MILITARY TECHNICAL COLLEGE

CAIRO - EGYPT

DEVELOPMENT OF PHASE-SENSITIVE CONTROLLER WITH PARTICULAR REFERENCE TO HYDRAULIC SERVOS

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ABSTRACT

This papers presents a phase locking loop (PLL) suitable for use in aerospace and aircraft applications in addition to many other fields. The concept is novel in that it makes use of the state variables of two hydraulic servo loops, x and $\dot{x}$ in order to achieve detection of the phase error. The PLL consists of a phase detector and voltage controlled regulator (VCO). No need for a loop filter was necessary. Phase locking was tested in a simulation condition where two first order hydraulic servos were used as master and follower servos. Results were very satisfactory as shown by simulation results, Figs. 5, 6 and 7.

INTRODUCTION

The use of Phase-locked loops dates back sixty years to the "homodyne", receiver, where they were used for the synchronization of two received radio signals. This was followed by a much wider use of phase-locked loops in connection with television receivers for synchronizing the horizontal and vertical sweep oscillators of transmitted synchronous pulses. The work of Wendt (1) and Richman (2) is only representative of the huge amount of literature on the application of PLL to phase synchronization and automatic frequency and phase control of TV receivers.

The application of phase detectors, phase shifters and PLL grew much faster during the last three decades. One of their most important applications is in the reception of very weak signals from distant spacecraft. Tom (3) reports in his invention, an automatic phase alignment system for a satellite tracking antenna. Its principle of operation is mainly based on monitoring the output of the tracking receiver and adjusts phase shifters along the transmission paths of the azimuth and elevation channels, in a manner to maximize the outputs of the receiver. An excellent reference on the use of PLL in spaceflight can be found in reference (4) by Lindsey and Tausworthe.

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Motor speed control is another field where PLL proved useful in improving speed accuracy. Moore (5) reports a possible speed accuracy of 0.002% by using PLL. Carlson and Barr (6) and Regnier (7) report, in their inventions, important applications of PLL to motor speed Control systems.

Shakers and multi-point excitation is another field where PLL was applied successfully. Anderson (8) and Hufstedler, Weaver and slater (9) made use of PLL techniques to achieve modes of vibration and resonances of complex structures for aerospace and automotive applications.

This paper is dedicated to a new application of PLL techniques, mainly in the field of fluid power control systems. It is well known that in missiles as well as aircraft, hydraulic actuators are extensively used. They receive autopilot actuating signals to control vehicles' motion in the roll, yaw and pitch planes. This is usually achieved by means of two oppositely oriented fins, flaps, vanes or similar control surfaces. It is obvious that a phase difference in the position response of two opposite roll actuators, for example, is undesirable. Minimizing or locking the phase of one actuator to its counter-part is the objective to be achieved by a PLL. Obviously many other non-aerospace applications will benefit from phase-locking of hydraulic servos. Shakers, machine tools and process control systems all are candidate areas for PLL techniques to improve the dynamic performance of fluid power servos incorporated in these systems.

BASIC PLL OPERATION

Traditionally a phase-locked loop, Fig.1, consists of: a phase detector (PD); a loop filter and a voltage-controlled oscillator (VCO). The (PD) compares the phase of a periodic input signal to the phase of the VCO. The difference voltage is then filtered by the loop filter and applied to the VCO.

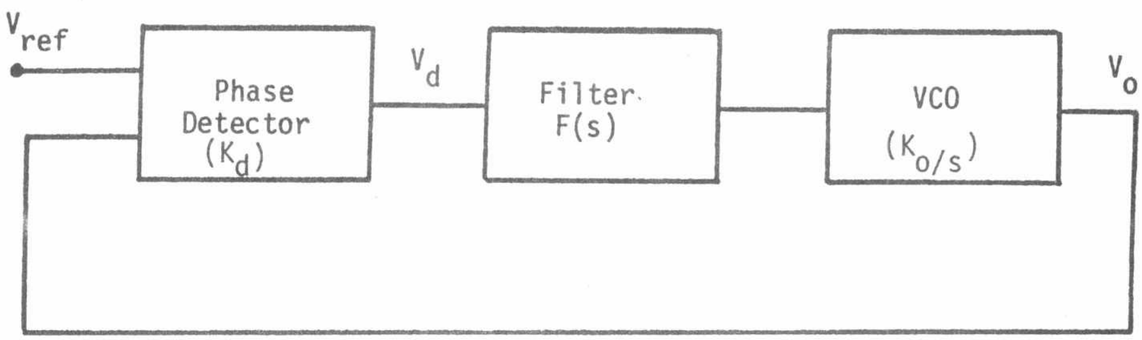

Fig. 1 : Basic phase locking loop

The basic PLL was analysed by many researchers and also was dealt with in text books. A typical analysis can be found in references (10) and (11). The transfer function of such PLL loops is given by:

$$\frac{V_o\ (s)}{V_{ref}\ (s)} = \frac{K_o\ K_d\ F(s)}{s + K_o\ K_d\ F(s)} \qquad (1)$$

The most well known circuits used for filter design are illustrated together with their transfer functions in Fig. 2. These are either active or passive networks dependent on whether they include an operational amplifier or not. The overall PLL transfer functions can be expressed as:

For PLL with a passive filter

$$H(s) = \frac{K_o\ K_d\ (T_2\ s + 1)/T_1}{s^2 + (1+K_o\ K_d\ T_2\ )/T_1\ s+K_o\ K_d\ /T_1} \qquad (2)$$

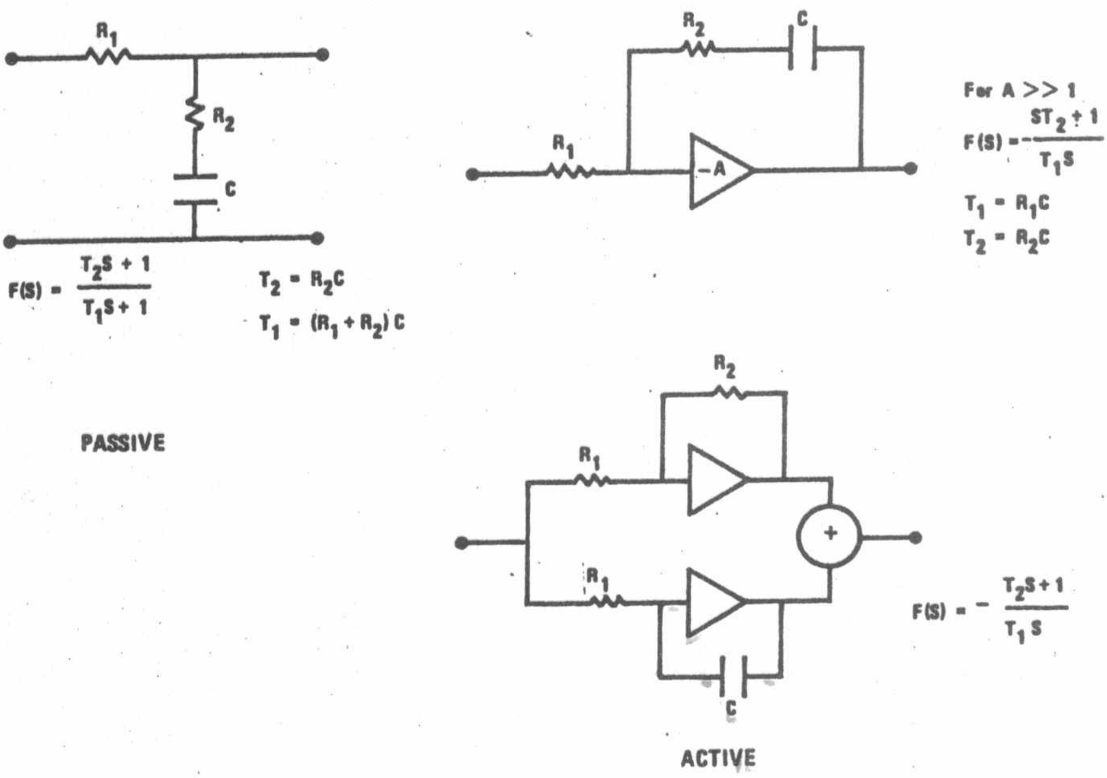

Fig. 2. Filter circuits and their transfer functions.

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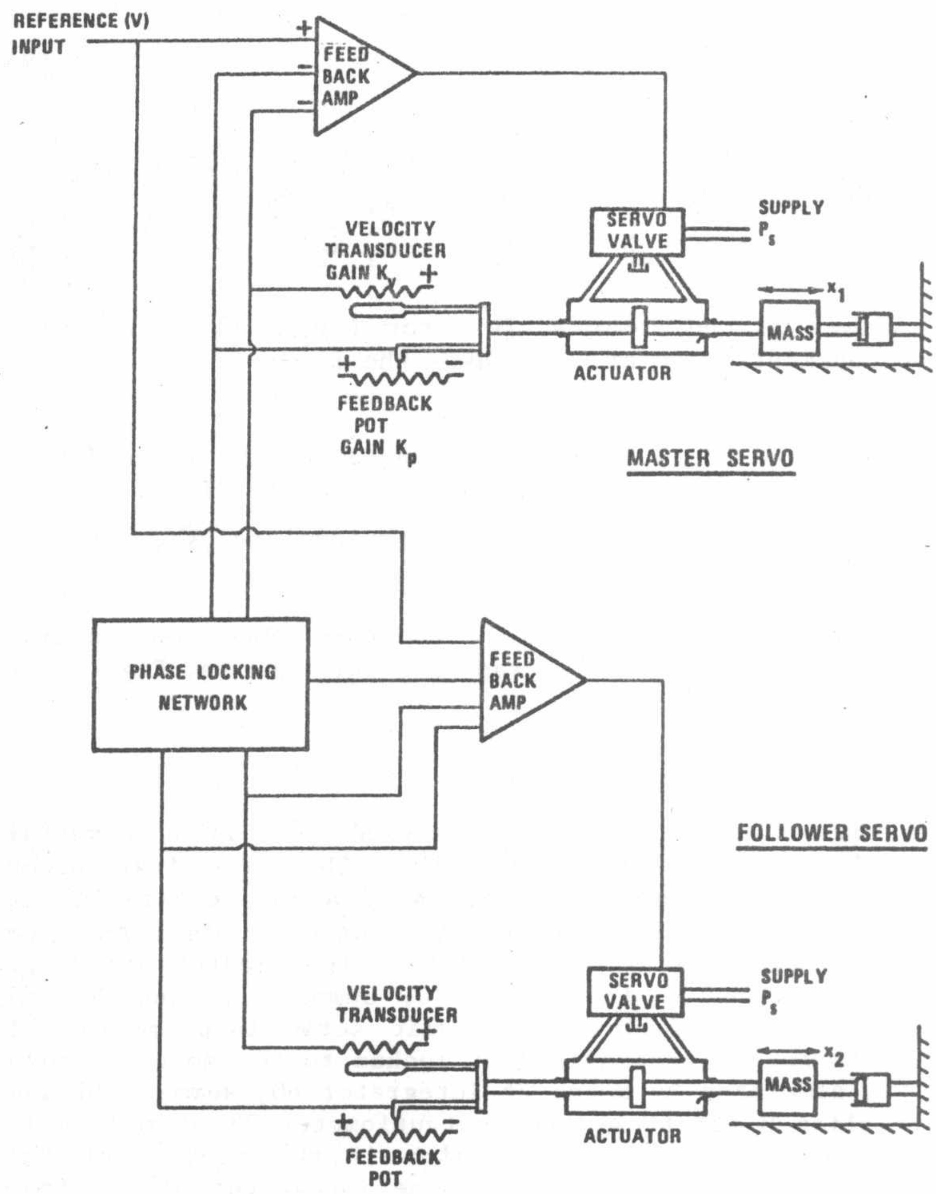

Fig. 3. Schematic diagram of system.

For a sinusoidal input signal V=sin ωt, applied to the two hydraulic servos of Fig.3, the output position and velocity responses, at steady state for the master servo will be given by:

$$x_1 = X_1 \sin(\omega t + \phi_1) \quad (7)$$

and $$\dot{x}_1 = \omega X_1 \cos(\omega t + \phi_1) \quad (8)$$

For the follower servo:

$$x_2 = X_2 \sin(\omega t + \phi_2) \quad (9)$$

and $$x_2 = \omega X_2 \cos(\omega t + \phi_2) \quad (10)$$

Combining equations (7) to (10) results in the following sinusoidal relationship for the phase difference $\phi_1 - \phi_2$:

$$\sin(\phi_1 - \phi_2) = \frac{2}{\omega X_1 X_2} (\dot{x}_1 x_2 - x_1 \dot{x}_2) \quad (11)$$

For small valves of the phase angle error ($\phi_1 - \phi_2$), equation (11) can be considered linear, and takes the form:

$$\phi_1 - \phi_2 = \beta (\dot{x}_1 x_2 - x \dot{x}_2) \quad (12)$$

Equation (12) is the basis on which the design of the phase detector (PD) module of the analogue simulation circuit, Fig.4.

The gain setting of potentiometer is proportional to β , i.e.

$$K_{pot8} = k\beta \quad (13)$$

This is a very important term as it controls the phase locking characteristics as seen from the graph plotter results, Figs. 5, 6 and 7.

SYSTEM SIMULATION

The simulation of the system was carried out on a powerful analogue-hybrid computer, type EAI 680. The two first order hydraulic servos were simulated by means of a loop consisting of one integrator, two summers and a potentiometer. As seen from Fig. 4, the hydraulic servo-loop, module I (the master actuator) is simulated by means of integrator 30, summers 31 and 34 and potentiometer 33. The follower hydraulic servo loop, module II (whose phase is to be synchronized or locked to the master actuator phase) is simulated by means of integrator 60, summers 61 and 64 and multiplier 8 which replaces potentiometer 33 of module I. Multiplier 8 generates a function which is the product of the detected phase error and the input to the integrator of the follower hydraulic servo, module II. Module III simulates the phase detector as represented mathematically by equation 12. Module IV represents the voltage controlled oscillator (VCO) consisting of an integrator whose initial condition is a function of the time constant of the hydraulic servo of module II. Module V is a straight forward sinusoidal signal generator whose amplitude and frequency can be adjusted via potentiometers 2 and 3. Time scaling was achieved by means of the parallel hybrid facility of the analogue computer. The cycling period was arranged such that 10 H_2 of the master servo output would correspond to one second.

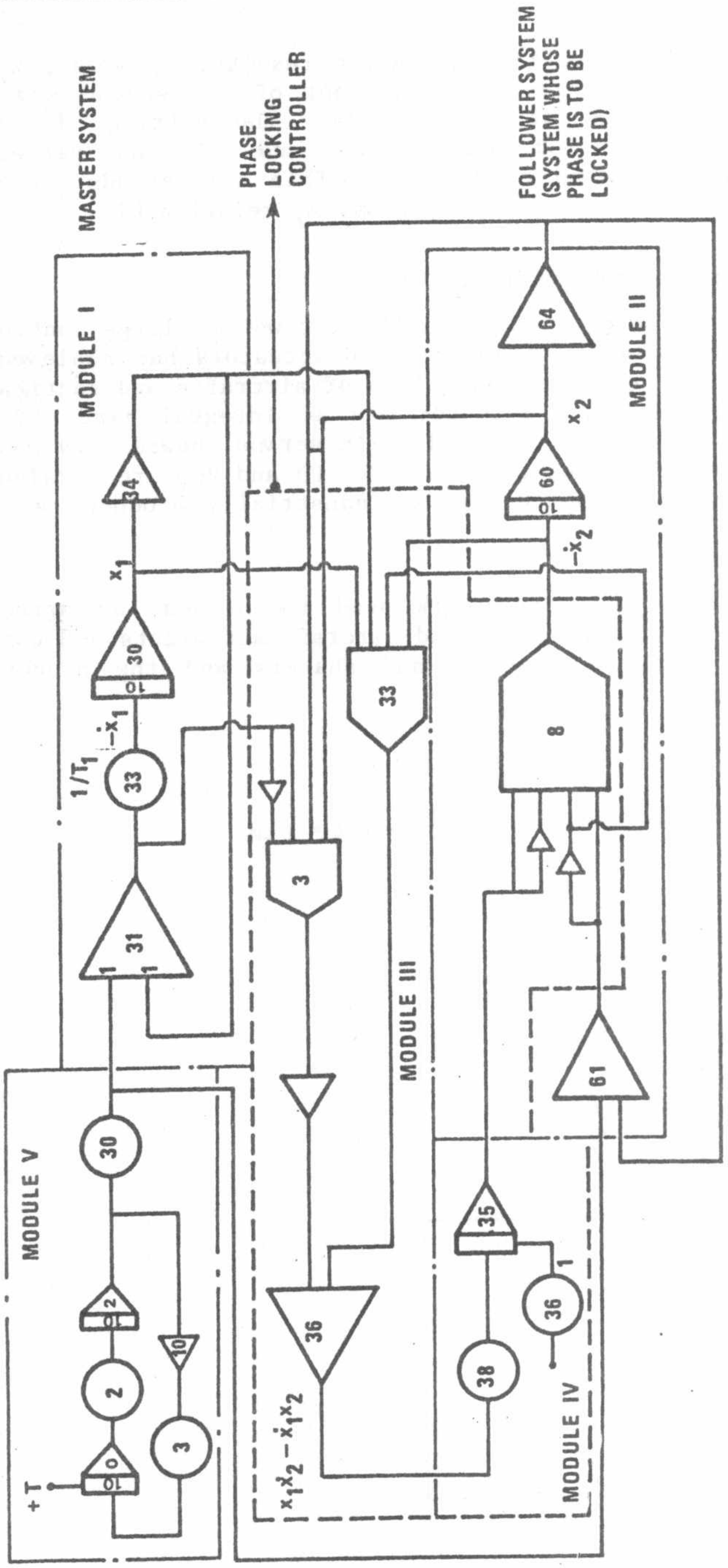

Fig. 4. Simulation circuit.

RESULTS

Fig. 5, 6 and 7 illustrate the simulation results, x_1 versus x_2, for a master hydraulic servo time constant of 0.1 second and a follower hydraulic servo of 0.2 seconds. The setting, β of potentiometer 38 was varied between 0.05 and 0.05 and perfect phase locking was achieved at β =0.01. This corresponds to an average slope of 45^o of the plotted x_1 vs. x_2 relationship.

CONCLUSIONS AND FURTHER WORK

Design and simultation of a PLL suitable for use in large control systems employing multi fluid power servo actuators has achieved. Typical applications occur in autopilots of aircrafts and tactical missiles where fluid power actuator are an integral part. The results of phase locking the two hydraulic servos showed very good performance and stability of the PLL. The PD and VCO are straight forward simple circuits which can be industrially produced at a low cost.

Further experimental and field work need to be done on actual hydraulic servos used in missiles and aircraft autopilots and control systems of tanks, vibrators and shakers and the process industry.

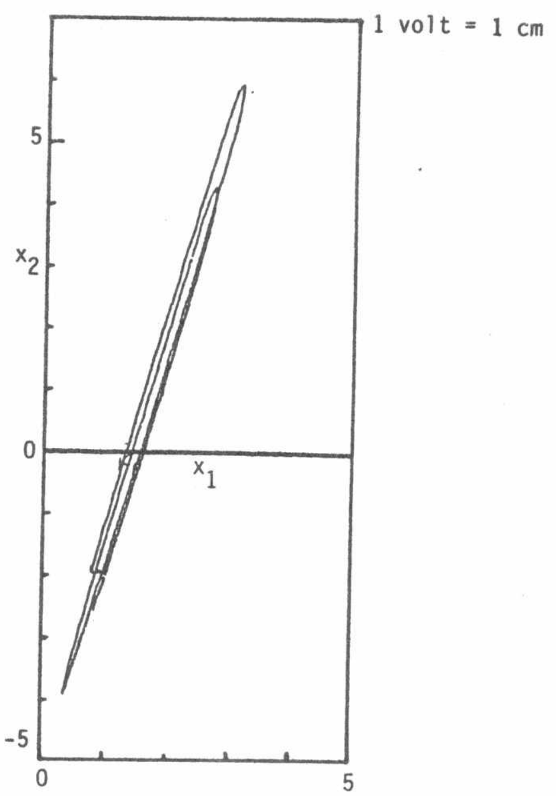

Fig. 5: x_1 vs. x_2 for β = 0.05

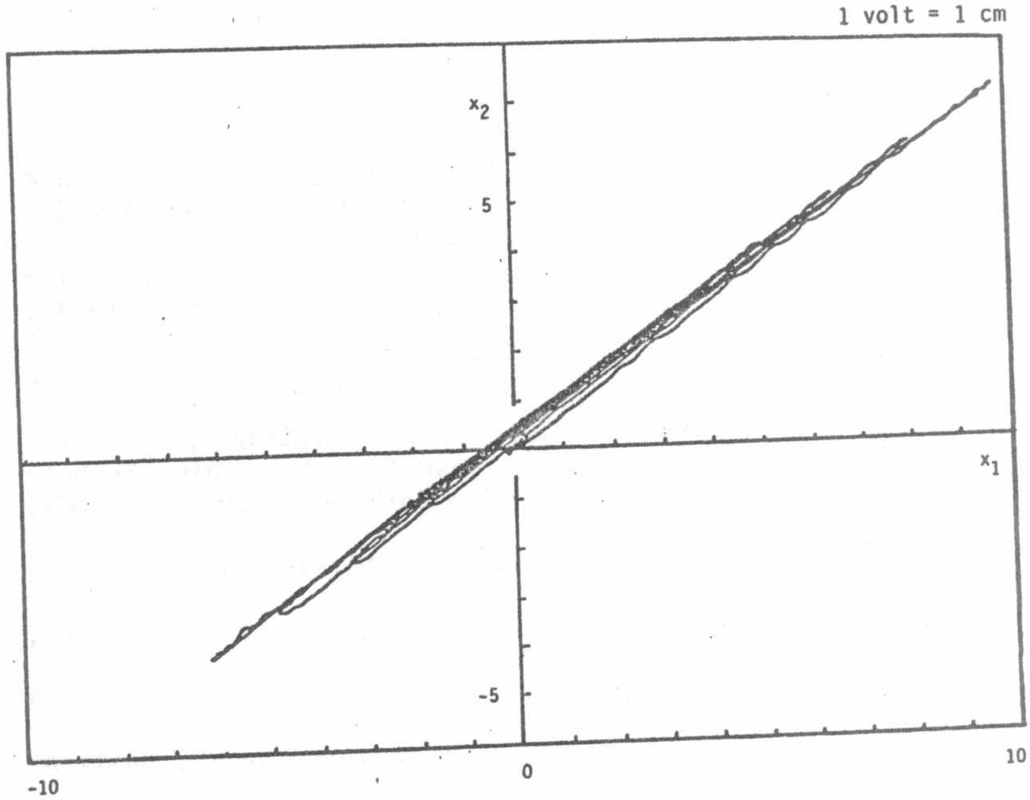

Fig. 6: x_1 vs. x_2 for β = 0.01

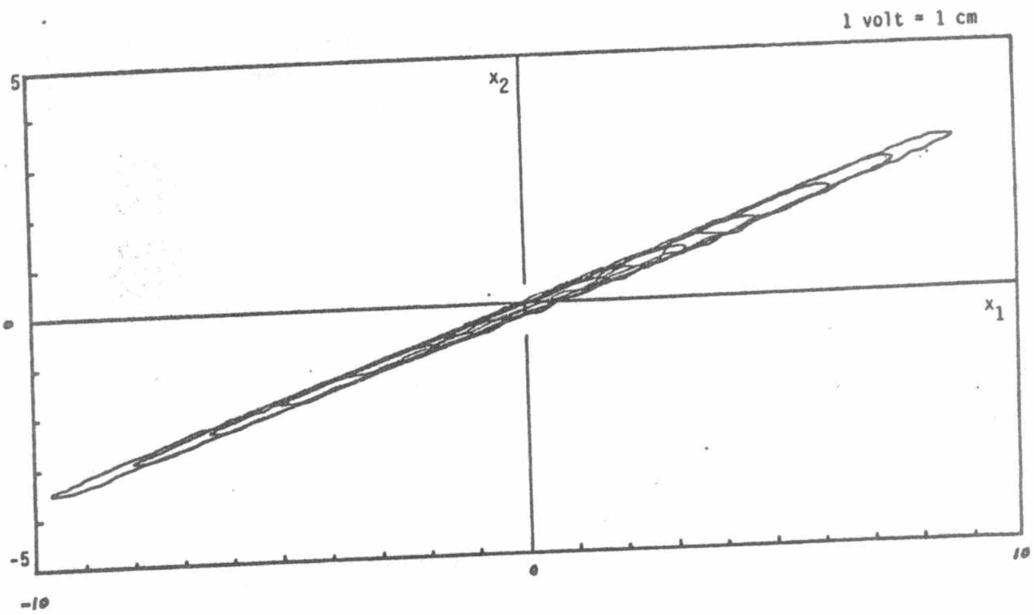

Fig. 7: x_1 vs. x_2 for β = 0.005

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NOMENCLATURE

A	piston area
b	load coefficient of viscous friction
C_d	valve discharge coefficient
$F(s)$	Transfer function of the filter
K_a	amplifier gain
K_d	phase detector gain
K_L	servo valve pressure gain
K_o	VCO gain
K_p	feedback potentiometer gain
K_q	servo valve flow gain
K_s	$A K_a K_q K_t / m k_L$ = system overall gain
K_t	servo valve torque motor gain
K_v	feedback velocity transducer gain
m	load mass
P_L	difference of pressure across the piston
P_s	supply pressure (constant)
s	Laplace operator
t	time
X	amplitude of the steady state sinusoidal servo output
x	system position response
T	servo time constant
V	reference input signal
W	valve port width
ω	input signal frequency

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ω_n undamped natural frequency = $\dfrac{A\ K_a\ K_t\ K_q\ K_p}{m\ K_L}$

ϕ phase angle

ρ Fluid density

$$\zeta = \frac{1}{2}\sqrt{\frac{m\ K_L}{A\ K_a\ K_t\ K_q\ b}}\left(1 + \frac{K_a\ K_t\ K_q\ K_v}{A} + \frac{b\ K_L}{A_2}\right) = \text{Damping ratio}$$

$$\beta = \frac{2}{X_1\ X_2} = \text{gain of potentiometer 38, Fig. 4.}$$