AMERICAN CONSULTING ENGINEERS COUNCIL'S

HEAVY MOVABLE STRUCTURES
MOVABLE BRIDGES AFFILIATE

3RD BIENNIAL SYMPOSIUM

NOVEMBER 12TH - 15TH, 1990

ST. PETERSBURG HILTON & TOWERS
ST. PETERSBURG, FLORIDA

SESSION
WORKSHOP NOTES

Session (3-12)
"Operational Tests of Swing Span with Multiple Independent Drives",
C. Birnstiel, Consult'g Engr'g, NY

OPERATIONAL TESTS OF SWING SPAN WITH MULTIPLE INDEPENDENT SPAN DRIVES

by

CHARLES BIRNSTIEL
Consulting Engineer, Forest Hills, NY 11375

ABSTRACT

Tests to determine pinion shaft torques during normal operation of a center bearing swing span having multiple identical, independent, span drives are described. The effect of the absence of mechanical equilization between the multiple pinion shafts was apparent from the simultaneous torque measurements which showed the instantaneous variations in torque between the pinion shafts during driving and braking.

While driving, both during acceleration and at running speed, the multiple pinion shafts were stressed to the same order of magnitude. However, during braking the measured stresses were markedly different due to the fact that the action of the three independent brakes was not identical. The need for control of sequence of brake setting and limits on the brake torque of that brake which sets first, in order to avoid damage to the machinery, was demonstrated.

INTRODUCTION

Swing bridges are sometimes constructed with span drives comprising two or more pinions engaging a common rack mounted on the pivot pier, each pinion being driven by an independent drive. In such machinery arrangements the multiple pinions are not connected together mechanically in order to equalize the pinion shaft torques. It is usually assumed that because the same size and model motors, speed reducers, and brakes are used for each drive that the driving torques applied to the pinion shafts are alike for all shafts, or nearly so.

Sometimes the brakes are wired and adjusted such that they are intended to set simultaneously. In other cases, the setting of the brakes is under bridge operator control. In either situation of brake control, the reality is that one brake will set before the others. The consequence is that the braking forces are not applied simultaneously to the rack at all pinion locations. If the braking capacity of the first brake that sets is excessive, for whatever reason, the machinery for that drive, and the common rack, may be overstressed under some conditions of deceleration.

The George P. Coleman Memorial Bridge is a tandem swing bridge with multiple independent drives for each draw. Because of repeated failures of pinion shafts and racks, tests were conducted to determine which brakes set first and the variation in pinion shaft torque due to braking under normal operating conditions. Some of the results of that investigation are described in this paper.

BACKGROUND

The George P. Coleman Memorial Bridge is a two-lane highway bridge that supports U.S. Route 17 over the York River at Yorktown, Virginia. Included within it's overall length of 3,750 feet between abutments are two center-bearing swing spans, each 500 feet long, arranged in tandem. The spacing of the two pivot piers is 500 feet, giving a horizontal clearance of 450 feet for the navigation channel. The vertical clearance under the closed draw is about 60 feet. In this paper the bridge is considered oriented north-south.

Each draw is rotated by a mechanical span drive driven by electric motors. As shown in Figures 1 and 2, each span drive comprises three electric motors with associated reduction gearing which drive three pinion shafts that engage a circular rack mounted on top of the pivot pier. In this paper each one of these electric motors and gearing is termed a drive unit. The three drive units are completely independent except for the final gear reduction stage at the common rack. There are no mechanical differentials to equalize the torques of the three pinion shafts. Each unit has a spring-set, thrustor-released, shoe brake located between the motor and the speed reducer. The brake wheel is bolted to one hub of the coupling that connects the motor shaft to the bevel input shaft of the reducer.

Because of the lack of mechanical or electronic load-sharing between the three pinion shafts, and because the motors and controls are not identical, the torque in the shafts can differ during driving. During braking unequal loading of the pinion shafts was almost assured because the controls were such that each brake could be set and released individually. Even if all three brakes could have been applied or released simultaneously, the pinion torques would likely have differed because of the variation in braking characteristics due to differences in the mechanical and hydraulic adjustments of the brakes and variations in brake-wheel friction.

Prior to 1989 components of the north span drive failed, including the rack and some pinion shafts. Because of these repeated failures the Virginia Department of Transportation (VDOT) decided to measure the magnitude of the torques in these shafts under normal operating conditions. Of particular interest was the variation of torque between the shafts. Accordingly, VDOT authorized Charles Birnstiel, Consulting Engineer, P.C., to simultaneously measure the torque in the pinion shafts of each draw by the strain gage technique.

SCOPE

The scope of work was limited to measurement of torque in pinion shafts, determining the order in which brakes were released during operation, the examination of brake wheel faces, and measurement of brake spring lengths. No other mechanical or electrical components were inspected.

EQUIPMENT

Strain Gage Instrumentation

In order to determine the torque in the pinion shafts the torsional shear strain at the surface of the shaft was measured. The value of the shaft torque can be computed from these strains using structural mechanics principles.

Foil strain gages were installed on the shafts at the locations shown in Figure 2. In effect, the instrumented shafts were used as transducers. They were approximately of the same diameter. In the area where the gage was to be mounted the shaft was ground down to a level below the machining marks by means of a portable grinder. Grinding was followed by surface treatment per instructions of the strain gage manufacturer for the type of adhesive used. Dual-arm strain gage rosettes were installed with the arms oriented at 45 degrees to the shaft axis. The gages on a shaft were wired to a channel of an amplifier/conditioner in a half-bridge configuration. Lead wires were "heavy copper", of the shortest length practicable (with all leads of the same length) so as to minimize lead-wire desensitation. The lead cables were shielded. The lead cables were wrapped around the shafts and tensioned with a pulley and weight arrangement in a manner such that they unwrapped and then wrapped around the shaft as the draw was rotated 90 degrees. Output of the amplifier/conditioner was inputed to a strip chart pen recorder.

Calibration of the strain recording system was by means of the shunt calibration resistor built into the amplifier/conditioner. Because the shear strains in the three pinion shafts of a draw were to be measured simultaneously, the first three channels of the amplifier/conditioner and the recorder were assigned to this purpose.

Brakes Released Detection

The fourth channel of the recorder was utilized to record the brakes released at any instant and to count the number of revolutions of the pinion shaft. A "black box" circuit was custom designed and assembled for the purpose of putting four channels of "black box" information on the fourth channel of the recorder.

Three channels of the "black box" were used to indicate which brake thrustors were completely extended. The circuit was such that an excursion of the Channel 4 pen (brown) occurred when a brake release limit switch (normally-closed contact) opened. The pen returned when the limit switch contact closed. It should be noted that a functioning brake will be effectively released before the thrustor activates the brake release limit switch. The time advance depends on the settings of the mechanical and hydraulic adjustments of the brake. Similar behavior occurs on brake setting, except that actual setting lags behind the pen indication.

Revolution Counter

A signal was superimposed on the brake-released channel to indicate when an event counter switch was opened, thereby indicating that a magnet attached to the pinion shaft had passed from proximity to the stationary event counter switch. The brake numbers marked on the strip charts (Figures 3 and 4) correspond to those on the span drive diagram (Figure 1).

TEST PROCEDURE

The procedure for making a measurement run for a normal draw opening, after all wiring is completed and tested, was as follows:

1. With the draw closed, calibrate all strain gage channels using the shunt calibration feature of the 2100 System.

2. Initialize all pens and start chart paper motion.

3. Release all span drive brakes (from drum switch on control desk). Nudge draw open a bit to free it from the seating buffers.

4. With brakes released and the draw "floating", reset all strain gage channel pens to zero. Do not reset the brake release pen (Channel 4).

5. Energize motors to open draw in the normal manner. However, make an intermediate stop at about 45 degrees of opening in order to determine effect of brake application at this angle.

6. Continue opening draw to fully-opened position in the normal manner. Hold open for a short period.

7. Close draw in normal manner except make an intermediate stop at about 45 degrees of opening.

8. After the draw has been seated and the span drive wound up, set all brakes and stop chart paper motion.

DATA OUTPUT FORMAT

The format of the recorded measurements will be described with the aid of Figure 3, a typical annotated strip chart. On the top edge of the chart are lettered black station numbers (STA) which are distances from the left edge of the chart in centimeters. This stationing is used to aid in referring to features of the chart. Below the stationing, also in black, are remarks concerning the draw position and the direction of motion. The green trace is the measured shear strain on Shaft N-2 which, in this case, is output from Amplifier Channel 1 through Recorder Channel 1. The scale for shear strain is marked in green at the left edge of the chart. Similarly, the blue trace is the measured shear strain on the surface of Shaft N-1.

The correspondence between shaft numbers and amplifier and recorder channels is given in the table near the right end of the chart. In this table are also listed the strain gage bridge excitation voltage, amplifier gain, recorder channel span, and chart travel speed.

The brown trace near the chart bottom is output from the "black box" which indicates the released brakes. This trace also shows when the event switch is closed. That switch is mounted such that it is closed when the draw is in the fully-closed position. When the draw starts to move the event magnet, which is mounted on the pinion shaft, moves and the event switch opens thereby increasing the excursion of the brown pen. At the completion of the first revolution as the magnet passes by the proximity switch it closes the circuit and produces the tick mark. One revolution of the pinion shaft represents about 11 degrees of draw rotation. The angle of draw opening is marked in black along the bottom of the chart.

The pen recorder is constructed such that the pens are stationary and offset in the direction of paper motion. The paper moves to the left and hence the traces are considered to advance to the right.

ANALYSIS OF RESULTS

Five test runs were made, three for the north and two for the south draw. The observed behavior among the runs for a draw was similar, hence only one run for each draw will be described subsequently.

North Draw - Run 3 - Opening

At the time of the tests, Shaft N-3 had been removed from the north draw span drive and Brake 3 was hand-released. Therefore, there are only two strain plots in Figure 3 and the brown trace records the release of Brakes 1 and 2.

Figure 3 shows that, after preliminary initialization, all brakes were released (STA 3) with the result that some wind-up strains in the shafts were released, as indicated by the upward motion of the green and blue pens. Because the completeness of strain release was uncertain the draw was nudged open and the pens for the strain plots re-zeroed with the draw "floating". By STA 16 the zeroing was accomplished. Motors 1 and 2 were then energized step-wise by the Draw Tender at the control console to open the draw. The maximum power point applied to the north draw was No. 4 (PP 4) by administrative order inasmuch as one of the three drives was not functioning. From Station 17 through 23 (STA 17-23) the draw accelerated and the maximum shear strain was about 350 microinches, experienced by Shaft N-2. From STA 23-27 power was at PP 4 and both shafts drove the draw. During this region of nearly uniform speed the strain in Shaft N-1 averaged 25 microinches and that in Shaft N-2 about 50 microinches. Power was reduced step-wise starting at STA 28 and Brake 2 was set at STA 34 (Brake 1 was still released) for an intermediate stop. The braking shear strain in Shaft N-2 was in excess of 1200 microinches. Brake 1 was set after Brake 2 had decelerated the draw with the result that the strain in Shaft N-1 was about 400 microinches.

The plots in region STA 34-37 illustrate two aspects of braking behavior on this draw. Firstly, the shear strains (and consequently torsional stresses) in Shaft N-2 due to braking were at least three times as large as those due to acceleration by Motor 2 under PP 4. Secondly, the work done by Brake 2 was at least three times that done by Brake 1. This situation is due to many factors, but the major one is the delay between setting Brake 2 and 1, which was mainly due to the speed at which the Bridge Tender turned the drum switch on the control console.

The draw was held open from STA 36-44. During this period the strains in the two shafts were alike in sign and nearly alike in magnitude. They were caused by wind. At STA 43, Brakes 1 and 2 were successively released and power applied at STA 44 to continue the opening. Power was cut at STA 57 (automatic cut-out) and the draw coasted till Brake 2 was applied at STA 60 in order to make the Nearly-Open stop. During coasting the draw was back-driving the machinery as evidenced by the reversal of sign of the shear strains in both shafts. The braking strain in Shaft N-2 was about 800 microinches. Brake 1 was applied about 11 seconds after Brake 2. By that time the draw had stopped and Shaft N-1 was strained to about 200 microinches by the oscillations of the draw.

The draw was held in the nearly-open position for about 12 seconds and then the two brakes were successively released, and then the motors were energized at STA 64. While the draw was open the braking strains were small because of the nearly calm wind condition. Opening was restarted at STA 64 under PP 1, then PP 2, and then PP 1 till de-energization at STA 68. Brake 2 set soon thereafter to stop the draw at the fully-open position. Brake 1 was applied about 7 seconds after Brake 2. The braking action at this stop was similar to that at the previous stop except that the strains in Shaft N-2 were about 25 percent greater.

North Draw - Run 3 - Closing

Referring again to Figure 3, after being held in the fully open position for about one minute, Brakes 1 and 2 were successively released (STA 79) and the draw accelerated in the counterclockwise direction starting at STA 81. The maximum shear strain was 330 microinches, in Shaft N-2. PP 4 was held from STA 84 to 91. During that time the torque in Shaft N-2 was about double that of Shaft N-1. This behavior was similar to that recorded during opening. The motors were not equally loaded during driving beause there is no positive load-sharing device in the span drive.

At STA 91 the power was reduced step-wise till Brake 2 was set at STA 96 for an intermediate stop. The strain in Shaft N-2 was about 1120 microinches. By the time Brake 1 set most of the braking had been done and Brake 1 served mainly to dampen oscillations. The maximum strain in Shaft N-1 was 270 microinches.

At STA 103 the brakes were released and the motors energized at STA 106 to continue the closing. After deceleration Brake 2 was applied at STA 120 to stop the span at the nearly-closed position. The strains in Shaft N-2 exceeded 800 microinches. Brake 1 was not set, and therefore Shaft N-1 was strained only by the interaction of the vibrating system - the maximum strain was about 100 microinches.

At STA 126 the motors are shown energized for closing the draw against the buffer device and seating it at the Fully-Closed position (STA 136). After seating the motors were wound-up at PP 2 for about a minute before Brakes 2 and 1 were successively set at STA 145. The wind-up strain locked into each shaft was about 200 microinches. After the brakes were set for about 15 seconds the motors were de-energized and the remaining actions necesssary to secure the draw accomplished.

South Draw - Run 2 - Opening

The result of the second run on the south draw are shown in Figure 4. As the format and the results are very similar to those of Figure 3, these results will be described briefly, highlighting only the significant features. All three drives functioned and hence there are three strain plots and Channel 4 records the release of three brakes. The normal order of brake release (at the drum switch control) is 1, 2, 3 and that of brake set is 3, 2, 1.

For this run the draw was partly opened and then almost closed in order to free the shafts of residual wind-up strains. The strain pens were zeroed at STA 9 with all brakes released and the draw "floating". During opening acceleration (STA 10-15), Shaft S-1 experienced the largest maximum strain, about 400 microinches. Drives S-1 and S-2 exerted about the same effort. The work done by Shaft S-3 was less than half of either Shafts S-1 or S-2.

At the Intermediate Stop (STA 23) Brake 3 was set first, followed by Brake 2 and Brake 1. (See discussion under Instrumentation for the reason that Channel 4 may show a different sequence when the drum switch is moved rapidly, as it evidently was at this stop) The maximum braking strains in Shafts S-1, S-2, and S-3 were 120, 850, and 600 microinches respectively. Brake 3 participated only in resisting rebound.

When opening continued at STA 31, the distribution between work done by the three shafts was similar to that at the start of opening; Drives 1 and 2 did about the same amount of work and Drive 3 about half of either Drive 1 or 2.

At the Nearly-Open stop (STA 44) Brake 3 was set first and Brakes 2 and 1 set after the draw was virtually stationary. As a consequence Shaft S-3 was strained in excess of 800 microinches and Shafts S-1 and S-2 to about 100 microinches.

At the Fully-Open stop the drum switch was turned so fast that the order of set was probably 2, 1, 3. The maximum braking strains were >1000, 850, and 520 for Shafts S-2, S-1, and S-3 respectively. Brake 3 resisted mainly rebound.

South Draw - Run 2 - Closing

Closing started at STA 60 and the drives shared the load in about the same ratios as at opening. At the Intermediate Stop (STA 75) the brakes were set in the sequence 3, 2, 1. Brake 3 did most of the work as evidenced by a strain in excess of 1200 microinches. Closing continued at STA 88 with Drives 1 and 2 doing most of the work.

At the Nearly-Closed stop (STA 99) the braking action was similar to that at the previous stop. Seating started near STA 111 and wind-up at STA 115. The windup strains were 330, 320, and 200 microinches for Shafts S-1, S-2, and S-3 respectively.

Summary of Measured Shaft Strains

The maximum shaft strains measured during various phases of draw operation are summarized in Table I. Obviously, the largest strains are produced during braking; by that brake which sets first. The maximum observed strain exceeded 1200 microinches which represents a torsional shear stress of at least 15 ksi.

CONCLUSIONS

Based on the dynamic strain gage measurements and brake release data recorded on the annotated strip charts reproduced as Figures 3 and 4, and a visual examination of the brake wheels, it has been concluded that:

1. The maximum torque observed in any shaft was due to braking.

2. The observed ratio of maximum braking torque to maximum acceleration torque produced by a motor varied from 1.3 to over 3.

3. On both draws, at any stop, the maximum braking torque occured in the shaft connected to the brake which set first. Usually this was Shaft N-2 on the north draw and Shaft S-3 on the south draw.

4. On the north draw, Drive N-2 did approximately twice the work of Drive N-1 during acceleration and rotating the draw.

5. On the south draw, the work done during acceleration and rotating the draw by Drive S-1 was slightly more than Drive S-2. Drive S-3 did half the work of Drive S-1.

Note that the measurements recorded in Figures 3 and 4 were made under good environmental conditions. The weather was warm and the wind velocity low. Under other weather conditions the braking forces may be larger.

ACKNOWLEDGEMENTS

This paper is essentially an extract from a report entitled "Measurement of Torque in the Pinion Shafts of the George P. Coleman Bridge Over the York River" submitted to the Department of Transportation of the Commonwealth of Virginia in July, 1989, by Charles Birnstiel, C.E., P.C. The Author is grateful to Mr. Charles E. Morris, Assistant District Engineer VDOT, for permission to use material from that report and for his assistance during the field investigation.

TABLE I - MAXIMUM MEASURED SHAFT SHEAR STRAINS FROM FIGURES 3 AND 4 IN MICROINCHES

	Shaft				
Loading Condition	N-1	N-2	S-1	S-2	S-3
Opening:					
Acceleration	300	350	400	310	120
Intermediate Stop	400	>1200	600	850	1120
Nearly-Open Stop	100	800	60	120	>800
Fully-Open Stop	220	1060	850	1000	520
Closing:					
Acceleration	280	330	530	360	230
Intermediate Stop	270	1120	350	540	>1200
Nearly-Closed Stop	100	>800	560	560	>1200
Seating	270	270	330	400	270
Wind-up	200	220	330	320	200

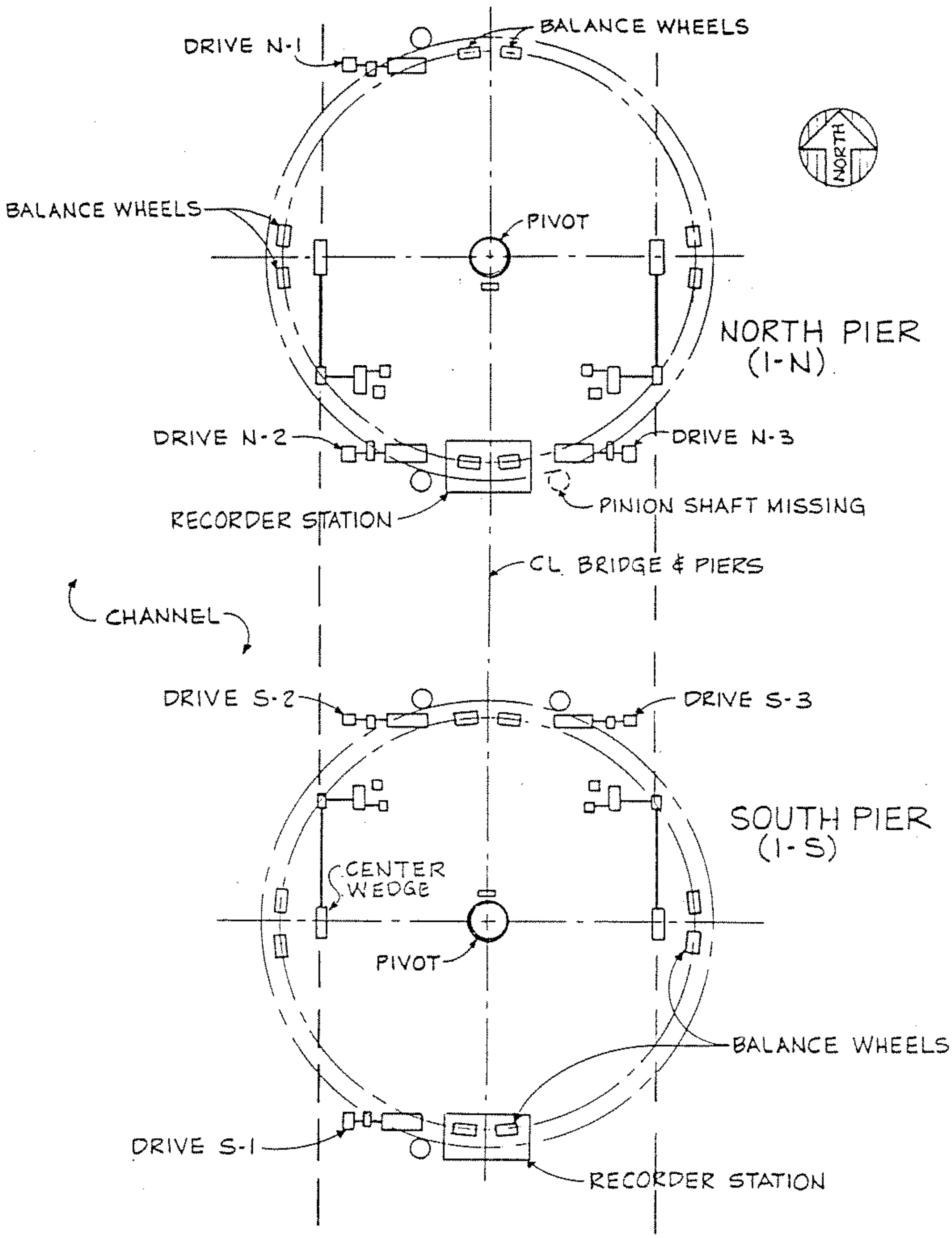

FIG. 1 - DIAGRAM OF SPAN DRIVE UNITS AND PINION SHAFTS AND NOTATION

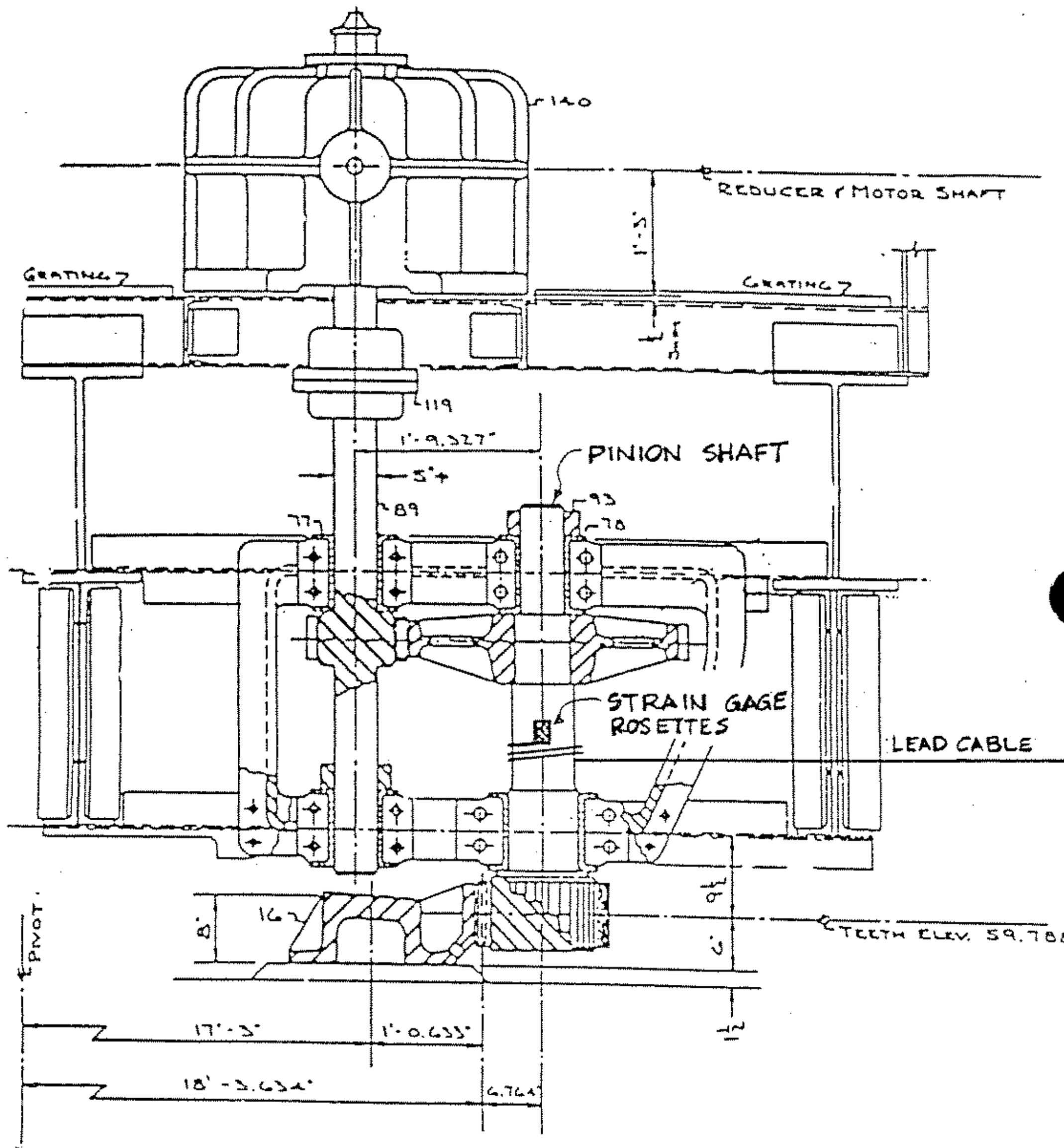

FIG. 2 - CROSS SECTION AT DRIVE UNIT SHOWING LOCATION OF STRAIN GAGE ROSETTES

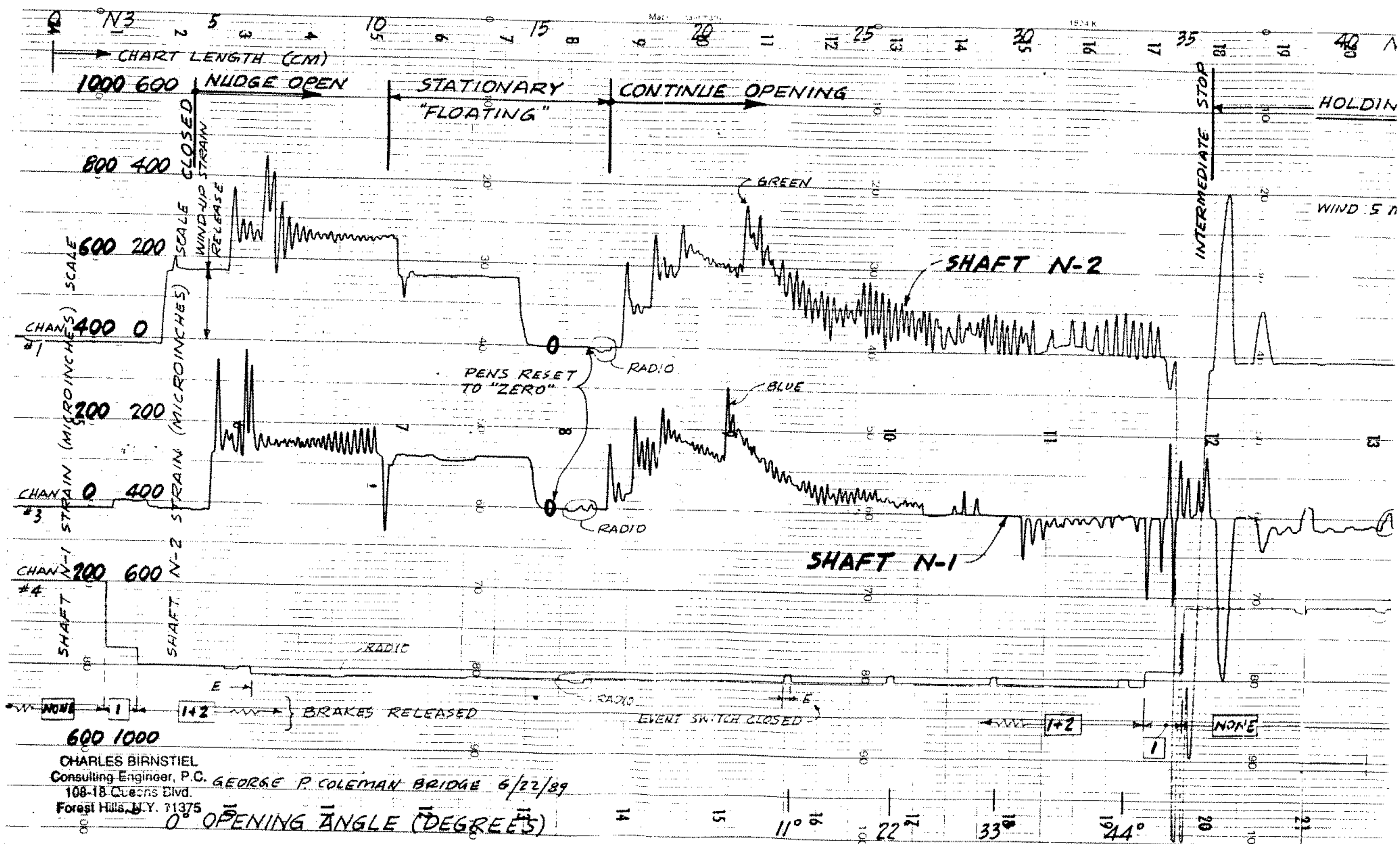

FIG. 3(a) - NORTH DRAW - RUN 3. PLOTS OF MEASURED SHEAR STRAIN AND BRAKE RELEASES

FIG. 3(b) - NORTH DRAW - RUN 3. PLOTS OF MEASURED SHEAR STRAIN AND BRAKE RELEASES

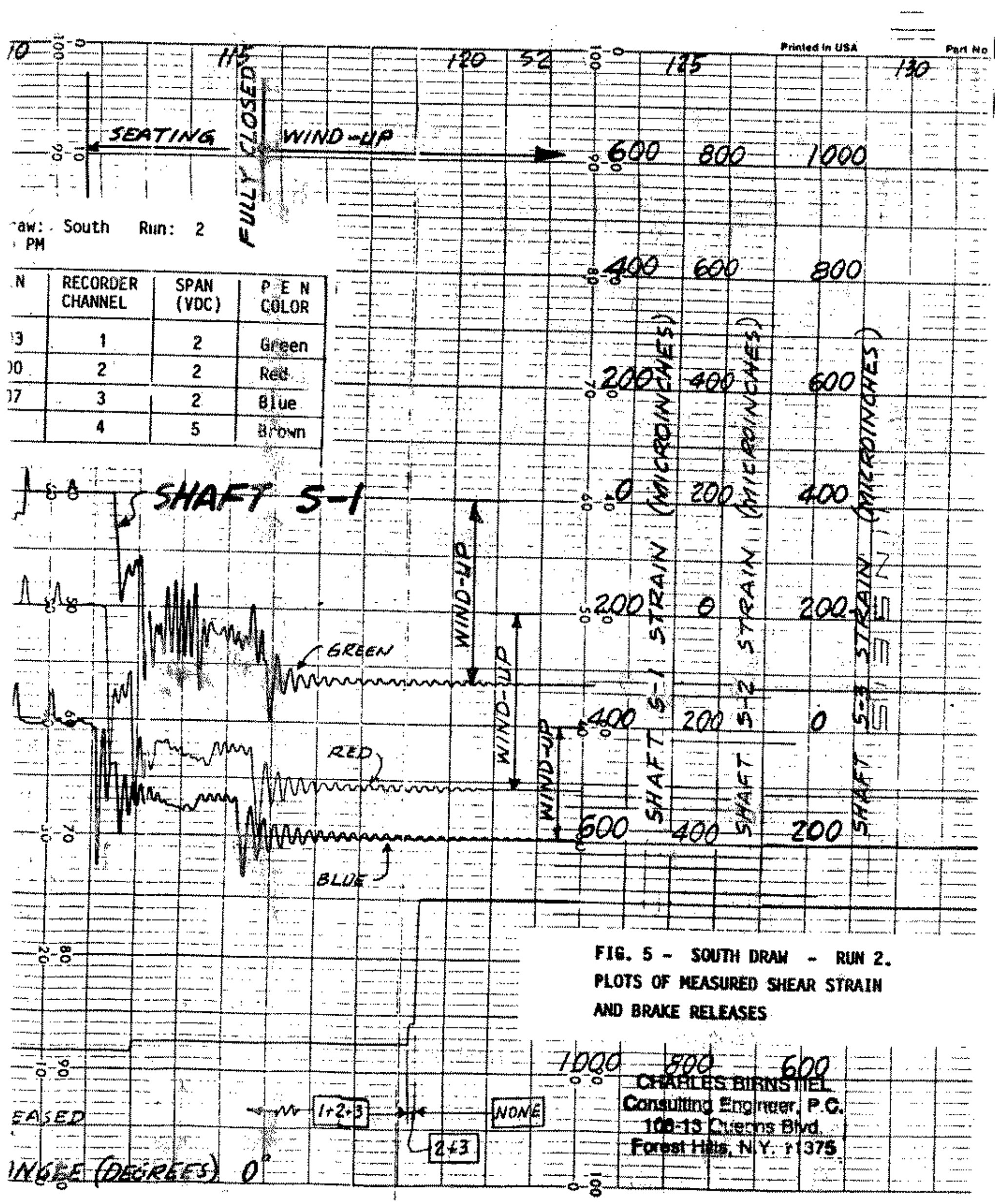

FIG. 4(d) - SOUTH DRAW - RUN 2. PLOTS OF MEASURED SHEAR STRAIN AND BRAKE RELEASES