the prototype design is the detent mechanism, but it presently seems necessary in order to control step size. The detent plunger was the only part of the prototype which exhibited a highly undesirable wear rate, but the duration of testing was limited so that no assurance of satisfactory life exists for other parts. Special attention in work on future PSMs should concentrate on eliminating or improving the detent mechanism. Incorporation of a positive stop device in addition to the detent to prevent overshoot (i.e. making more than one step for each step signalled) may be required. This would eliminate the undesirable sensitivity to detent adjustment exhibited by the prototype which required resetting to match each change of signal input or load inertia and torque in order to achieve the best performance. If use of variable speed input pulses is desired, reduction of sensitivity of operation to detent adjustment must be achieved. Perhaps a more positive continuous drive method could be devised to convert pawl-carrier motion to output steps.

5. Use of the worm and gear was not entirely satisfactory for the prototype, because under high load torques the detent did not fully control step size uniformly. Careful adjustment of the gears to avoid binding minimized this difficulty. Reduced unit efficiency and backlash are two other undesirable factors resulting from the use of the output gearing. The high output torque and small size typical of the prototype would not always be desirable. For convenience, most of the tests were conducted with the gearing removed and with an inertia load attached directly to the worm shaft. This approach would be practical in some applications.

6. Materials and parts used for the prototype were selected with emphasis on availability and ease of fabrication. Significant improvements in size, weight, and performance can be achieved by selecting materials, parts, and lubrication for a specific application.

7. The outside dimensions of the prototype unit are 5.5 x 5.5 x 3.5 inches. Weight is 3.8 pounds.

8. Performance achieved to date with the restrictions imposed by the present air bags and the pulse generator is as follows:

Maximum pulse pressure - 70 psig

Average useful air bag neutral pressure employed - 12 psig

Maximum air bag area - 8.2 in.^{2}

Torque - 10 lb-in.

Stepping rate - 35 steps/sec

Response to a single input pressure pulse--responds to a single pulse of 5 millisecond duration.

This work is described in fuller detail in an M.S. Thesis, written by the author (10). The work has been supported by NASA Grant NGR 39-009-023.

HYDRAULIC STEPPING MOTOR

R. W. Schiller, Instructor

This work is a continuation of the project started by Mr. David L. Ruppert, who completed his Master's Thesis in June. Subsequent investigations have been concerned with analog computer studies of changes in geometry, mass and power requirements. In addition, a function generating circuit capable of producing sine and cosine space functions has been developed with Dr. R.S. Raizada. A digital program was used to check analog results.

The basic schematic diagram of the Hydraulic Stepping Motor is shown in Fig. 13. The system is actuated by doublet pulses of hydraulic pressure, which may be sinusoidal. This pressure may be applied by a single doublet of pulses or a series of doublets depending on the number of desired cycles. Cycling of the system in both directions is possible and desirable.

Original design studies were concerned with a two horsepower unit and a cycle time of 0.01 sec, (11), (12). The pin radius was fixed at four inches and the cam groove profile was parabolic with an amplitude of 0.5 inches. These studies concluded that such a unit was feasible for practical applications in indexing. Subsequent studies have been concerned with the development of a one-half horsepower unit. The cycle time of 0.01 sec. has been retained and a sinusoidal shape has been used for the input pressure pulse doublets. Also retained was the total number of rotor pins. This preserves the five revolutions per second of the rotor for a continuous operation.

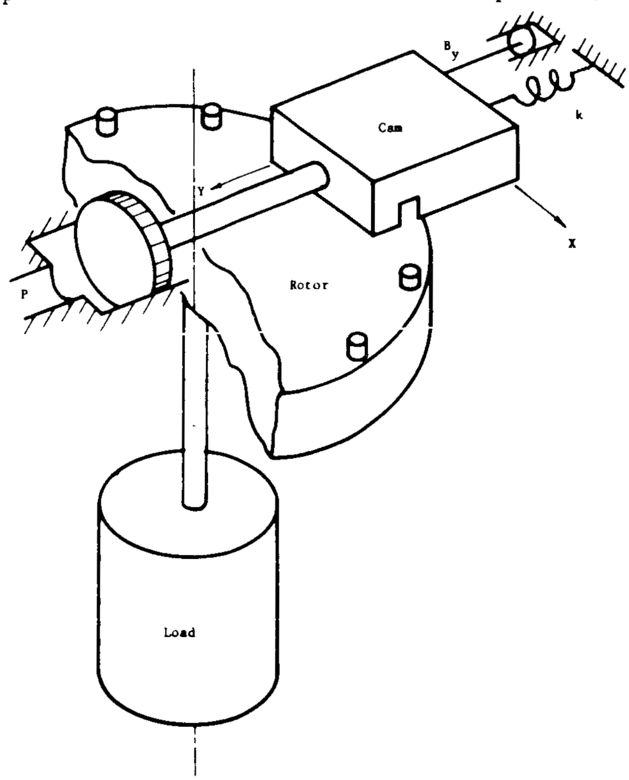

Fig. 13 Schematic Diagram of Stepping Motor Mechanism

One major change was to substitute a sinusoidal cam groove for the previously used parabolic shape. It was felt that this shape would be easier to manufacture. This means that the computer programs had to be changed accordingly. In the case of the digital program, this was accomplished by simply inserting new statement cards. However, for the analog program a new function generating circuit was devised. By using two multipliers and two integrators, it is possible to generate sine and cosine space functions. This block diagram is shown in Fig. 14. The input to the circuit is the velocity of the rotor in the tangential direction. Values of sine and cosine then can be displayed as a function of displacement. The complete analog computer block diagram for the system (including the new function generation) is shown in Fig. 15.

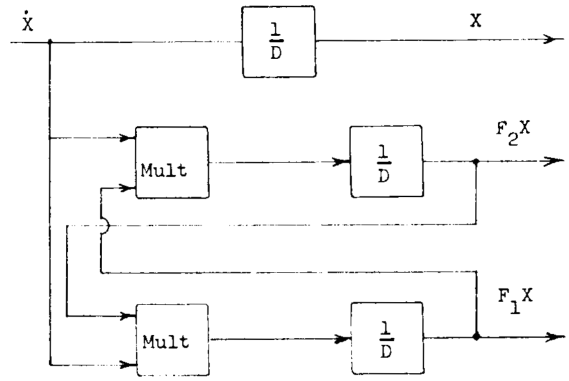

Fig. 14 Sine - Cosine Block Diagram

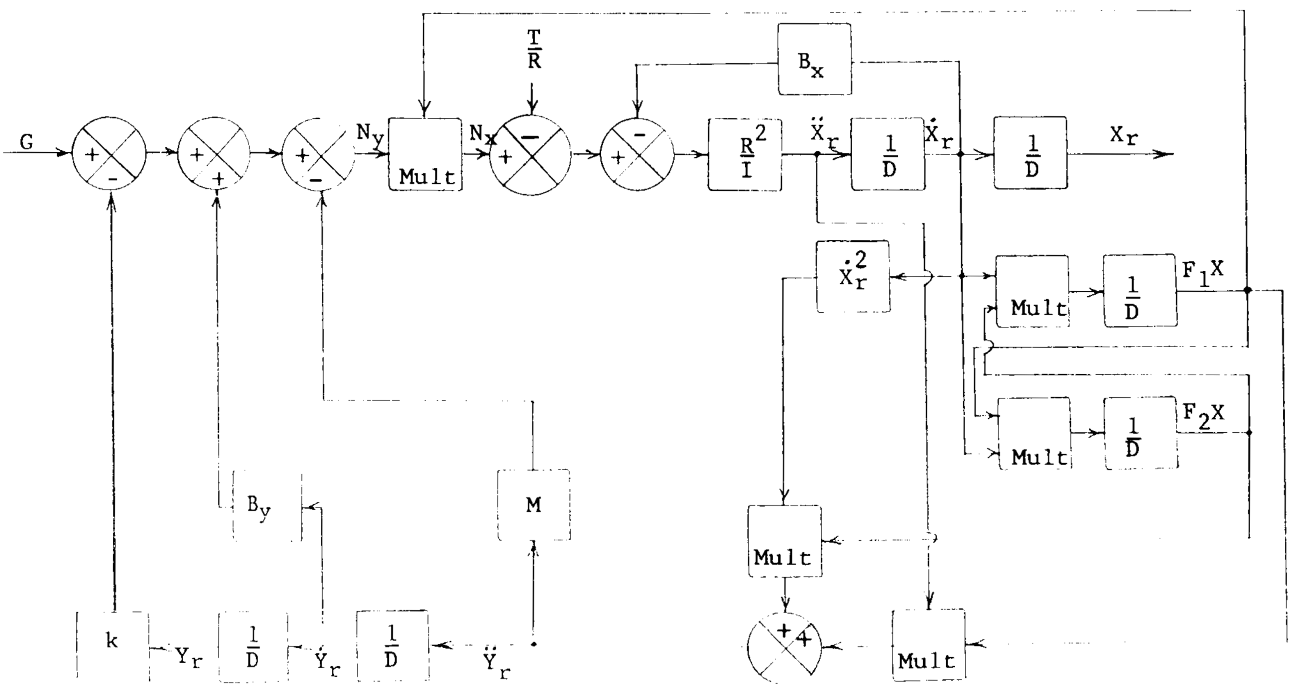

Fig. 15 Analog Computer Block Diagram

As a basis for study, the rotor pin radius was fixed at two inches for the one-half horsepower unit. The displacement amplitude of the cam groove was reduced to 0.25 inches. Rough calculations of the cam weight were made and this value was also fixed for the study. The investigations were mostly of a qualitative nature, using the analog computer set-up described in reference 11. After a satisfactory solution was apparent from the analog studies, a more exact solution was obtained by inserting appropriate values in the digital program. This procedure has been used because of the drift-like instability of the analog solution at the end of each cycle. The instability is due to small residual errors in the voltage inputs to the multipliers. When these small errors are integrated over extended periods of time, they propagate and grow until they swamp out the desired solution.

A number of interesting results were obtained from the studies. First of all, the stiffness of the spring did not affect the response of the system to any great extent. For one run the spring was removed entirely and the system still performed satisfactorily. However, the spring needs to be retained for holding the system in a static position.

The system seemed to be very jerky with the smaller geometry. It is felt that this is due to the increased R^2/I value for the rotor. Since the moment of inertia, I, is a function of R^4, halving the radius will cause the R^2/I value to increase by a factor of four. It appears that future studies will have to be made with a larger rotor weight. It was also found that the system could not operate satisfactorily at the desired power level. Again, this appears to be due to the lightness of the rotor as well as the amplitude of the cam groove. This rough operation was shown also by the widely varying values of accelerations in digital program results.

There seemed to be a definite relationship between the value of the damping factor, b_y, and driving force amplitude. This means that for a particular value of b_y there is a single value of the driving force amplitude for which the system will cycle. In fact, if too great an amplitude was used, the system cycled in reverse. As was previously mentioned, the value of the spring stiffness did not greatly affect this relationship.

It appears then that continued studies must be made in order to find a suitable rotor weight for smooth operation. The rotor radius of two inches will be retained if possible. Also to be studied are the effects of cam mass and pin forces. It may be that pin forces will be too large for the pin diameter. This would also have an effect on cam groove curvature and amplitude.

These studies are supported by NASA Grant NGR 39-009-023.

EXPERIMENTAL ELECTRIC SERVOMOTOR

M. C. Justice, Graduate Assistant

Design work is nearly complete on the experimental high performance D-C motor. The original configuration of the working model (11) has been refined with respect to available materials and simpler construction.

The present design, shown conceptually in Fig.16, includes an armature with a standard wave winding bonded in epoxy in the form of a hollow shell which revolves around a stationary ferromagnetic core. A portion of the armature shell surface is machined

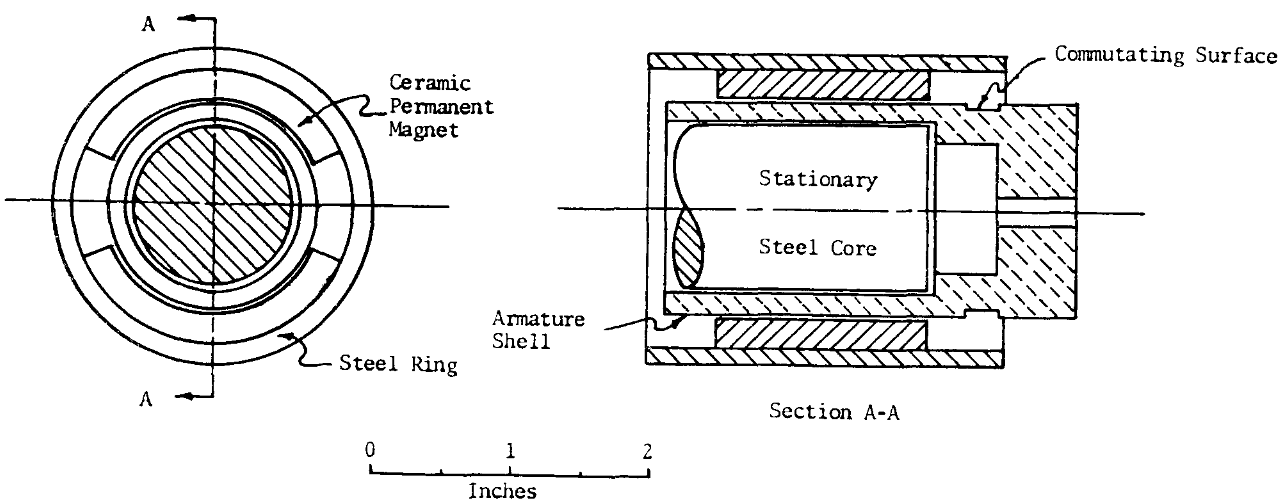

Fig. 16 Schematic Diagram of Refined Experimental D-C Motor Design

such that the copper wires themselves may serve as a commutator.

The field flux through two poles is provided by ceramic permanent magnets. The ceramic magnet was chosen for its compact design, high resistance to demagnetization, and suitability to the limited production of a specific size and shape. Currently under analytical study is a performance improvement by using higher energy permanent magnets such as the Alnico series.

Thermal transients measured from the experimental model are expected to aid in finalizing an analytical study of the heat transferred from the current-carrying armature and to reveal the extent of needed improvements.

The total performance of the experimental motor will be analyzed as to the loss in efficiency sacrificed for a gain in dynamic performance.

In reference to the previous investigation (11) on finding roots of a polynomial, a new digital computer program, using Muller's Method (13), has been acquired in addition to the previous Lin-Bairstow Program (14) for use by the Systems and Controls group. A feasibility study is continuing on a method of guaranteed convergence that does not require an approximate set of roots as an input (15).

This work is being supported by NASA Grant NGR 39-009-023.

HYSTERETIC NONLINEARITIES IN CLOSED LOOP SYSTEMS

R. S. Raizada, Assistant Professor of Mechanical Engineering

This project previously led to the development of a switching-logic to eliminate instability due to the presence of hysteretic nonlinearities in a closed loop system (16). The limit cycle was eliminated and the improved system was stable. Figs. 17 and 18 represent the typical behavior of a second order closed loop system having a hysteresis type of backlash in the forward loop before and after the introduction of the switching logic. The switching logic is shown in Fig. 19.

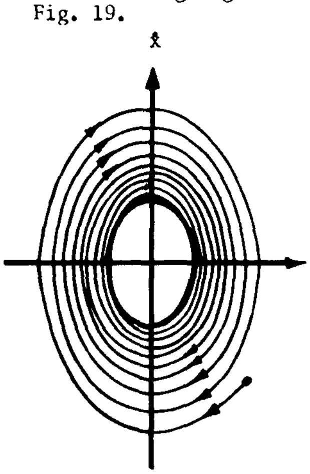

Fig. 17 Limit Cycle Oscillations in a Second-Order Closed Loop Control System with Hysteresis

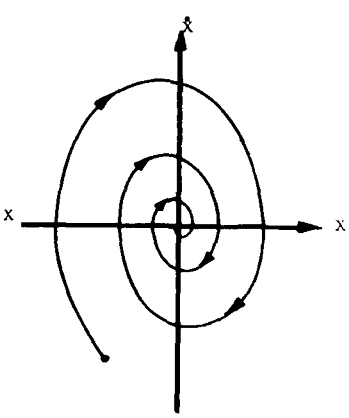

Fig. 18 Damped Response After the Introduction of the Switching Logic

Present efforts, arising out of this study, are being concentrated on the problem of synthesizing the switching-logic networks required to compensate for more complex nonlinearities. The problem here is that of minimization of a Boolean function and its synthesis using available hardware. Continuation of this study is expected to yield results having wider applications, especially in the design of digital computational networks involving multi-functional logic building-blocks.

In addition to the preliminary project report (16), a paper is being prepared to present the results of this research at a professional society meeting.

DYNAMICS OF FLUID TRANSMISSION LINES

R. S. Raizada, Assistant Professor of Mechanical Engineering

Dynamics of loaded transmission lines is being studied using a number of models. A fairly comprehensive account of this project can be found in (17), which was presented as a set of notes in the special Summer Seminar on Fluid Control Systems at The Pennsylvania State University in July 1965.

Recent highlights of the project are further studies of the Matrix-transfer function model and a linear lumped parameter model using electrical network theory. The latter was used to study the locations of the singular points, poles and zeros mainly, on the complex plane for the simplified linear model. It was shown that the first few natural frequencies for the transmission line can be estimated quite easily, and with reasonable accuracy, using this model; and a criterion for the "equivalence" of the model and the actual transmission line was developed. The next phase in the research on this project includes the development of a digital computer program for estimating the transient behavior and frequency response for any given line. Experiments to examine the validities of the analytical models are also under consideration.

Both of these projects were supported by NASA Grant NGR 39-009-023.

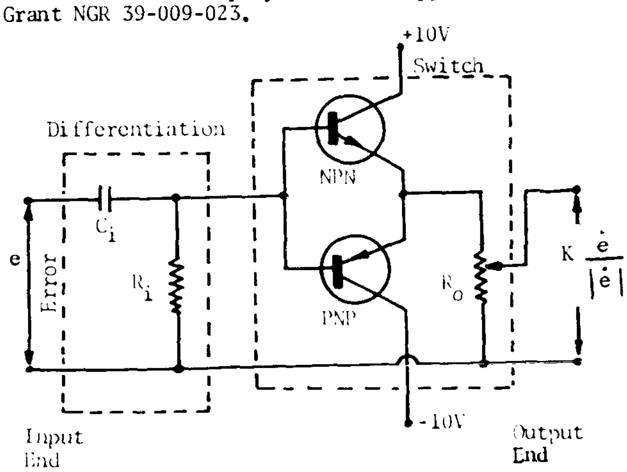

Fig. 19 Schematic Electronic Circuit for Correction of Hysteresis Type of Nonlinearity by Means of a Switching Logic Network

SOME UNUSUAL ANALOG COMPUTER CIRCUITS

R. S. Raizada, Assistant Professor of
Mechanical Engineering

As extensive users of analog computing equipment, the Systems and Controls group often needs to develop special computing circuits. Some of the special circuits developed and tested by the Systems and Controls Laboratory staff include circuits for spatial integration and spatial function generation. What makes these circuits unusual is the fact that the independent variable, usually the free running time t, has been replaced by a system variable x(t) or θ(t). One such circuit developed to generate Sin θ and Cos θ, θ = θ(t), has been used by R.W. Schiller (Figs. 14 and 15) in simulation of the hydraulic stepping motor.

Let us consider, for example, the generation of a function y = f(x), x = x(t). We can then write,

$$\begin{aligned} y &= f(x) \\ &= \int_0^x \frac{df(x)}{dx}\, dx + f(x)_{x=0} \\ &= \int_0^t \frac{df(x)}{dx} \cdot \frac{dx}{dt} \cdot dt + y(0) \qquad (1) \end{aligned}$$

Eq. 1 can now be simulated on an analog computer, using a multiplier and an operational amplifier, as shown in Fig. 20

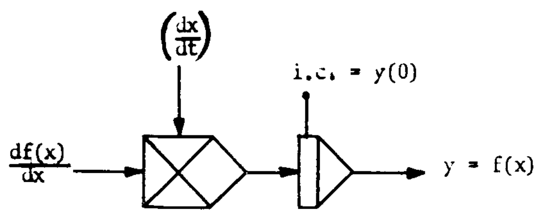

Fig. 20 Generation of a Spatial Function, y = f(x)

The function, df(x)/dx, can usually be simulated by using coefficient potentiometers and a summer if y = f(x) is a polynomial of second order.

For a parabola, $y = a + bx + cx^2$, the analog computer circuit is shown in Fig. 21.

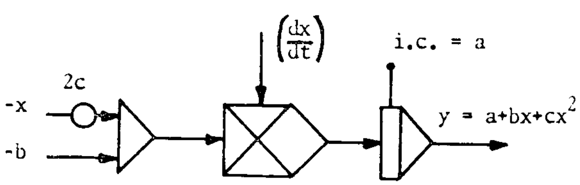

Fig. 21 Analog Generation of a Parabola $y = a + bx + cx^2$

The circuits shown in Figs. 17 and 18 assume that x = (dx/dt) is available for computation which is the case, however, in many practical analog set-ups.

The technique outlined above can be used to generate functions other than polynomials. For example, to generate Sin θ and Cos θ, θ = θ(t), we write,

$$\text{Sin}\,\theta = \int \text{Cos}\,\theta\, d\theta = \int \dot{\theta}\, \text{Cos}\,\theta\, dt$$

and (2)

$$\text{Cos}\,\theta = -\int \text{Sin}\,\theta\, d\theta = -\int \dot{\theta}\, \text{Sin}\,\theta\, dt$$

from which, we can now proceed to construct the analog computer circuit as shown in Fig. 22.

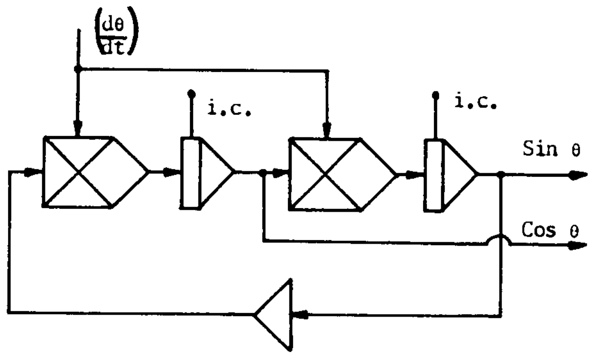

Fig. 22 Generation of Cos θ and Sin θ

In order to generate the exponential function (anti-logrithm circuit), we proceed as follows,

$$y = e^{kx} \quad (\text{i.e } y = \text{Antilog}_e\, kx) \qquad (3)$$

however $dy/dx = ke^{kx} = ky$, which suggests that,

$$\begin{aligned} y &= k\int e^{kx}\, dx \\ &= k\int e^{kx} \left(\frac{dx}{dt}\right) dt \\ &= k\int y\, \dot{x}\, dt \qquad (4) \end{aligned}$$

Eq. 4 can be simulated on the analog computer as shown in Fig. 23 to generate the function y.

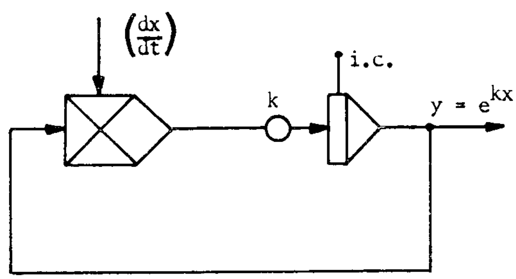

Fig. 23 Generation of an Exponential Function, $y = e^{kx}$

This work has been supported by NASA Grant NGR 39-009-023

STEAM-TO-AIR ENERGY CONVERTER

R. T. Harper, Graduate Assistant

The many potential advantages of high-pressure air over superheated steam in fluid power control systems prompted the study of a steam-to-air energy converter suitable for use in naval systems. The design proposal specified a 15-hp unit capable of delivering 3000 psi air using 500 psi, 1000 deg F supply steam. Specified design parameters, which must be kept to minimum values, include size, weight, and operating noise. The present scope of the project has been limited to an investigation of the application of the free-piston concept to the problem. An extensive search of the literature in this area was conducted, but little pertinent information was obtained.

After surveying various free-piston design configurations, the most promising was selected for intensive investigation. The study of this design configuration includes calculations to optimize the various parameters, instrumentation of a single free-piston laboratory model to provide experimental data for confirmation or refinement of the theory.

An electrical analog model was set up with assistance from ORL computer laboratory personnel to simulate the dynamics of the free-piston design configuration selected. The data obtained from this simulation was processed to determine the engine's critical parameters, and to develop a procedure for optimization of the engine with respect to size.

A design for a single free-piston laboratory model was fabricated and instrumented concurrent with the analog simulation. All attempts to start the model have thus far been unsuccessful. Data is currently being taken to determine areas in which the laboratory model departs from ideal in order to provide a basis for modification of the analog model and for redesign of the laboratory model.

A rough draft of a detailed report for this phase of the project has been submitted to the Department of Mechanical Engineering. This report will constitute a Master's Thesis. This work has been carried out under Exploratory and Foundational Support from Penn State's Ordnance Research Laboratory.

FLUID AMPLIFIER PRESSURE SENSOR RESEARCH

A. K. Stiffler, Graduate Assistant

Present studies of fluid amplifiers at the Systems and Controls Laboratory are concerned with analytical modeling of the devices in order to improve their incorporation into engineering systems. Of primary interest are the proportional type amplifiers which employ knife edges and pressure control ports to position the power jet. The early work which culminated Simson's PhD Thesis at M.I.T. (8) revealed basic design parameters for subsonic amplifiers of this type, and included investigation of amplifier geometry and prediction of static characteristics. It is this writer's interest to study the dynamics of such amplifiers from the point of view of state space methods. An outline of this approach would be the following: Define inputs $\vec{U}$ and outputs $\vec{X}$, a set of measurable pressure and/or flow variables. Develop a set of differential equations describing the system in terms of this primary set of variables. Then redefine variables if necessary and describe the system with a nonlinear vector equation, $\dot{\vec{Y}} = \vec{f}(Y_n, U_n)$, relating these variables and their first derivatives. Both analytical and experimental techniques may be required in order to reach this point. Interactions with adjacent components connected at the input and output ports usually need to be incorporated into this description of the system also. Some pertinent theoretical background was presented briefly in the preceding report (11).

Experimental investigations of the static characteristics are being extended to include various conditions of amplifier operation. In particular, the pressure control device can be used easily as a pressure sensor. In this application one control port pressure is held at a fixed reference value. The sensed pressure is applied to the other port. The difference between the control port pressures then is amplified by one or more stages of fluid amplification in order to provide a higher power level output signal.

The approach employed so far has been to build an amplifier and compare its characteristics with those predicted by Simson. Several different designs were fabricated from photoceram by Corning Glass Works in Bradford, Pa. These devices, whose design parameters were based on Simson's work, proved to be unsatisfactory. They exhibited little gain and were unstable. It was observed that control port pressures were quite high and tended to increase with increasing power jet supply pressure. Also, a change in one port pressure directly influenced the other port pressure. This behavior could be explained if the free jet profile development involved faster spreading of the jet than Simson found. An amplifier then was fabricated in our laboratory with slightly larger knife edge separation, larger input port passages, and receivers which provided a center dump (11). The modified laboratory-constructed prototype still exhibited many of the same characteristics as the prototypes made for us by Corning. Interaction between the power jet and control ports was still very strong.

It was decided to further investigate geometry effects. Two large scale (10:1) models were designed and built with provisions for variable geometry (See Fig.1 in this report). The optimal dimensions recommended by Simson again produced the control port -- power jet interaction phenomena. Good results were achieved when the knife edge separation was increased or when the edges were moved closer to the jet nozzle exit plane. The knife edge separation of the lab prototype was then changed to about double the previous value and satisfactory operation was attained. According to Albertson (18), jet profile establishment is a weak function of Reynolds Number, Re, with increased rate of spreading occurring at lower Re. However, the degree of this spreading was not large enough to completely explain the behavior of the prototype. After increasing knife edge separation, the resulting measured pressure gain exceeded that predicted by Simson for optimum pressure amplification (28 vs. 16).

Parallel to the above prototype work, development of instrumentation has continued in order to facilitate the determination of gain, input impedance, and output impedance. The schematic diagram shown in Fig. 24

illustrates the way in which an amplifier is set up for experimental measurement of its characteristics. The essential features are stagnation chambers and calibrated high-flow fluid resistors coupled with transducers which enable pressure and flow to be plotted directly on an X-Y Recorder. The curves are obtained easily for various operating conditions such as supply pressure, control port mean pressure level, and receiver load. A typical family of pressure-flow curves for various constant control port pressures is shown in Fig. 25.

Aside from determining the effect of these parameters on the static characreristics, the main problem is to determine what effect geometry and/or scaling have on gain and impedance characteristics. A modified prediction of the static characteristics should follow along the lines of Simson's work; but it should incorporate such effects as variations in jet profile establishment and other phenomena which may come to light as we learn more about these devices.

This work on fluid amplifier pressure sensors is sponsored by the Hamilton Standard Division of United Aircraft Corporation, Hartford, Connecticut.

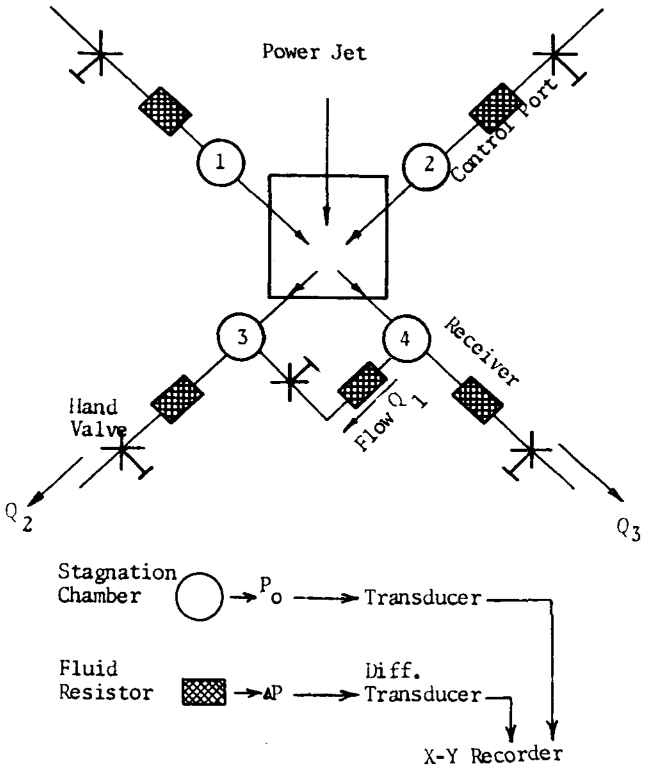

Fig. 24 Experimental Setup for the Determination of Fluid Amplifier Static Characteristics

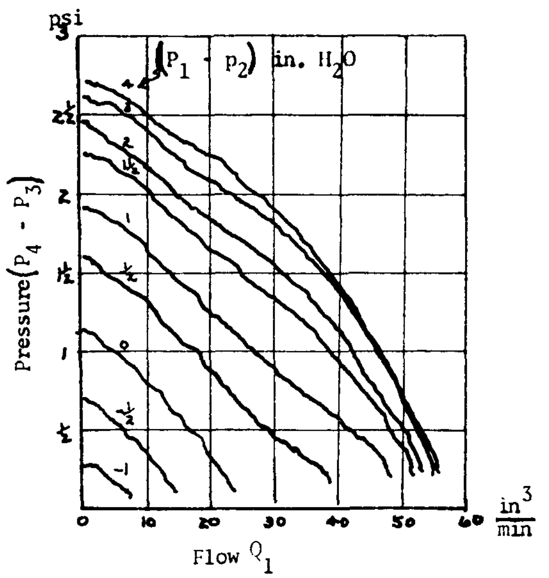

Fig. 25 Load Impedance for Pressure Controlled Amplifier

For further information about the projects mentioned in this report or the activities of the Systems and Controls Laboratory, inquiries should be addressed to: Director, Systems and Controls Laboratory, 214 Mechanical Engineering Building, University Park, Pennsylvania, 16802

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