LOW TECH CONTROL SYSTEM FOR SWING SPAN BRIDGES

by

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ABSTRACT

The State of Louisiana Department of Transportation and Development (LaDOTD) is unique in many ways which pertain to movable bridges: it has its own design staff which prepares the contract plans for all but the largest movable bridge projects; it has its own maintenance section which is responsible for the up keep of all of its bridge; and it has a preference for the swing-span type of movable bridge as opposed to the bascule or vertical lift. This preference is due to economics, aesthetics, low elevations, the fact that most of our crossings are over relatively narrow streams, and in large part to the success we have had with a unique control system. While performing the necessary functions, it is able to be maintained by men of ordinary mechanical skill. This system has been in operation since 1962 when Louisiana first went to hydraulic operation of swing bridges and has remained relatively unchanged in concept and design from that time. This has given the state the reliability and continuity which is so necessary in the training of maintenance personel. We present this paper in the expectation that there are those outside of our state who will have an interest in this type of bridge operation.

We shall first describe the operation of the bridge control system and then analyze it through the use of automatic control theory. The system will then be examined from the points of view of fabrication, maintenance and reliability.

OPERATION

The reader is asked to refer to figures 1 and 2 at the end of the report. Figure no. 1 is a copy of a typical LaDOTD contract drawing showing the span driver and control equipment locations on the center pier. Figure no. 2 is a physical schematic of the system operation. The span drive and control system operate automatically by signal from the operator. This signal begins the bridge movement and selects the amount (degrees) of swing. The control system automatically accelerates, rotates and decelerates the bridge bringing it slowly into the selected position. This operation is accomplished simply through the use of a differential. A section through the differential unit is shown in figure 3. The control signal output from the gearmotor cranks into the cam a certain degree of turns as pre-determined by a limit switch at the same time putting the pump lever on stroke and moving the bridge. The bridge motion through the rack follower then subtracts out the turns until the pump returns to neutral thus stopping bridge motion. Acceleration and deceleration are accomplished by a ramping groove on the cam. This control system is nonlinear and uses no semi-conductors. Control is manipulated through gears, levers, a cam, squirrel cage motors, rotary limit switch and hydraulic cylinders. Components are reliable, easily maintained and readily available.

SYMBOLS

K_i = linear gain

N_i = nonlinear describing function

Q_{max} = maximum pump flow

D^n = $\frac{d^n}{dt^n}$, differentiation with respect to time

θ = angular displacement, deg.

$\sum$ = summation

① = component number, see figures 1 & 3

Subscripts

gm - gearmotor

c - cam

l - pump control lever

p - span pump

cyl - span hydraulic cylinders

s - span

f - feedback

cb - counterbalance

o - set point for component

THEORY

A typical swing span control system layout is shown in Figure 1. An understanding of some control theory is assumed in its analysis. Circled numbers in text refer to components in figures 1 & 2.

The control system is composed of electrical, mechanical and hydraulic components. The electrical components transmit the control signal and consist of a gearmotor, brake, and rotary limit switch. A differential is used as the summer, feedback is by a rack gear and the error signal is by linkage rod. These are the mechanical units. The hydraulics provide the muscle and speed variations to move the movable span by means of a variable volume pump, counterbalance values, and hydraulic cylinders.

A block diagram of the control system is shown in Figure 4. The reversible electric gearmotor , ①, transmits the control signal, which is the angular displacement of the electric motor. This signal is changed proportionally by the gearmotor gear ratio (Kgm). The angular displacement of the gearmotor output shaft (θgm) is transmitted by line shaft to the rotary limit switch, ②. The limit switch contacts are set to turn off the gearmotor at a predetermined angular displacement. A miter gearset is used at the rotary limit switch to change the rotation vector and to insure that the angular displacement of the gearmotor output shaft does not exceed the limits of the limit switch. A motor mounted brake on the gearmotor prevents a signal from being transmitted into the gearmotor.

The signal (θgm) is transmitted by mechanical line shafting from the gearmotor to a miter gearset. The system constant, Kmg, is 1 since the miter gear ratio is 1:1. The signal is now inputed into the differential, the mechanical comparator. The other input into the differential is from the feedback subsystem to be detailed later. The error signal, or the difference between the input signal and the feedback signal, is the angular rotation of the cam (θc). Refer to Figure 4 for location of θc on the block diagram. The control system, to this point, is a combination of proportional system constants.

The next component in the system introduces the first nonlinearity. The component is the linkage between the cam and the pump (see figure 3). Analyzing the linkage geometry results in the pump angle as an inverse sine function of the cam angle. The mathematical expression would be:

$$\theta p = \sin^{-1}(K\theta_c) \text{ for } 0 < \theta_c < \theta_{co}$$

$$= \theta p_{max} \qquad \text{for} \qquad \theta_c > \theta_{co}$$

The nonlinearity in the system is handled as a variable gain, therefore, the control system equations are handled accordingly. The pump flow is proportional to the angular displacement of the pump lever. The porportional gain (Kp)is
$$\frac{Qmax}{\theta pmax}.$$
Ignoring the second summer and proceeding to the next component, the counterbalance valves, ⑤ . These valves are nonlinear because they are an on-off element. For the moment, assume the valve is on (Np=1) and hydraulic fluid can flow through it. Therefore, the counterbalance gain is one. The hydraulic cylinders, ⑥ , are the system integrators. Referring to Figure 1, the hydraulic cylinders are laid out as two four bar systems sharing a common link. Specifically, the four bar system is the third inversion of the slider crank mechanism. Nonlinearities in the gain (Ncyl) results from the geometry of slider crank linkage. The nonlinearities can be visualized easily. Referring to Figure 1, when the span is closed, a movement of one inch in the cylinder rod turns the span a relatively large angle. This is because a small component of this rotary movement is acting in the direction of the cylinder. However, when the cylinder rods are normal to the span moment arm, an inch movement is fully effective on the moment arm. Therefore, one would expect the describing function to resemble a U in shape with the bottom of the U at a minimum when the movable span has moved halfway. This is exactly what happens.

Recapping, the gear motor inputs a signal into the differential unit. The signal is transformed by gears and levers to a variable hydraulic flow rate. This variable flow is integrated by the hydraulic cylinders resulting in movement of the movable cylinders resulting in movement of the movable span. Following this signal path on Figure 4, one traces tne forward feeding of the signal, or "feed forward signal".

There are two feedback signal paths shown in Figure 4. The first is transmitted through the rack , ⑦, and pinion at the bottom of the differential unit, ③ . This produces a nonlinear gain (Nr). The second is internal to the hydraulics as a counterbalance valve, ⑤ . This path is labeled by the nonlinear gain 1/Ncyl.

Refer to Figures 1 and 2 to trace the first feedback signal path. The movable span is attached to the rack gear, ⑦, by a rod pivoted at both ends. The rack movement drives the pinion mounted at the bottom of the differential unit (see figure 3). The angular displacement of the rack pinion is transmitted by vertical shaft to a miter gear in the cam. The angular displacement of this miter gear subtracts from the angular signal of the gear reducer, thus completing one control circuit. This feedback loop provides span position sensing by returning a compatible signal to the differential unit.

Referring to Figure 4, the first feedback loop may be expressed as:

$$\frac{\theta s}{\theta gm} = \frac{(KgKmgKcNlKpNcbNcyl)}{(KrNrKcNlKpNcbNcyl + D)}$$

Let A = numerator, $KgmKmgKcNlKpNcbNcyl$, degrees and
$B = KrNrKcNlKpNcbNcyl$, min.

The range of A, due to the non-linearities Nc, Ncb and $Ncyl$ is between .135 and .159. The range of the time constant, B, is $.173 \text{ min} < B < .222$. See figure 7.

An external disturbance is introduced into the system at the position indicated in Figure 4 to represent the moving span reacting to a wind load. Figure 5 is the control schematic of this signal path. The disturbance is additive if the wind is blowing in direction of bridge movement and negative if against it. Reducing the characteristic equation and applying the root locus method of analysis, an instability is predicted. Indeed, this is what happens. Observing the bridge in wind gusts, the span responds in an oscillatory or hunting manner as the span is brought to the closed position. This divergence is caused by the gust impulse input coupled with the inertial properties of the span to move in the direction of movement.

A second feedback loop is added to counter this instability. This second feedback loop is employed as an internal feedback path. The internal feedback modifies the system as shown in Figure 4 and 6. The physical element used is a counterbalance valve, . The valve mounts in the return line from the span cylinders. Essentially, this valve operates as an on-off valve. Flow through the valve is off until the fluid, displaced from the span cylinders, obtains a specified pressure. At this pressure, the valve allows fluid to pass. Thus, the resisting pressure maintained on the span cylinders prevents wind loads from carrying the movable span past its proper position.

The second feedback loop modifies the equations of the control system to this final form:

$$\theta s = \frac{(KgmKmgKcNlKpNcbNcyl)\ \theta gm + E}{[(KrNrKcNlKpNcbNcyl + Neb) + D}$$

Figure 7 plots systems gains versus system root loci for the control system with and without internal feedback. The effect of the internal feedback shifts the system one unit in the negative direction resulting in a more stable system.

The swing span bridge control system is a stable, automatic, low technological first order system. The system minimizes the number of feedback paths which makes it simple. Components of the system are readily available commercially or are readily fabricated by a machine shop. Accuracy is within 7.2 arc minutes. Repeatability to one arc minute. The system is tolerant of marine environments and temperature and resistant to high winds and gusts.

FABRICATION

The swing span control system components are fabricated by mechanical and hydraulic subcontractors. The mechanical subcontractor shop fabricates the differential system, component bases, operating linkages and supplies the gear motor and bolting hardware. The hydraulic subcontractor shop fabricates the pump unit, counterbalance valve manifold and relief valve manifold. These components are shipped to the construction site and assembled into a complete operating system by the general contractor.

The differential system consists of a housing, rack, rack pinion, cam shaft, differential gear set, motor gear set, pillow blocks, ball bearings and needle bearings. The housing combines a cast iron bottom frame upon which is stacked steel weldments. The bottom frame bolts to the pivot pier, acts as a guide for the feedback rack gear and supports the welded differential housing. The welded upper housing contains the differential assembly, supports the signal input shaft and separates the differential assembly from direct environmental contact. Commercial items for the differential summing unit are ball and needle bearings, pillow blocks, miter gear set and bolting hardware. All other items are machined. Machining processes used are turning, drilling, reaming, boring, planning, milling and gear cutting. Examples of materials used are ASTM A-48, Cl. 30, ASTM A-108, AISI 1018, 1020 and 1045, ASTM A-322, AISI 4140, ASTM A-36, ASTM A-276, AISI Type 303 and 304, and ASTM B-22 Alloys 863 and 905. These materials are readily available and reasonably priced.

The gearmotor and limit switch bases are steel weldments. Material used are ASTM A-36 and A-500, Gr. A or B. The gearmotor and rotary limit switch are commercial items.

Operating linkages are fabricated from cold finished carbon steel, ASTM A-108, AISI 1018 and 1137. Commercial items such as rod ends, turn buckles, and lock nuts are available from any convenient source.

The hydraulic component group consists of a pump unit, counterbalance manifold, relief valve manifold and hydraulic cylinders. An electric motor, variable displacement pump and reservoir make up the pump unit. Pump flow is varied by linkage between the pump servo lever and the differential lever. The pump unit is assembled and tested in the shop, verified, then shipped to the construction site.

The counterbalance and relief valves, piping and flanges are supplied from any number of hydraulic suppliers. Pipe is used in lieu of tubing due to pipe's durability to rough handling. The components are fabricated into their respective manifolds and tested in the hydraulic subcontractor's facilities. After validation in this shop, the manifold assemblies, along with the hydraulic cylinders, are forwarded to the bridge site at any convenient time.

In summary, components used in the swing span control system are readily available easily fabricated from common materials.

MAINTENANCE AND RELIABILITY

Maintenance of the swing span control system is the responsibility of the Bridge Maintenance Section of LaDOTD. Maintenance work is performed by work crews, located in districts around the state, and by a statewide crew, supervised by engineers or Engineers-in-Training. Maintenance on mechanical and hydraulic systems performed by crews, the majority of which have no formal machinist, millwright, or hydraulic journeyman training. Electrical maintenance is performed by crews with limited electrical training. Therefore, to minimize having to draw on external consultants for maintenance of the swing span control system, the control system components are designed to be intuitive. This allows limited skilled workers to quickly determine faults and make repairs.

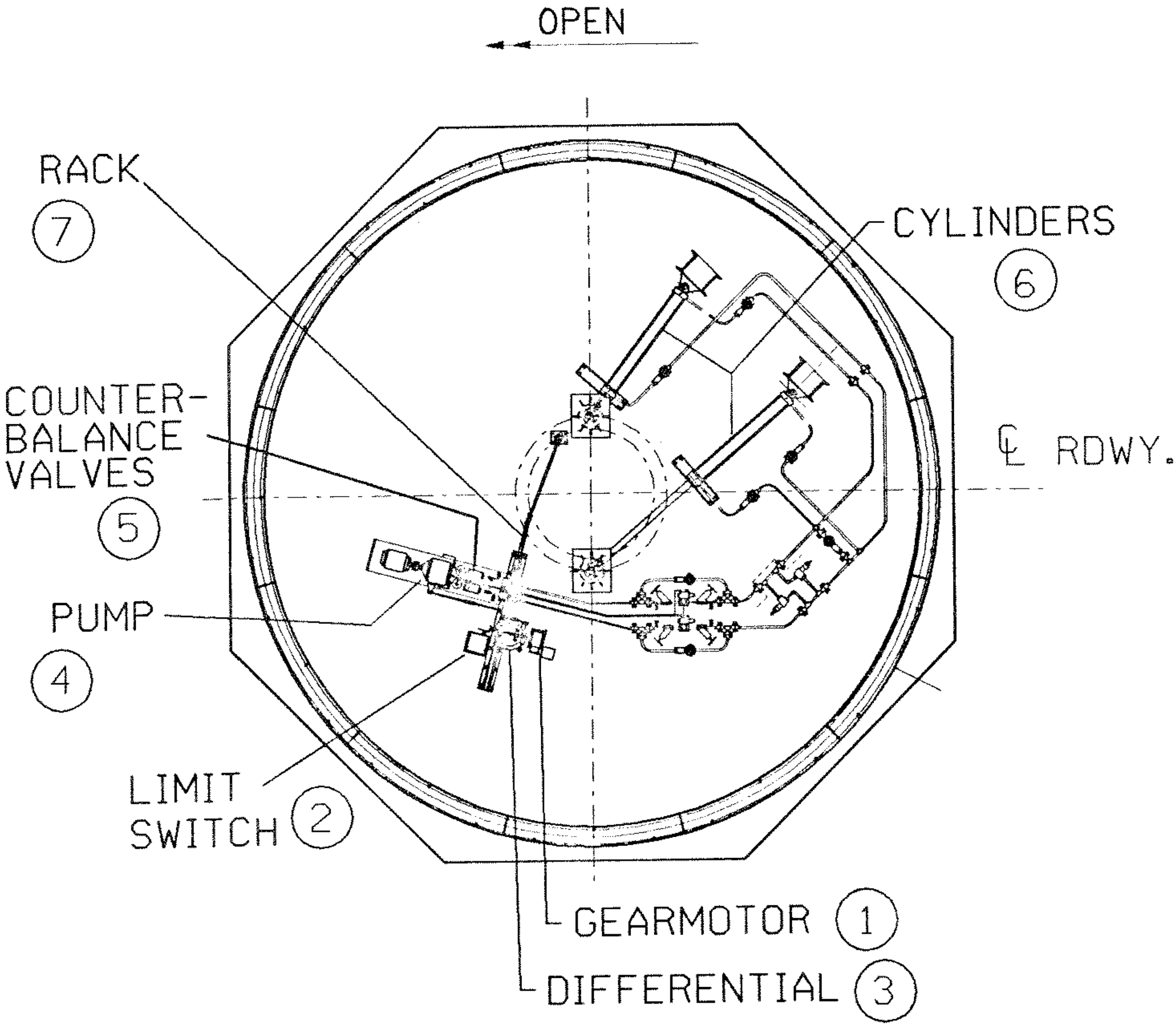
Downtime and cost are reduced by drawing on available personnel for inspections of reported breakdowns. Hours would be lost should the Department request a consultant to travel to a bridge to determine the cause of a malfunction. Available maintenance personnel can be at the sight quickly and are capable of determining most causes of system failures. Should state of the art electronics be used, fragile electronic diagnostic equipment would have to be transported, at additional cost, to the bridge. In some cases, control system parts would have to be removed from the bridge and transported for shop testing. A convenient machine shop can fabricate any new part. The sophisticated electronics may require replacement of a card or a printed circuit board for the failure of one component on that board. Additionally, vendors can't guarantee that a particular printed circuit board will be available in five or ten years from installation which means the system would have to be completely rehabilitated in case of failure.

Disassembly and adjustments to the control system are made with common tools. The limits of the swing span are set in the rotary limit switch. Removing cap screws, loosening lock nuts, adding, removing or shifting adjustment shims are made with a handful of wrenches, pliers and screwdrivers. Moving parts are provided with easily accessible lubrication points. Areas susceptible to vibration are bolted with prevailing torque nuts. Electrical connections are made in easily serviceable junction or device boxes. All electrical conductors are marked with easy to read markers. Continuity and voltage tests are made with a portable volt-ohm meter. Hydraulic oil filters are accessible for easy replacement. Oil reservoir filler necks are conveniently located for oil replacement. Large access doors in the reservoir allow maintenance crews to mop the inside as required.

Reliability of the swing span control system has been very good. This design has been used for 25 years. Statistical analysis of the system is not available since there has been only four failures. One failure was the cylinder piston seals. This failure was caused by fluid contamination. Sand and water in the fluid pitted and eroded the seals and cylinder bore. This failure could have been prevented by changing the 10 year old fluid. Two failures were caused by marine vessel impacts. One impact knocked the movable span off its pivot onto the cylinders and pump unit. The second impact bottomed the cylinders. One cylinder rod end was stripped off, the other cylinder had the rod buckle. The fourth failure was caused by high water flooding the system. The system components were flushed, refurbished and returned to service.

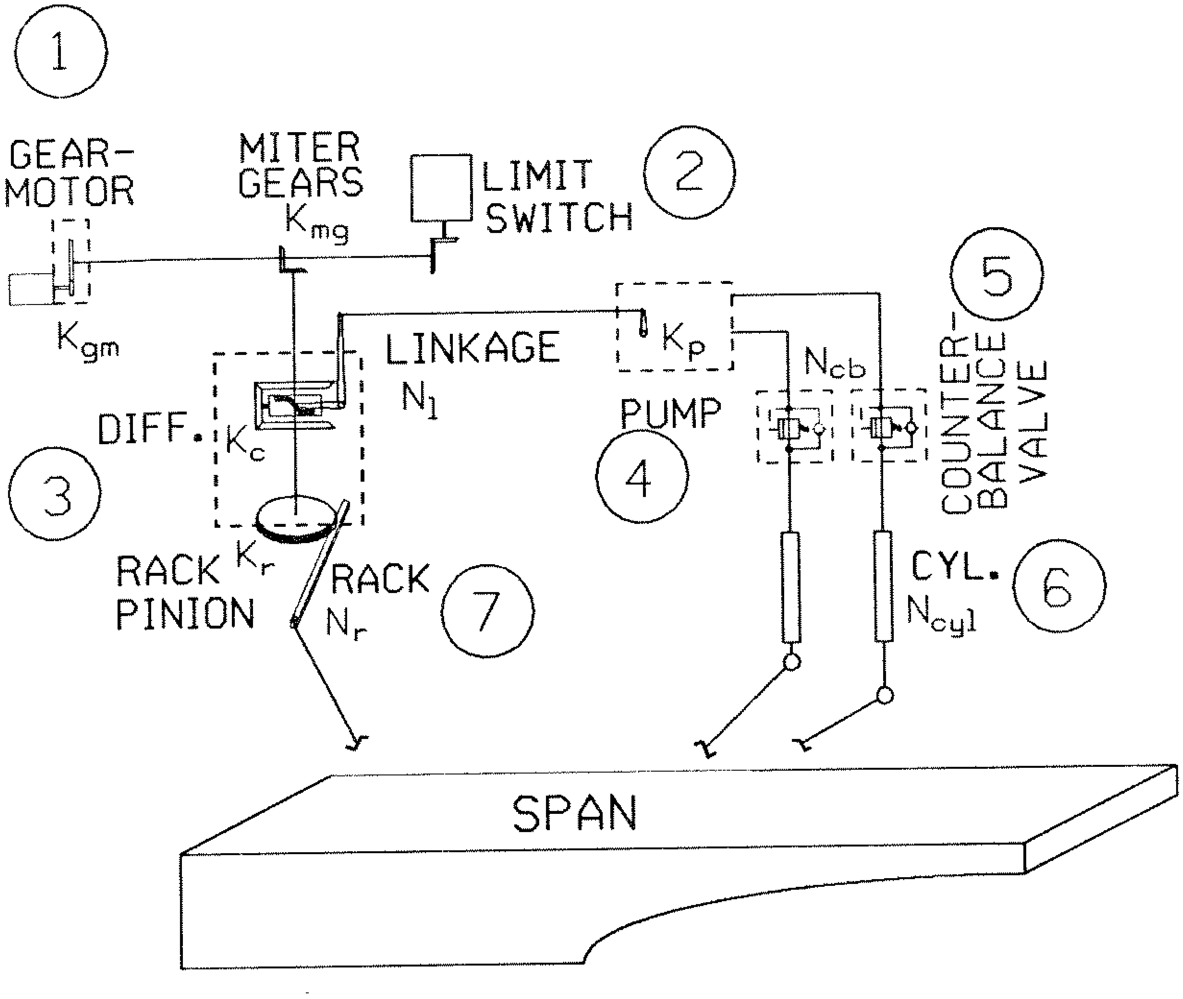
This system or variants there of, has been used since 1962 with only one failure not caused by external forces. Frequency of operation varies from 1982 openings/month to 6 openings/month. The Department is proud of the swing span control system's maintainability and reliability record.

FIGURE 1



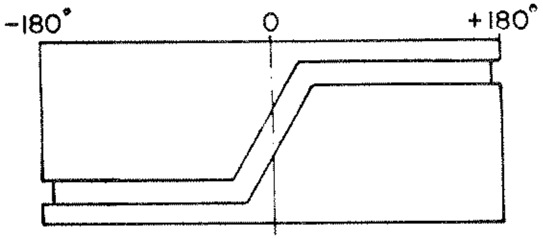
Swing Span Control System Layout

FIGURE 2

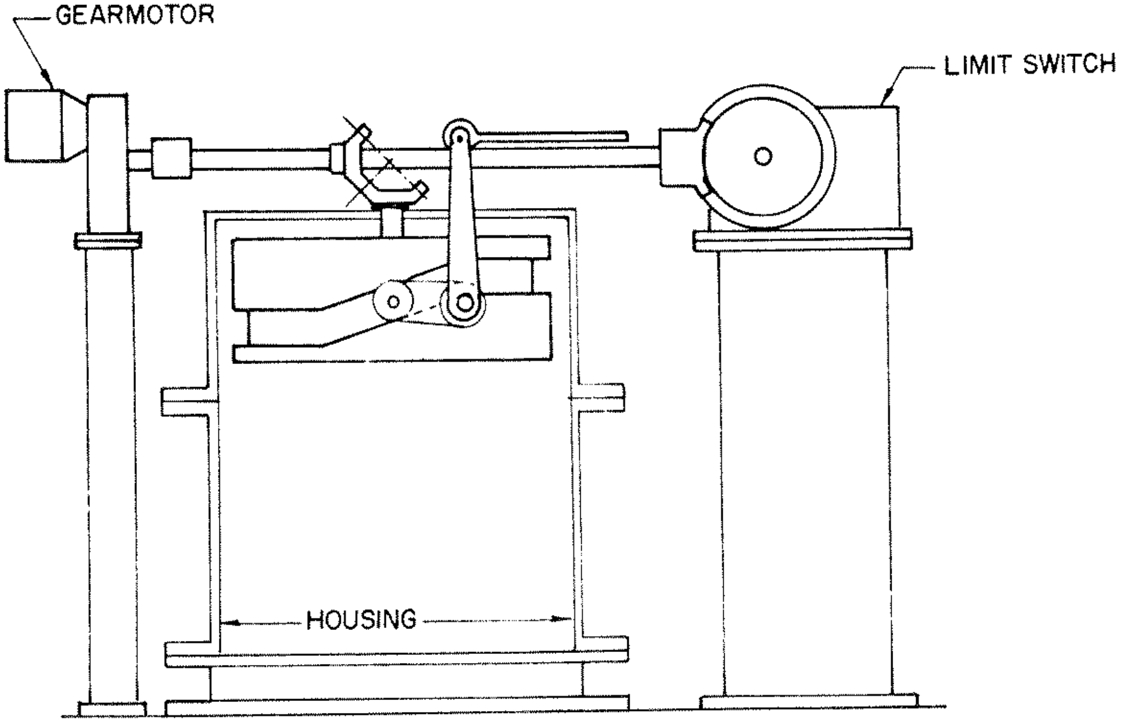


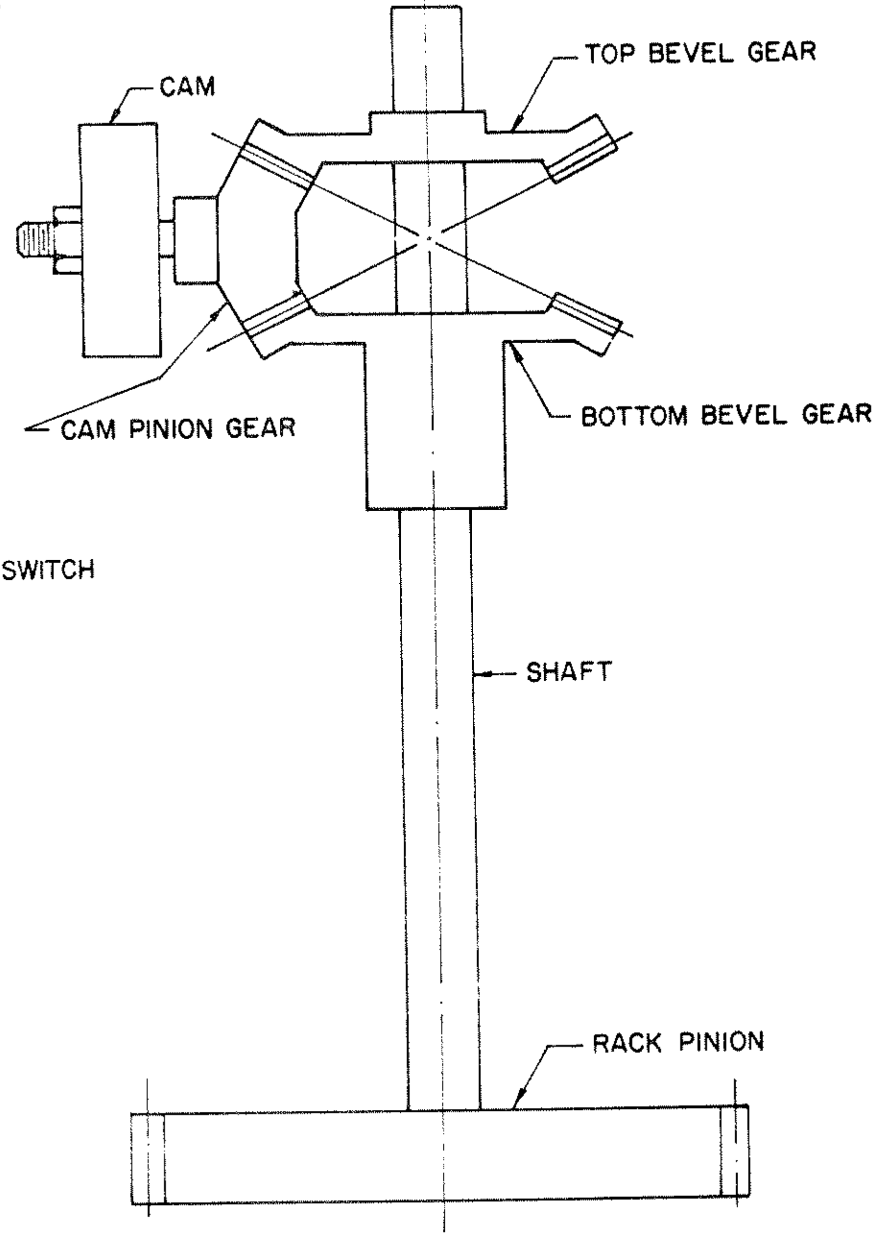
Swing Span Control System Schematic

FIGURE 3



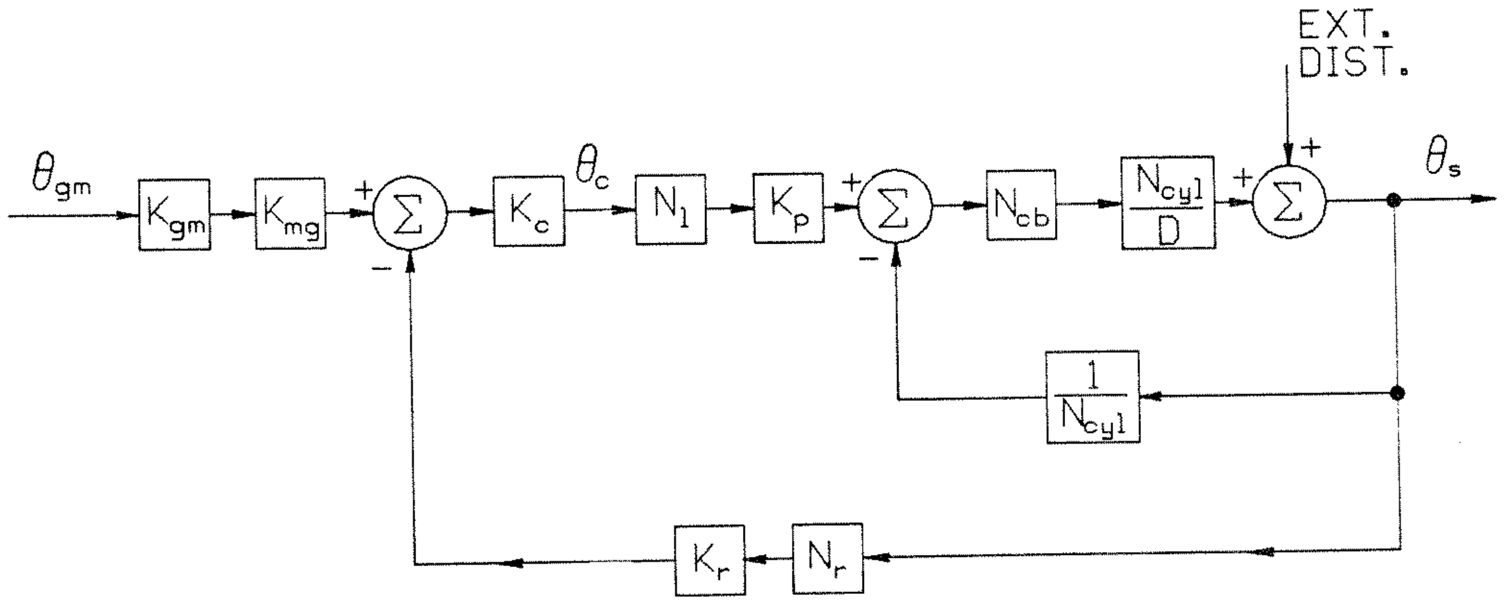
CAM DEVELOPMENT





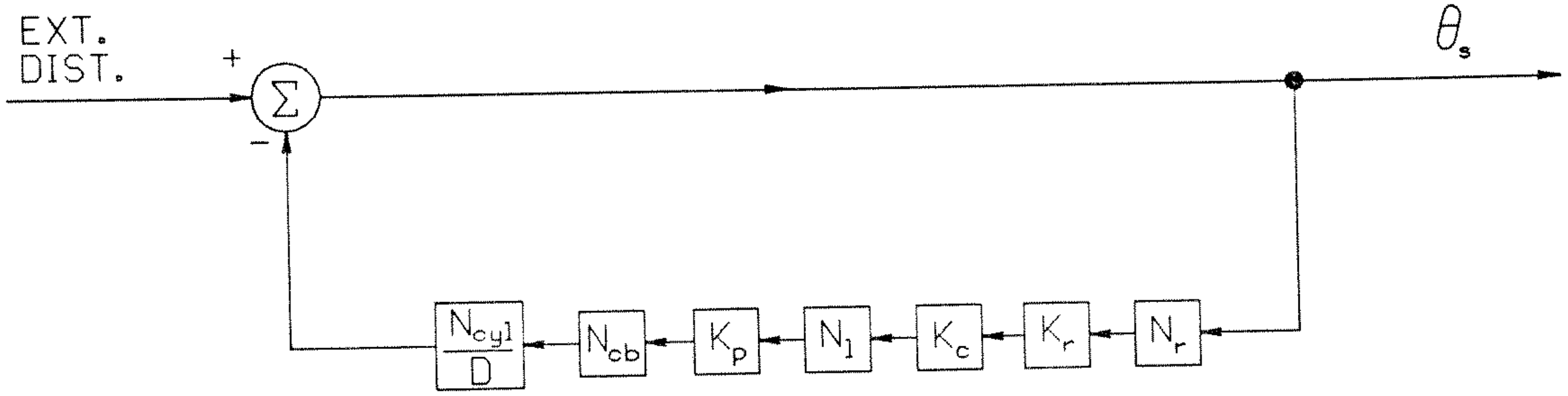
DIFFERENTIAL SCHEMATIC

FIGURE 4



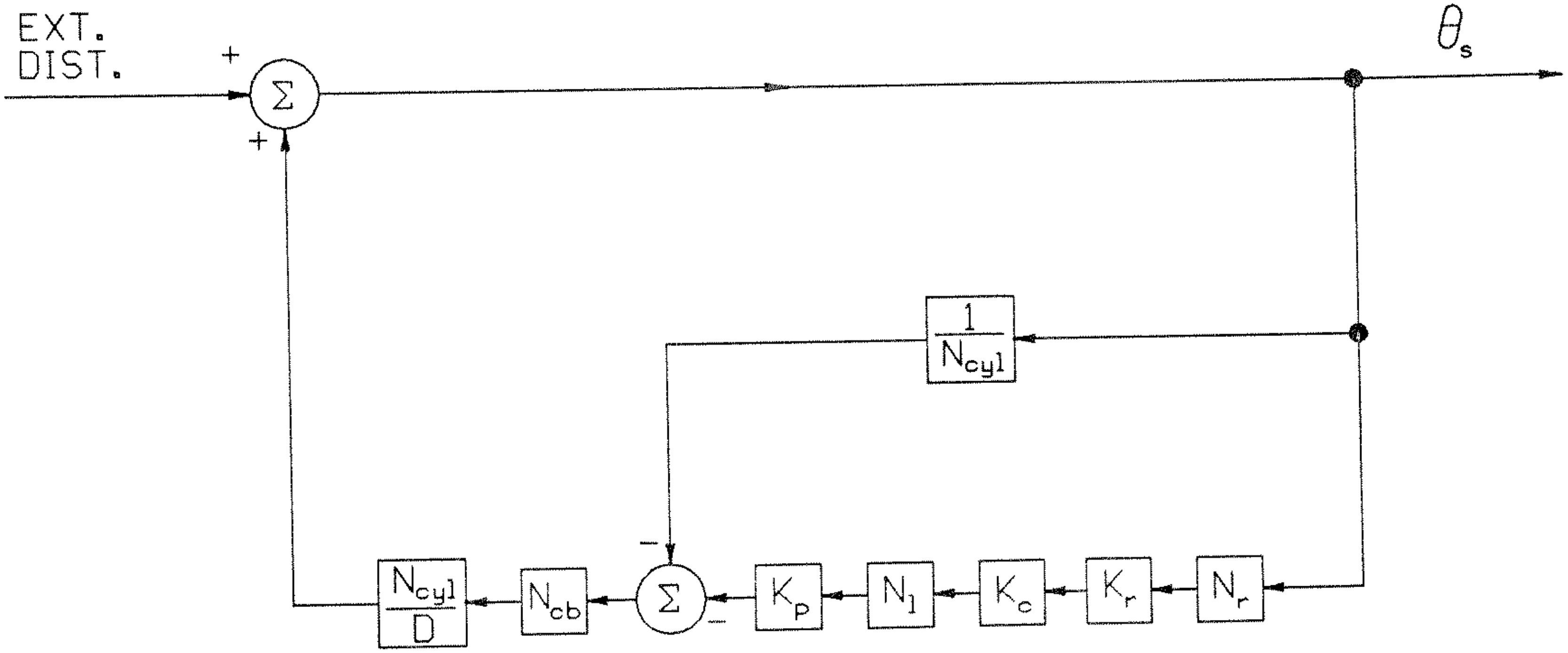
Swing Span Control System

FIGURE 5



External Disturbance Signal Path
Without Internal Feedback

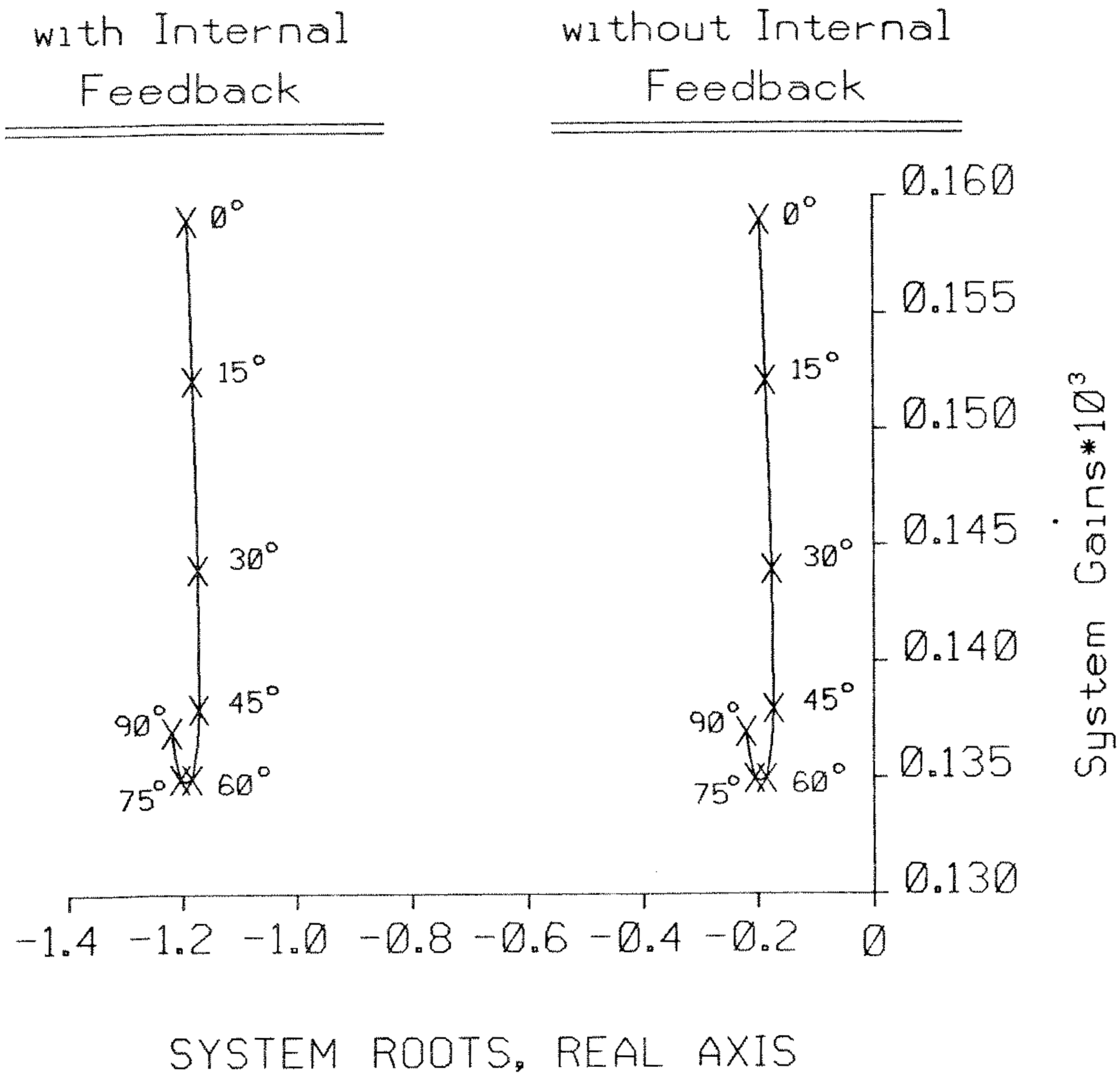
FIGURE 6



External Disturbance Signal Path
With Internal Feedback

FIGURE 7

System Gain vs.
Real Root Loci at
Various Span Angles



with Internal Feedback

without Internal Feedback