BALANCING OF TRUNNION-TYPE BASCULE BRIDGES

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1. INTRODUCTION

Since about 1925 most of the movable bridges built for United States highways have been of the bascule type, where the opening leaf is balanced by a counterweight (2). In the trunnion type of bascule the combined leaf and counterweight structure pivots about fixed trunnion bearings, and the center of gravity of this rotating part is at or near the axis of rotation (2,3). Accumulation of paint, dirt, structural additions and other changes often lead to excessive imbalance and increased motor torque and power requirements. In 1980 the University of Florida began a study of bascule bridge balancing under a contract with Florida's Department of Transportation (DOT). At that time, the Florida DOT operated and maintained 194 movable bridges with an average age of 31 years. Thirty-nine of the bridges had been in operation more than 50 years. Costly refurbishments necessitated by the wear out of machine elements in the drive systems of bascule bridges provided an impetus for minimizing unnecessary loading of the machinery.

Leaf balancing of trunnion-type bascule bridges in Florida had previously been accomplished by engineering judgment based on observation of the downward drift rate of an open span with no power, observation of motor current during opening, and torque wrench measurements. In 1977 Ecale et al. (1) reported a new balancing technique. Strain gages on the final pinion drive shaft measured the torque that was required to hold the span in two or more partially open positions. The trial and error correction was then performed mathematically on a cosine curve representing the torque versus opening angle instead of physically with the movable weights. This has the advantage of reducing traffic interruption time. A modification of the technique of Ecale et al. (1) was developed at the University of Florida and is reported here.

The modification consisted first of continuous recording of the strain-gage outputs representing driveshaft torque during opening and closing of the leaf. In the first applications of the revised procedure the amplified signals were recorded by plotting torque versus angle of opening of the span on an xy-plotter for subsequent analysis. Because of a large amount of superimposed mechanical noise on these continuous records, the imbalance analysis was made on two parallel smooth curves drawn through the opening and closing curves instead of on the original curves. A cosine curve representing the impalance state was fitted to the average curve halfway between the opening and closing smooth curves. The basis for the analysis will be explained in Section 2. Details of the procedure have been reported in a handbook for the DOT (4) and a brief account of the analyisis in a published paper (5).

The procedure was further revised by the authors under another Florida DOT contract (6) completed in March 1985. The revised procedure includes automatic data acquisition with a microcomputer and data storage on floppy disks for subsequent analysis. With the first procedure the cosine curve was fitted to five to ten data points on each of the smoothed opening and closing curves, selected at the same opening angles on the opening curve and the closing curve. With the automatic data acquisition equipment the fit is made typicaly to some 250 points chosen on each of the original unsmoothed curves, not necessarily at the same opening angles on the two curves. A computer program determines the impalance state and the average effective frictional torque. Bridge instrumentation and recording procedures are discussed in Section 4 following the discussion of analysis and correction procedures. The computer-based system is described in Section 5 and Conclusions and References are given in Sections 7 and 8.

2. BASIS FOR THE ANALYSIS

2.1. Required Bridge-Opening Torque T and Correction Block Moment D

Figure 1 shows schematically a trunnion-type bascule leaf: (a) in the closed position where $\theta = 0$, and (b) opened to angle θ (THETA). A similar illustration for a roller-type bascule is shown in Figure 2. The distance L from the axis O to the center of gravity G has been greatly exaggerated. (For a leaf of weight W = 500,000 lb with maximum imbalance moment of order WL = 100,000 lb-ft, the distance L would be about 0.2 ft or 2.4 inches.) The angle α (ALPHA) is the angle of elevation of G above the axis O when the span is closed. The horizontal moment arm X of the weight W with respect to the axis O (or with respect to the point of rolling contact C of the roller bascule) is

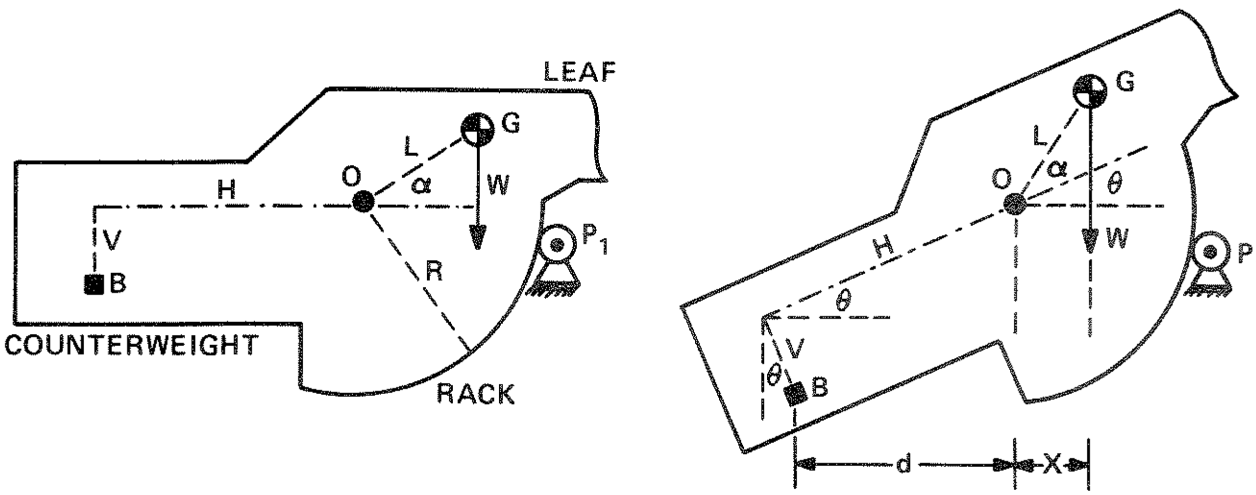
$$X = L\cos(\alpha + \theta)$$

when the span is opened to angle θ. The imbalance moment is therefore $WL\cos(\alpha + \theta)$. The total required bridge-opening torques T with reference to the trunnion axis (taking into account the friction torque T_f but assuming constant speed and therefore not including inertia) during opening and closing are

$$\begin{aligned} T_{\text{opening}} &= WL\cos(\theta + \alpha) + T_f \\ T_{\text{closing}} &= WL\cos(\theta + \alpha) - T_f. \end{aligned} \tag{1}$$

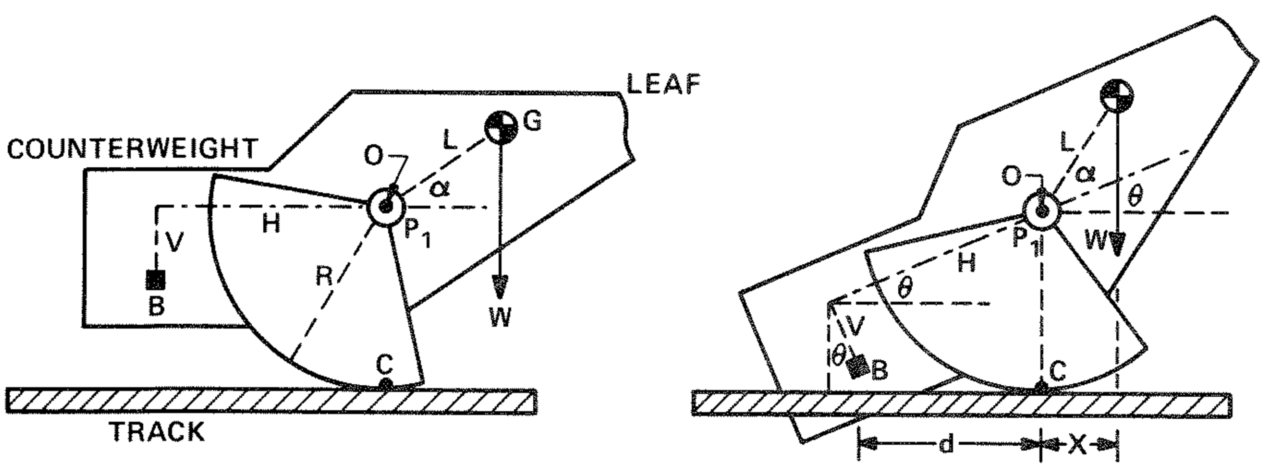
T is considered positive when it tends to open the span. Positive T during closing means a torque opposing the closing motion. Since friction always opposes the motion it adds to the required T during opening and subtracts from the amount of applied torque T required to oppose the motion during closing. In the analysis the friction torque T_f is assumed to be constant during the opening or closing and to be of the same magnitude during closing as during opening.

The same equations (1) also apply to the roller bascule of Figure 2 if the bridge-opening torque is referenced to the point of rolling contact (directly underneath the axis O of the rollers and drive shaft). The friction torque is, however, much smaller for a roller-type bascule than for a trunnion-type.



(a) Span closed, θ = 0.   (b) Span open to angle θ.

Figure 1. Schematic drawing of counterweight and part of leaf of trunnion-type bascule.



(a) Span closed, θ = 0.   b) Span open to angle θ.

Figure 2. Schematic drawing of counterweight and part of leaf of roller-type bascule.

If a correction block of weight W_B is placed at B in a counterweight pocket with coordinates, H horizontally from O in the counterweight direction and V vertically down from O when the span is closed, the horizontal moment arm d with respect to the axis O (or with respect to the rolling contact point C of a roller bascule) is

$$d = H \cos \theta - V \sin \theta$$

when the span is opened to angle θ. Placing one block at B therefore decreases the required bridge-opening torque T by an amount D given by

$$D = W_B (H \cos \theta - V \sin \theta) \qquad (2)$$

Equation (2) has been programmed to give the one-block correction (1 BL D) as a function of θ when the 1 BL WT (= W_B) and the coordinates H and V DOWN are entered.

2.2. Relationship of Drive Shaft Torque to Bridge-Opening Torque T

In the trunnion-type bascule of Figure 1, if M is the torque in one final drive shaft of a span with two drive shafts, then it provides half the total T, so that

$$\text{(Trunnion-type)} \qquad T = 2(R/C_1)M \qquad (3)$$

where R is the rack radius and C_1 is the pitch radius of the pinion gear P_1 driving the rack.

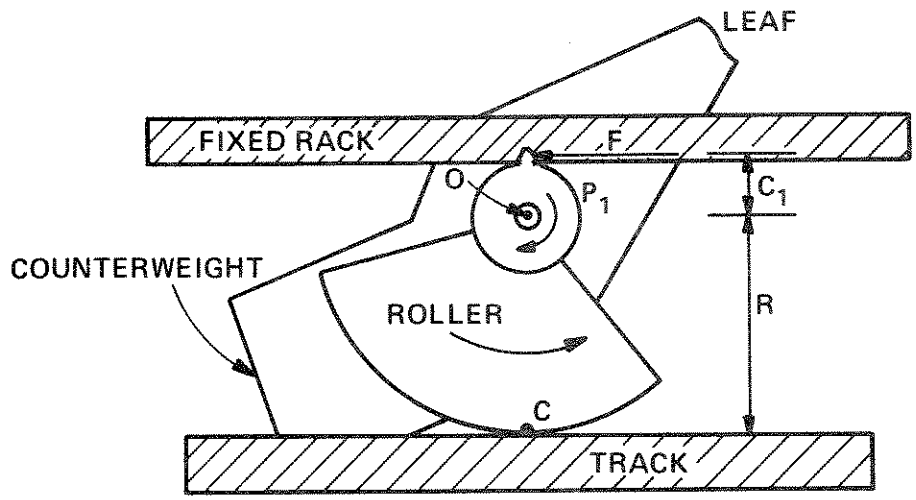


Figure 3. Operation of pinion gear P_1 (shown enlarged) and fixed rack of a roller bascule.

For the roller-type bascule the relationship is slightly different. Figure 3 shows schematically the tooth force F exerted by the fixed upper rack on a representative pinion gear tooth at distance C_1 above O. Half the total applied bridge-opening moment T about C is therefore

$$T/2 = F(R + C_1). \qquad (4)$$

In the roller bascule the motor and drive shaft are mounted on the movable leaf and move with it. As the roller rolls to the left during opening (counterclockwise) in Figure 3 the drive shaft and pinion gear P_1 rotate clockwise as shown. The force F exerted by the fixed rack on a representative gear tooth is related to the final drive shaft torque M by

$$M = FC_1 \qquad \text{or} \qquad F = M/C_1.$$

When this is substituted into Equation (4) the relationship

$$\text{(Roller-type)} \qquad T = 2[(R/C_1) + 1]M \tag{5}$$

is obtained.

If the final drive shaft is the one that is instrumented and it is a solid shaft of radius C then

$$M = \frac{GJ}{C}\gamma$$

where G is the shear modulus, γ is the engineering shear strain on the surface of the shaft, and

$$J = \frac{1}{2}\pi C^4$$

is the polar moment of inertia of the cross-sectional area. Thus

$$M = \frac{1}{2}\pi G C^3 \gamma. \tag{6}$$

For steel $G = 12 \times 10^6$ lb/in^2. With C in inches and γ in radians we obtain

$$\begin{aligned} M &= \frac{1}{2}\pi(12 \times 10^6)C^3\gamma \qquad \text{lb-in} \\ \text{or} \qquad M &= \frac{1}{2}\pi(10^3)C^3\gamma \qquad \text{klb-ft.} \end{aligned} \tag{7}$$

When this is substituted into Equations (3) and (5) and the units of γ are changed to microstrain (10^{-6} radian), the results are

$$\text{(Trunnion-type)} \qquad T = 10^{-3}\pi(R/C_1)^3\gamma \tag{8}$$

$$\text{(Roller-type)} \qquad T = 10^{-3}\pi[(R/C_1) + 1]C^3\gamma \tag{9}$$

[T in klb-ft for γ in microstrain (μs)].

The factor multiplying γ in Equations (8) and (9) is the MECHANICAL FACTOR (klb-ft/μs) if the final shaft is instrumented. If an intermediate shaft of radius C is instrumented, it is necessary to introduce an additional factor equal to the gear ratio (greater than unity) between the final shaft and the instrumented shaft.

Notice that this derivation has assumed that there are two drive shafts on each span. The factor 2 in Equation (3) or (5) was canceled by the factor ½ in the formula (6) for drive-shaft torque. In the exceptional case where there is only one drive shaft, the result should be divided by 2.

2.3 Analysis of Imbalance State

Equations (1) of Section 2.1 are the basis for the imbalance analysis. Subtracting them and adding them gives the two equations

$$T_f = \frac{1}{2}(T_{opening} - T_{closing}) \tag{10}$$

$$AVT = \frac{1}{2}(T_{opening} + T_{closing}) = WL\ \cos(\alpha + \theta). \tag{11}$$

for the frictional torque T_f and the average imbalance torque AVT (halfway between the opening and closing cosine curves. The following procedure was used when the records were obtained on an xy-plotter as described in the introduction. Figure 4 shows an example of the two parallel smooth curves drawn through the recorded curves on the xy-plotter.

The two parameters WL and α characterizing the imbalance state are determined as follows. In order to use a linear regression procedure, the cosine factor in Equation (11) is expanded

$$\cos(\alpha + \theta) = \cos\alpha \cos\theta - \sin\alpha \sin\theta.$$

Then with

$$A = WL\ \cos\alpha, \qquad B = WL\ \sin\alpha \tag{12}$$

Equation (11) becomes

$$AVT = A\cos\theta - B\sin\theta. \tag{13}$$

Data are entered for a sequence of angles θ_k, $k = 1,2,\ldots,N$ by reading the data from smooth curves like those of the example in Figure 4 and averaging the two values read from the upper and lower curve to get the measured AVT. Let

$$\begin{aligned} T_k &= \text{measured AVT at } \theta_k \\ T_k^* &= \text{AVT by Equation (13) at } \theta_k \\ C_k &= \cos\theta_k, \qquad S_k = \sin\theta_k. \end{aligned} \tag{14}$$

The least-squares regression procedure chooses A and B to minimize the sum

$$f = \sum_{k=1}^{N} (T_k^* - T_k)^2$$

or

$$f = \sum_{k-1}^{N} (AC_k - BS_k - T_k)^2 \tag{15}$$

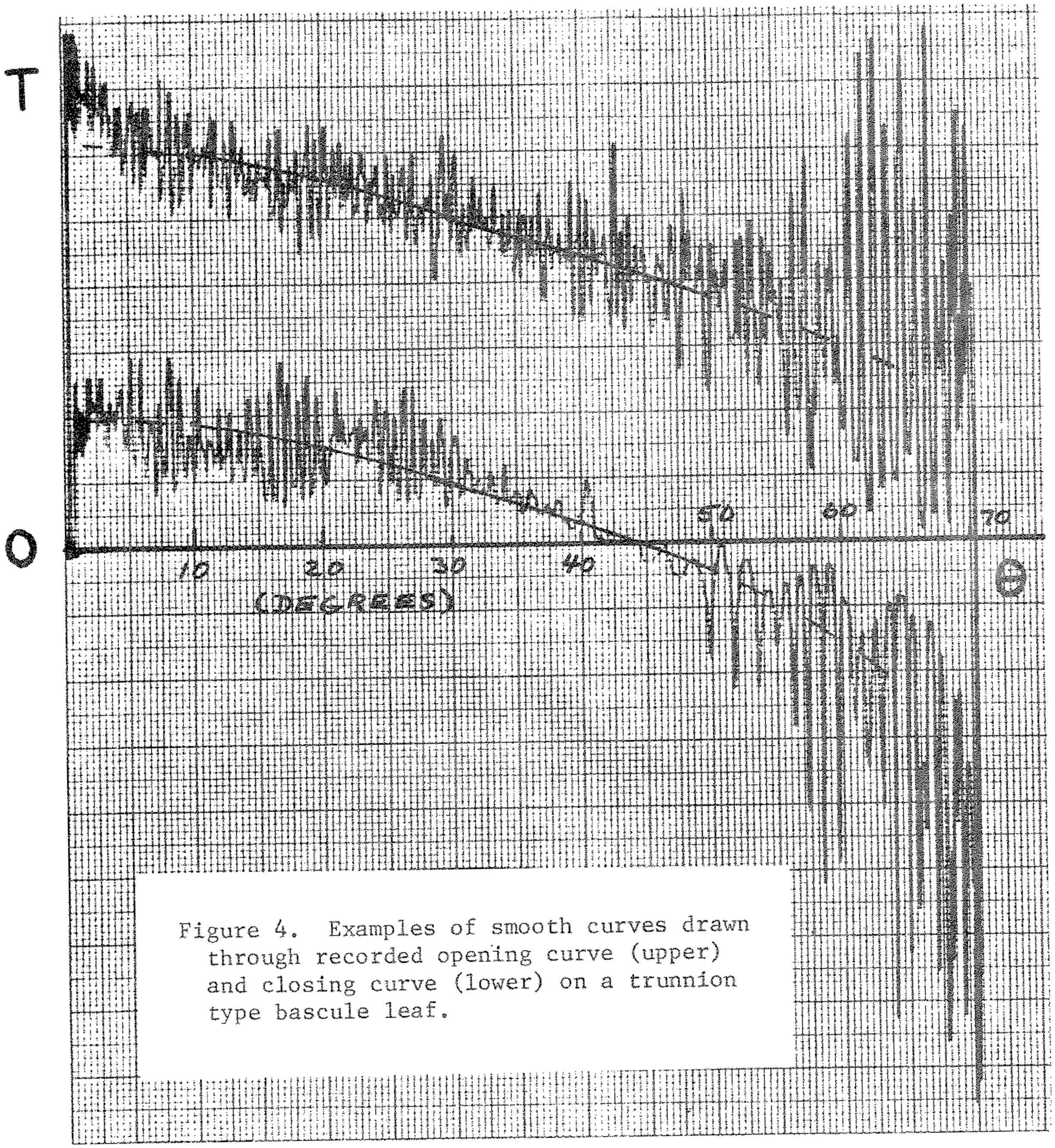


Figure 4. Examples of smooth curves drawn through recorded opening curve (upper) and closing curve (lower) on a trunnion type bascule leaf.

Necessary conditions for a minimum are $\partial f/\partial A = 0$ and $\partial f/\partial B = 0$, which yield two simultaneous linear algebraic equations to solve for A and B, namely

$$\begin{aligned}(\Sigma C_k{}^2)A - (\Sigma C_k S_k)B &= (\Sigma T_k C_k)\\ -(\Sigma C_k S_k)A + (\Sigma S_k{}^2)B &= -(\Sigma T_k S_k)\end{aligned} \tag{16}$$

where all summations over k run from 1 to N.

A programmable calculator program "AVFIT" solves these two equations for A and B, and then calculates

$$WL = (A^2 + B^2)^{1/2} \tag{17}$$

and

$$ERROR = (f/N)^{1/2}/WL \tag{18}$$

the root-mean square error in Equation (15) as a fraction of WL. It also calculates the parameter α , choosing the correct value between -180° and +180° to satisfy both of the equations (12).

In the revised procedure using a microcomputer, a menu choice calls a program which makes a least-squares fit of two parallel cosine curves to two records (opening and closing) for one opening-closing sequence selected by the operator from a displayed directory of translated data files. It first plots on the screen all the translated data points for the opening and the closing, with successive points joined by straight lines. This includes all the large transients, especially at the beginning and the end of the opening and closing records and the automatic stop near the end of the closing, as well as the vibrations and noise during the whole event. Vertical scale of torque in klb-ft and horizontal scale of angle in degrees are shown. This plot remains on the screen while the fitting program runs. See the example in Figure 5.

For purposes of fitting the cosine curves, the large transients near the beginnings and ends are ignored, and the least-squares fit is made to points of the opening and closing curves between about 10° and 60° of opening. This usually means about 250 opening points and about 250 closing points. The fitting program determines the three parameters WL, ALPHA, and AVTF for the two parallel cosine curves

$$T = WL \cos(THETA + ALPHA) + AVTF$$

representing opening, and

$$T = WL \cos(THETA + ALPHA) - AVTF$$

representing closing. Here T is the calculated torque (moment about the trunnion axis), according to the fitted cosine curves representing the imbalance state, when the leaf is at angle THETA from the closed position. The parameter WL is the total leaf weight W times the distance L from the trunnion axis to its center of gravity, ALPHA is the angle of elevation of the center of gravity when the leaf is closed, and AVTF is the apparent average torsional friction about the trunnion axis. The least-squares fitting procedure is similar to that described above in Equations (12) through (18), except that the sum of squares extends simultaneously over the opening and closing curves instead of being applied to the average curve halfway between them, and it is not necessary to choose points at the same angles on the opening curve as on the closing curve.

After the parameters have been determined, the fitted curves and the average torque (AVT) curve halfway between them are plotted on the screen for visual comparison with the recorded data curves, which are still on the screen on the same axes. The three parameters WL, ALPHA and AVTF are then printed on the screen, along with A [= WL cos(ALPHA)] and B [= WL sin(ALPHA)]. A and B are the rectangular coordinates of the center of gravity multiplied by the weight. Also printed is the RMS error of the least-squares fit to the data between 10° and 60°. These six printed values are also appended to the disk file which summarizes the results of all the balancing data that are obtained on an inspection trip.

The program stops execution with the curves and printed parameters still displayed. If the printer is connected, the screen display can be copied by depressing the print-screen key (PRTSC) along with the shift key. An example of the copy produced by the printer is shown in Figure 5. The three parallel fitted cosine curves (indicated by symbols representing + signs) are extended all the way from 0° to 90°, although they are determined only by the recorded data between about 10° and 60°. The number 505 near the left margin is the number of angle-torque data pairs actually used in the fitting. The RMS error of the least-squares fit was 0.318 times the calculated WL. The upper curve is the opening curve, and the lower one is the closing curve. The horizontal small steps in the plotted curve come from the digital nature of the data, combined with some small pendulum swinging and stick-slip in the pendulum-type angle transducer mounted on the leaf near the trunnion. Some of the initial transients were off-scale (greater than 300 klb-ft in magnitude) at the beginning of opening and again at the beginning of closing. The visual display confirms that the fitted opening and closing cosines are a good representation of the imbalance state, despite the large oscillations in the recorded data. The oscillations cause the computed RMS error to be large because so many of the points in the record are far away from the fitted cosines. The copying operation takes about three minutes; it uses a GRAPHICS routine that is resident in the DOS 2.11 operating system and is automatically loaded by the field program disk during the initial start-up before MENU is displayed.

2.4. Correction Block Analysis

The decrease D in the required bridge-opening torque produced by adding one correction block in a specified location has already been given in Equation (2). When N_A blocks each of weight W_A are added with their center of gravity at (H_A, V_A) and N_B blocks are added at (H_B, V_B) the resulting decrease D in AVT is given as a function of θ by

$$D = N_A W_A (H_A \cos\theta - V_A \sin\theta) + N_B W_B (H_B \cos\theta - V_B \sin\theta). \qquad (19)$$

A computer program "COR2" evaluates this equation for any θ after the parameters N_A, W_A, H_A, V_A and N_B, W_B, H_B, V_B have been entered. Coordinate definitions for (H, V) were given in Figures 1 and 2.

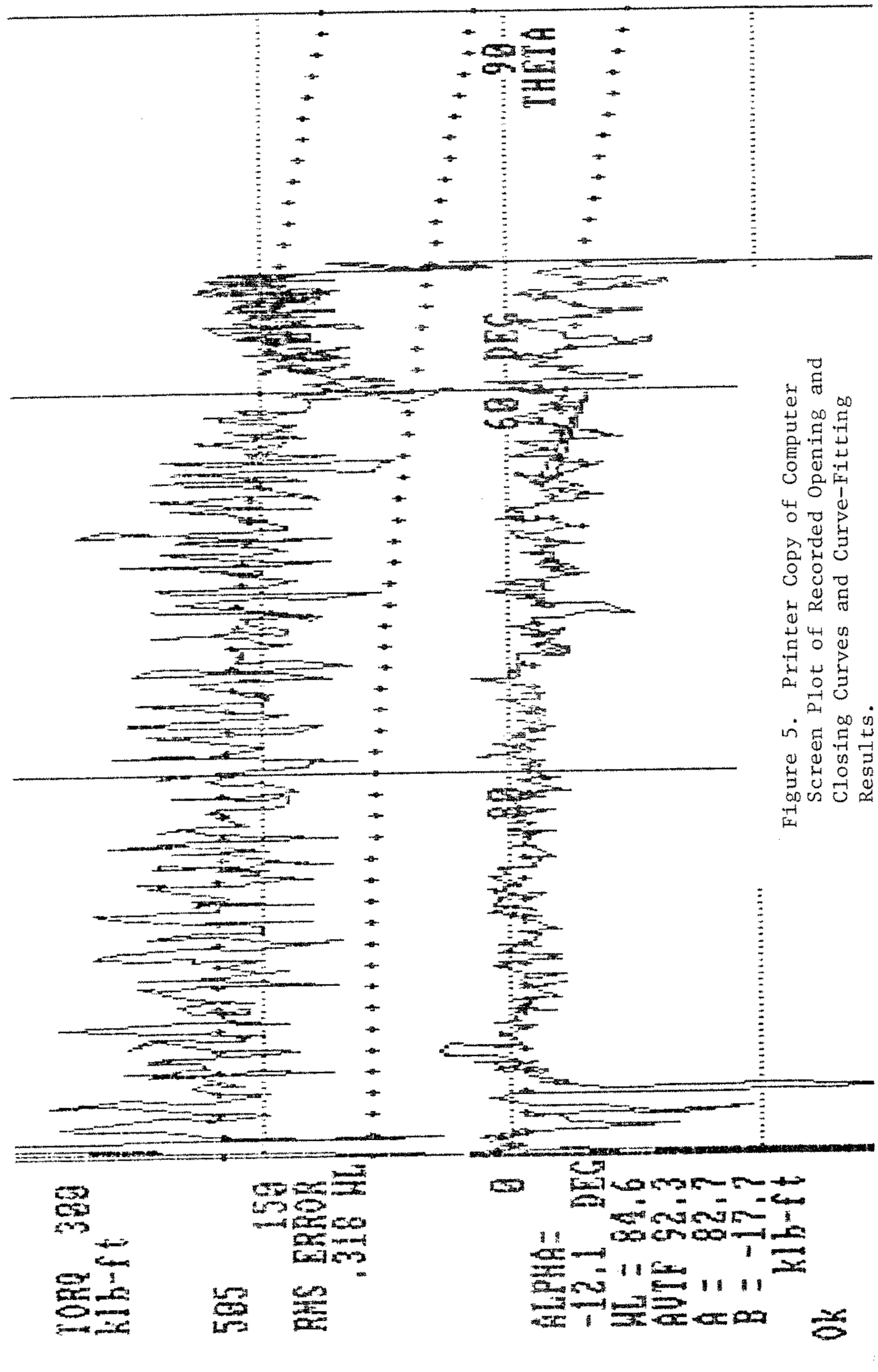


Figure 5. Printer Copy of Computer Screen Plot of Recorded Opening and Closing Curves and Curve-Fitting Results.

When two suitable correction block positions, A and B, are available it may be possible to tailor the shape of the AVT versus THETA curve by prescribing the total decreases D_1 and D_2 at two chosen opening angles, as follows. Equation (2) is used to find the decreases at θ_1 and θ_2 by adding one block at A or B. Let

A_1 = decrease at θ_1 produced by adding 1 block at A.

A_2 = decrease at θ_2 produced by adding 1 block at A.

B_1 = decrease at θ_1 produced by adding 1 block at B.

B_2 = decrease at θ_2 produced by adding 1 block at B.

Then the total decreases, D_1 at θ_1 and D_2 at θ_2, produced by adding N_A blocks at A and N_B blocks at B are given by

$$D_1 = A_1N_A + B_1N_B, \qquad D_2 = A_2N_A + B_2N_B. \tag{20}$$

To determine the numbers N_A and N_B required to produce prescribed decreases D_1 and D_2, we solve Equation (20) for N_A and N_B. Thus

$$N_A = \frac{B_2D_1 - B_1D_2}{A_1B_2 - A_2B_1}, \qquad N_B = \frac{A_1D_2 - A_2D_1}{A_1B_2 - A_2B_1}. \tag{21}$$

A computer program "NAB" first calculates A_1, A_2, B_1, B_2 by using Equation (2) twice after the 1-block weights and positions and the angles θ_1 and θ_2 have been entered. Then it calculates the required N_A and N_B by Equations (21). The solution is always possible provided the denominators $A_1B_2 - A_2B_1$ are not zero, but the required corrections N_A and N_B may not be technically or economically feasible. Negative values obtained for N denote blocks removed instead of added. Negative values for the decreases D denote increases in AVT. See the examples in Section 3.2.

3. CORRECTION PROCEDURES

3.1 Desirable Balance States

There seem to be no established standards for what is the optimum balance state for a drawbridge leaf. The conventional wisdom is that it should be somewhat leaf heavy in order that it can be closed manually without too much effort in the event of a power failure. In the absence of quantitative measures of the imbalance, some maintenance engineers seek by trial-and-error with the correction blocks to achieve a condition where the leaf will drift slowly downward without power during the major part of the closing operation. Power (or manual effort) may be required to overcome the static friction at the start of the closing operation, and it may be needed again after the automatic stop near the closed position in normal operation in order to complete the closing. This is probably a good procedure for routine balancing of a well-designed bridge that has not been subject to extensive structural alterations.

It would appear that a desirable balance state would be one where the maximum leaf-heavy imbalance occurs in the half-open position (around $\theta = 35°$ to $\theta = 40°$ in most cases). If the cosine curve representing the average imbalance moment (midway between the opening and closing curves) peaks at the half-open position, then it will have equal values at $\theta = 0°$ and at

$\theta = \theta_{max}$, and the curve will neither rise nor fall steeply throughout the opening. Figure 6 illustrates three cases. The average imbalance torque (AVT) curves are shown. Curve 2 has approximately the optimal shape just described with maximum at about 45°.

It is not necessary to achieve the optimal shape. For example, Curve 3 in Figure 6 was determined as representing the imbalance condition on a leaf at South Bridge, New Smyrna Beach. The shape is far from optimal, but the maximum imbalance (at $\theta = 0°$) is so small that the span can be operated quite satisfactorily in this condition, and yet it is sufficiently leaf heavy at $\theta = 0°$ that there is no likelihood that it will open under its own weight if center locks and brakes are not engaged. Because of the limited choice of correction block pocket positions available on most of the bridges examined, the optimal shape could not be achieved simply by adding or removing blocks in the existing pockets.

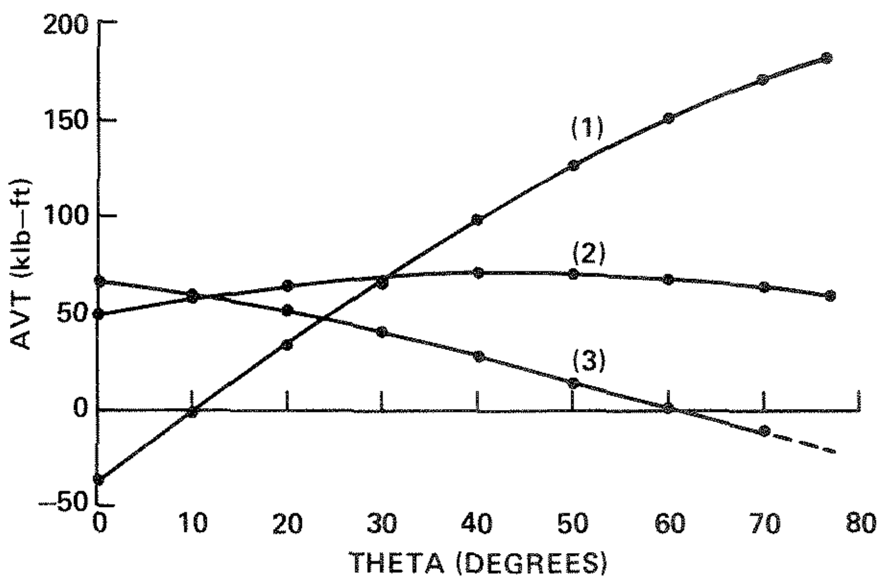


Figure 6. Examples of AVT versus THETA.
(1) Unacceptable because of negative torque at theta = 0.
(2) Near Optimal. (3) Acceptable.

Curve No. 1 in Figure 6 is a case that definitely requires correction. The maximum imbalance is considered to be too high, although standards for maximum imbalance in relation to available power have not been established. Note that the trunnion friction torque (about 35 klb-ft) must be added to the values shown to get the opening torque values. More seriously, the negative value, -38.2 klb-ft at $\theta = 0°$, presents a real possibility that the bridge might open itself if inadvertently left unlocked. This case was not one of the five bridges tested by the University research group. It was brought to our attention after the imbalance was measured on the Southeast Span of the MacArthur Bridge in Miami by DOT personnel trained under the research program. It was analyzed by us because it is a more serious case than any we encountered and presents a better opportunity to demonstrate possible corrective procedures. Curve 2 in Figure 6 is the calculated state that would occur after certain corrections are made. This near-optimum condition could not be achieved simply by adding or removing blocks in the existing pockets, but could be achieved by removing one of the two 11,812-pound piles that had preeviously been mounted on the bottom of the counterweight, adding concrete to the roadway near the trunnion axis and adding some blocks in the existing pockets. Three possible procedures will be discussed in the case study of Section 3.2.

3.2 Example: Case Studies of Correction Block Analyses On Northeast Span of MacArthur Causeway Bridge

Measurement by DOT personnel on June 22, 1982 on the northeast span of the MacArthur Causeway Bridge in Miami showed the initial imbalance state plotted as Curve 1 in Figure 6, with the average torque AVT (midway between opening and closing torques referred to the trunnion axis) varying from -38.2 klb-ft at $\theta = 0$ (leaf closed) to 181.2 klb-ft at $\theta = 77°$. This was deemed unsatisfactory because the maximum torque was too high, but more importantly because the negative torque of -38.2 klb-ft was so large that the recorded opening torque curve showed a negative dip at the beginning, suggesting that the span could open itself if left unlocked. The average friction torque was estimated as only AVTF = 33.6 klb-ft.Three possible correction procedures will be illustrated, beginning with the simplest procedure using only the existing correction block pockets.

First Procedure Using Existing Pockets

Because all four pockets on this bridge are in the same location relative to the trunnion axis (same H and V in Figure 1), not much could be done to change the shape of the torque curve by using only the existing pockets, but the torque magnitude could be adjusted at the most critical point, namely at $\theta = 0$. Position A for the following analysis is for the estimated center of gravity of a group of blocks that might be added or removed from this location. Equation (2) was evaluated to give the decrease in torque at various angles that would be produced by adding one 77-pound block at A. The correction desired at $\theta = 0$ is an increase (negative D); therefore blocks should be removed instead of added. To bring the AVT at 0 up to +33.6 klb-ft from its uncorrected value of -38.2 klb-ft would require an increase of 71.8 klb-ft. Since it was found that one block produces a change of 1.386 klb-ft at $\theta = 0$, the number of blocks required to be removed at A is given by 71.8/1.386 = 51.8 blocks. The proposed minimum correction is therefore

$$N_A = -52 \text{ blocks}$$

(negative to represent blocks removed).

The correction $D(\theta)$ at various angles THETA produced by removing 52 blocks at A was found by using Equation (2) again with $W_B = (-52)(77) = -4{,}004$ lb, negative to indicate weight removed.

The predicted CORRECTED AVT(θ) values range from +33.9 klb-ft at 0° to 198.4 klb-ft at 70°. The dangerous condition at $\theta = 0°$ would be corrected satisfactorily, but the maximum AVT shown in the table would be increased from 181.2 klb-ft at 77° to 198.4 klb-ft at 70°. The maximum would increase only about 17 klb-ft while the 0°-value increased by 72.1 klb-ft. If the maximum value is considered tolerable, this would be an acceptable correction procedure.

Second Procedure For Correction

Further improvement in the balance state would require some structural changes. The kind of additional correction that would be most effective in reducing the torque at large opening angles while still not making it too small at $\theta = 0°$ is weight added directly over the trunnion axis where it exerts no moment about the trunnion axis with the leaf closed, but would exert a leaf-opening moment in the open position.

It was ascertained that it would be possible to pour up to about 20,000 pounds of concrete in the roadway with center of gravity about 3.93 ft above the trunnion axis. The computer program "NAB" was run to determine the weight changes at two positions, A and B, to produce desired corrections, as follows:

Position A: H = 18 ft, V = -1 ft, 1 BLOCK WT = 77 LB

Position B: H = 0 ft, V = -3.93 ft, 1 BLOCK WT = 1,000 LB

Desired Corrections: D_1 = -98.2 klb-ft at θ_1 = 0°

D_2 = 120 klb-ft at θ_2 = 70°

These corrections would give AVT = 60 klb-ft at both $\theta = 0°$ and $\theta = 70°$ and would approach the optimum condition with maximum AVT = 73.2 klb-ft at $\theta = 35°$. The "NAB" program solution was

$$N_A = -70.85, \qquad N_B = 38.3.$$

Thus, about 71 blocks (5,467 lb) should be removed from the counterweight pockets and 38,300 lb of concrete poured over the trunnion axis. Since this was judged to be more weight than should be added over the trunnion axis, the optimum could not be achieved in this way. The second correction considered was therefore made by pouring only 20,000 lb at H = 0, V DOWN = -3.93 ft. The results of the two correctionss reduced the maximum imbalance from the initial 181.2 klb-ft at 77° to 124.5 klb-ft at 70° and removed the dangerous condition at $\theta = 0$. This is probably an acceptable correction though not optimal.

Third Proposed Correction Procedure

The steeply rising initial torque of Curve 1, Figure 6, was largely caused by two heavy concrete piles that had previously been attached underneath the counterweight to balance a guardrail installation on the leaf. These piles have a large moment arm when $\theta = 0$, but a much smaller one at $\theta = 77°$, so that the balancing effect at the open position is smaller than at the closed position. The third correction approach illustrated here is to begin by removing one of these piles. The result was a near-optimum shape but far too high an imbalance magnitude (maximumum about 227 klb-ft). Additional corrections proposed were to add correction blocks at A and to pour concrete at a new position B at H = -1 ft (one foot in leaf direction from trunnion), and V = -3.93 ft. (This new position B with H = -1 ft was selected after some preliminary trials with H = 0.) The "NAB" program was run with the following data:

Position A: H = 18 ft, V = -1 ft, 1 BL WT = 77 LB

Position B: H = -1 ft, V = -3.93 ft, 1 BL WT = 1,000 LB

Desired Corrections: D_1 = 122.3 klb-ft at $\theta_1 = 0°$

D_2 = 113.3 klb-ft at $\theta_2 = 77°$

These corrections (in addition to the first correction removing the pile) would give AVT = 60 klb-ft at both $\theta = 0°$ and at $\theta = 77°$ and maximum AVT = 76.7 klb-ft at $\theta = 38.5°$. The "NAB" program solution was

$$N_A = 102.9, \qquad N_B = 20.387.$$

Thus 103 blocks (7,931 lb) should be added at A and 20,387 lb of concrete poured at the new position B. A second iteration, made with W_B fixed at 20,000 lb gave $N_A = 110$. Removing the pile, adding 110 blocks at A, and pouring 20,000 lb of concrete at the new position B was predicted to achieve $\theta = 0$ the near-optimal shape plotted as Curve 2 in Figure 6 with maximum imbalance torque of 69.4 klb-ft.

Whether either the second or third proposal, or some other alternative involving structural changes, should actually be adopted depends upon economic considerations, and possibly structural considerations about adding weight in certain parts of the structure. These issues are not addressed here. What has been demonstrated is that to approach an optimal solution it is useful to be able to add weights in more than one position. Positions near the trunnion axis offer considerable possible variation in the angle of elevation of their centers of gravity as seen from the trunnion axis and hence considerable versatility in the qualitative nature of the correction achieved as a function of opening angle theta. Because of the short moment arm, however, large weights may be needed at positions near the trunnion axis. In the design of new bridges attention should be given to providing more versatile correction block pocket positions than are available on many of the current bridges.

The two following sections provide some additional details about the instrumentation of a bridge for imbalance measurement and the computer equipment and procedures now in use for imbalance analysis.

4. STRAIN-GAGE MEASUREMENT OF DRIVE SHAFT TORQUE

4.1 Principles of the System

The bridge-balance measurement system consists of a two-element strain-gage chevron, a battery operated strain-gage amplifier, a battery operated opening-angle transducer, signal cables and an X-Y recorder. Figure 7 shows the arrangement of parts in the original procedure using an xy-plotter (4). The strain-gage chevron and the amplifier are mounted together on either the final drive shaft or an intermediate drive shaft, while the angular transducer is attached to the side of the movable leaf. During a bridge opening and closing cycle, a recording is made of the torsional shear strain (and thus the torque) in the drive shaft as a function of the opening angle. From the shape of the curve produced in this way, the state of balance in the bascule can be determined. In the recent revision of the procedure (5), the xy-recorder is replaced by the portable computer used for data acquisition.

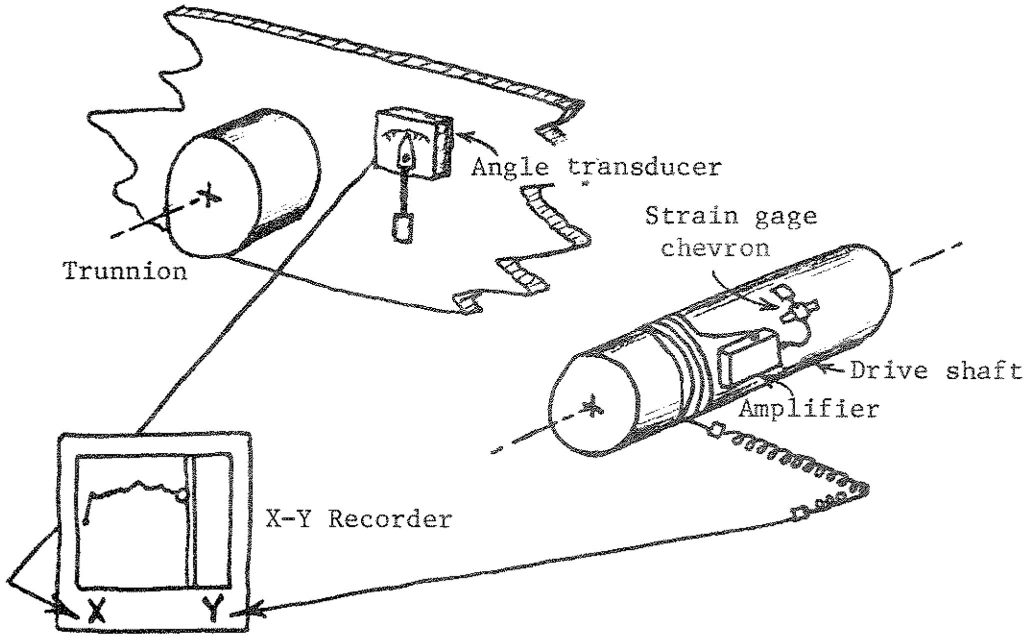


Figure 7. Bridge-balance measurement system.

Preparation of a bridge for this kind of measurement involves selecting a suitable shaft for instrumentation, mounting the strain gage chevrons and the angle transducer, connecting the recording instruments and performing a short calibration procedure. The various signal cables, amplifier, angle transducer and xy-recorder or computer form a portable kit that is moved from site to site, while the strain gages are permanently welded to the shaft, and are available for use again at that site in the future, if necessary.

4.2 Instrumenting the Bridge

A. Gage mounting

If sufficient space is available on the final drive shaft, the gage is mounted there, since cable wrapping and unwrapping are less trouble because of the fewer turns of the final shaft during operation. If an intermediate shaft must be used, greater care must be taken to ensure that the signal cables do not become fouled. The decision whether to use one or two strain-gage chevrons is based on whether the shaft is subject to direct shear in addition to torsional shear. If the segment of shaft selected between two bearings does not have a gear mounted on the segment, it will usually be free of direct shear and one chevron may suffice. If the gage installation must be between a gear and a bearing, then two chevrons should be mounted on opposite sides of the shaft and connected so as to cancel the direct shear. Figure 8 shows an example where this was not done, so that the smoothed opening and closing curves were not even approximately parallel.

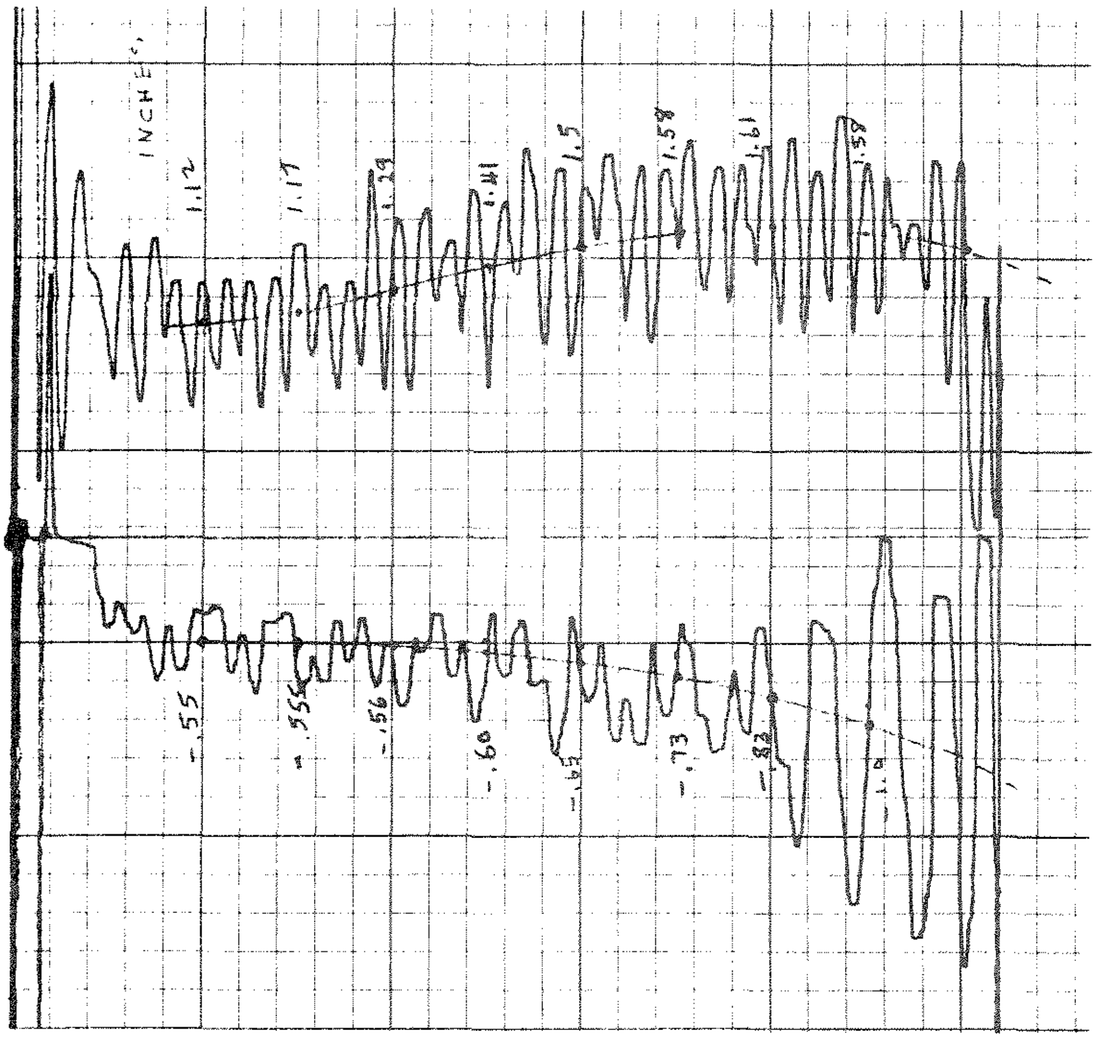


Figure 8. Unsatisfactory Non-Parallel Opening and Closing Torque Records.

For each gage position an area with a minimum of obstacles that might interfere with the amplifier or the cables, and so that the gages will not be near a bearing or a gear is chosen. Paint is removed from the shaft over an area (or areas) large enough to accommodate the strain-gage chevron (or chevrons) and the terminal (see Figure 9). The bared area is polished with 180 grit SiC paper to remove all traces of paint and primer. Then the strain-gage chevron and terminal are positioned and the terminal tabs spot welded to the driveshaft. The edge of the strain-gage chevron is aligned with a lathe tool mark (or a true circumferential line, if tool marks are not visible). When the gage is completely attached, the gage lead is connected to the "2 arm" amplifier (or the "4 arm" amplifier if 2 chevrons are used) and the amplifier is fastened to the shaft with double sided tape or tied with strong cord. Cable link #1 is connected to the amplifier and wrapped around the shaft in a direction so that it will unwrap when the span is opening. Sufficient turns are wrapped so that some cable remains wrapped when the span is fully open. The coiled link #2 is connected to link #1 and link #2 is tied to a convenient place 6 to 8 feet away so that the coiled link is considerably stretched and is pulling straight away from the wrapped cable. Finally, the long link #3 is connected to the end of link #2 and strung out to the location of the xy-recorder or computer, which is located in a secure place protected from adverse environmental effects. The battery-powered preamplifiers mounted on the shaft provide a high-level signal for transmission over the long cable, so that any electrical noise picked up is negligble in comparison to the signal.

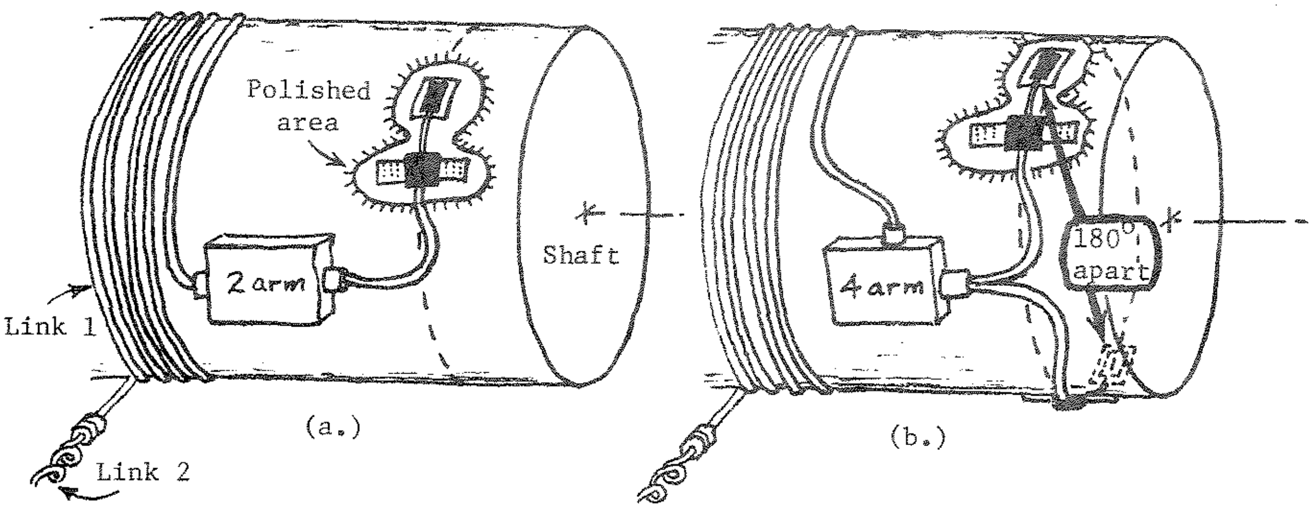


Figure 9. Placement of the components on the instrumented shaft:
a) Where one chevron is used. b) Where two chevrons are used.

B. The angle transducer

The angle transucer consists of a pendulum-operated battery-powered potentiometer. It is mounted in any convenient position on the side of the leaf, as near as possible to the trunnion (or to the center of the roller of a roller bascule) and connected to the recorder as shown in Figure 7. The mounting area is cleaned of any grease or oil, and the angle indicator is mounted with double sided tape, making sure that the pointer is on zero and that the pendulum is free to swing a full 90° in the direction it will move during a bridge opening.

C. Calibrating and Zeroing the Systems

Calibration of the angle transducer is performed by moving the pendulum to the 90° position and back to zero several times while the bridge is closed, and recording the results by pen motion on the xy-recorder or as voltages recorded by the microcomputer data acquisition system. To calibrate the strain gage circuit, the calibration switch on the amplifier is moved briefly to the "cal" position, and the total vertical pen travel is recorded on the xy-plotter or stored in the computer data acquisition system for use in the calibration program. The zero angle position can be set on the xy-recorder and left unchanged in subsequent recordings, or the voltage output representing zero angle stored in the computer. To establish a good zero torque condition, it is essential to release the brakes on the drive system temporarily and manually rotate the drive system until some backlash is apparent between the gears. Otherwise some torque may be locked into the system. When this has been done, the zero position is set on the xy-recorder or zero-position voltage recorded.

To interpret the strain information recorded by the equipment described in this section, it is necessary to determine a number of mechanical (and electrical) factors specific to the bridge under study. The gear ratio between the instrumented shaft and the rack on the movable leaf must be determined. Also, the exact diameter of the instrumented shaft must be measured to determine the torque-strain conversion constant or MECHANICAL FACTOR in klbft/microstrain. The two amplifers are each so designed that the built-in shut resistor simulates a calibration torsional shear strain of 180 microstrain when the 2-arm amplifier is used with a single strain-gage chevron or the 4-arm amplifier is used with two chevrons mounted on opposite sides of the shaft. An ELECTRICAL FACTOR in microstrain per vertical unit on the xy-plotter is determined by dividing 100 by the number of units deflection on the plotter produced by using the calibration switch on the strain-gage amplifier. The TORQUE CALIBRATION FACTOR in klb-ft per vertical division is obtained by multiplying the mechanical factor by the electrical factor. Calibration data is stored in a Mechanical Factors Worksheet when the xy-recorder is used and in data files on a floppy disk with the computer-based system.

5. COMPUTER-BASED DATA ACQUISITION AND ANALYSIS SYSTEM.

5.1 Objectives

With the methods of imbalance analysis developed in DOT research programs by University of Florida personnel, the maximum imbalance moment of a bascule span could be quickly determined from strain-gage data measuring torque in the final or next intermediate drive shaft, once the strain gages had been mounted on the shaft and the shaft diameters and gear ratios between the point of measurement and span had been determined from drawings and/or from on-site dimension measurements.

Determination of the optimum correction-block placement or of structural modifications that will reduce the maximum imbalance and also distribute it as uniformly as possible over the opening-angle range takes considerably longer.

Experience in the previous research programs and in the DOT balance maintenance program that had been implemented based on the research programs had also shown that the strain-gage torque measurements furnish diagnostic information about the bridge machinery operation, such as large transient torques and bearing deterioration as determined from friction. For example, instrumentation used in balancing tests of MacArthur Causeway Bridge identified an improperly constructed bearing that was causing deterioration of machinery; tests on Moore Haven Bridge indicated drive torque on one span that was approximately double the torque on the opposite span; instrumentation of

Jewfish Creek Bridge showed that suspect trunnion bearings were operating satisfactorily, providing a sound technical basis for avoiding a costly trunnion bearing replacement.

A new program was initiated whose primary objective was to develop automated analytical computer programs and acquire equipment that would

(a) analyze the imbalance state, using the strain-gage measurements and automatically plot the characteristic moment-versus-angle curve,
(b) quickly determine the optimum correction block placement in existing pockets and plot the revised characteristic curve, and/or,
(c) determine the revised characteristic curve that will be caused by specified structural modifications.

This objective was achieved. Equipment and procedures were demonstrated and equipment transferred to the DOT in March of 1985. Its use has already been implemented by the DOT, beginning with a field trip in April, 1985.

5.2 Equipment Selection and Procurement

Two types of equipment were needed, an automatic data acquisition system for use in the field and a base system for data-base storage and analysis at the DOT office in Tallahassee. The first concept considered was to use a dedicated data acquisition system for field work and a microcomputer for the base system. Some consideration was given to building the field unit at the University of Florida. Two commercially available data-acquisition units were demonstrated at the University of Florida. Both were rugged units that could be preprogrammed to do specific tasks and record data on disks. They were heavy and expensive and not convenient for communication with the base system. Recorded data with either of them could be transmitted in ASCII format by telephone modems, but direct transfer of disk data to a suitable microcomputer would not be easy because of expected incompatibility of the disk formats.

Preliminary consideration of the available microcomputers led to the idea that a microcomputer could also be used for the field unit and would actually cost less than the dedicated push-button systems, although it would not be as rugged. The field unit microcomputer could be preprogrammed so that it would operate almost as a push-button unit for data taking, but it could also do some data analysis in the field in a more convenient manner, using programs on floppy disks instead of sequential push-button commands. It would also be more quickly and easily adaptable to different kinds of data acquisition, either for imbalance analysis or for diagnostic information about machinery operation. After consultation with DOT personnel it was decided to purchase two portable microcomputers that could be modified to serve as field data-acquisition units and one larger desk-top microcomputer for the base system. The most convenient and reliable way to send the data to Tallahassee would be to send the diskette. This required that the two computers have compatible disk systems. The field unit would have a dual disk drive, one for programs and one for data. The base unit would have one floppy disk drive and one internal hard disk for data-base storage. The stored data should be backed up by copies on floppy disks.

After further study of the rapidly changing computer market it appeared that the only portable then available that met the requirements and was capable of running a DOS 2 operating system was the Columbia VP. To ensure complete compatibility between the field system and the base system, a Columbia MPC 1600-4 with a 12 megabyte hard disk was chosen for the base unit.Additional equipment purchased included a printer and a plotter for use with the base system, one smaller printer that could be used with a field system, a 16-channel data-acquisition board for each field unit, and modems for communication between the units when time does not permit waiting for the diskette to be sent.

5.3 Data Acquisition and Analysis Programs and Procedures

As currently programmed, only two channels of the Data Translation board in each field unit are used. These channels are used for input of electrical analog signals representing opening angle and drive shaft torque for a bascule bridge leaf. One of the floppy disk drives in the portable microcomputer is used for the field system program disk, which could be used on any brige, and one is used for a data disk dedicated not only to the particular bridge being examined but also to the particular inspection trip. One data disk file contains mechanical factors for the various movable spans of the bridge, such as driveshaft diameters, gear ratios, etc.; these ordinarily will not change between inspection trips to the same bridge and could be copied from a previous trip's data disk before the trip begins. When mechanical factors data is entered in this file it overwrites and replaces previously entered data. All the other data files pertain to a single trip, and the programs append data to these other files without erasing previously entered data.

The field system program disk contains the operating system commands (DOS 2.11) for the microcomputer and seven programs written in BASICA language for controlling the data acquisition and storage in data files on the data disk and for some data processing in the field. The actual data acquisition operation makes use of a machine- language subroutine which is called by the BASICA programs. The field system program operates in the AUTOEXEC mode, so that if the field system program disk is placed in Drive A before the computer is turned on, then when the power is turned on the computer skips some of the usual initial key-entry steps, boots up automatically and displays on the built-in screen of the portable computer a MENU of seven choices. A choice is made by typing a one-digit number and then depressing the carriage-return key.

1. Initial Setup. This choice is used only if the mechanical factors for the bridge have not been entered before the trip. Its use involves responding to a series of questions that appear on the screen by typing in the required information. The other choices require only a minimal push-button sort of keyboard activity.

2. Calibration. This choice will be used at least once for each leaf examined on the trip, and will probably be repeated one or more times for each leaf to ensure that the calibration is still satisfactory. When used this program directs the computer to:

A. Accept voltages from the angle transducer in two positions representing 0° and 90° of opening (leaf opening is not required for this), and calculate the angle-voltage calibration factor.

B. Accept voltages from the torque transducer with the calibration switch set in two different positions, access the mechanical factors data file for the required information, and calculate the torque-voltage calibration factor.

C. Append the two calculated calibration factors to the data file B:CAL.DAT and re-display the MENU. Any one of the calibration sets in the file can be selected for use in subsequent analyses, although usually the most recent one will be selected.

3. Bridge Balancing. This choice calls the main data-acquisition program. It is used to accept and store in two sequential data files the electrical signals representing (1) the opening torque and angle data, and (2) the closing torque and angle data for one drive shaft during one opening and closing sequence. It creates the two new files, and it also lists their names in the balancing data directory file "B:BALDAT.DIR". It also makes a rough plot of torque versus opening angle, without scales, which appears on the computer screen while the opening and closing are proceeding. The rough plot locates every tenth data point and joins the successive points by lines on the screen.

Torque and angle voltage pairs are taken and immediately stored on disk at the rate of about 10 pairs per second between interruptions for the screen point plots. During a normal opening or closing some 300 to 400 data pairs are recorded that can be used in the subsequent analysis. When the closing raw data record (voltages) is completed, control is transferred back to the MENU.

At any convenient time, with or without intervening operations and other menu choices, or even after the computer has been turned off and restarted, the next choice may be made, either in the field or at the base system.

4. Data Translation. This choice calls a program that translates the raw data records (representing voltages) into numbers representing drive shaft torque in kilopound-ft (klb-ft) and angles in degrees. It first displays a list of the raw data files on the disk, whose identifying names include the time they were recorded. When the desired file has been selected (and the most appropriate calibration for that recording selected from another display), the program translates the data, stores it in another disk file with a similar but not identical name (without erasing the original raw data record) and returns control to the main MENU.

5. Curve Fitting. This menu choice calls a program which makes a least-squares fit of two parallel cosine curves to the opening and closing curve data. The basis for this program has been described in Section 2.3.

6. Balance Block Analysis. This menu choice calls program "CORR.BAS", which predicts the effect of a correction block placement. It accesses the "B:BALDAT.SUM" data file to input the values of WL and ALPHA that characterize the inital imbalance state of the leaf. When prompted, the operator specifies the horizontal location H (ft in the counterweight direction from the trunnion axis) and vertical location V (ft below the trunnion axis) where a specified weight (lb) is added. Negative values indicate the opposite directions or weight removed, respectively. The program plots both the initial state's average torque (AVT) versus angle THETA curve and the corrected AVT curve that would be obtained after the correction block placement. It also prints on the screen both the initial and corrected values of WL, ALPHA, A and B and stops with these values and both curves still kn the screen, so that they can be copied to the printer if desired. This program and also a variant version,

"CORR1.BAS" that provides for typing in the inital WL and ALPHA instead of reading from "B:BALDAT.SUM" are on the hard disk of the office base system.

7. Quit. This choice ends operation from the MENU and leaves the computer in control of BASICA, so that it can be used as a computer, either in calculator mode or with additional BASICA programs from another diskette.

Program "NAB.BAS" is not accessed by the MENU but is on the field system disk and also on the hard disk of the base system. It is called in the usual way for a BASICA program and can be used to calculate the numbers NA and NB of correction blocks of specified weight that must be added at two specified positions A and B (or removed if the number is negative) in order to lower the average torque-angle curve by specified amounts at two specified angles THETA1 and THETA2. The numbers calculated may not be executable with the available correction block pockets. By specifying a block weight of 1 lb, the program can be used to calculate the total weight that must be added in specified positions instead of the number of blocks.

6. CONCLUSIONS

The data-acquisition system, based on the portable microcomputer with an installed Data Translation board, has been demonstrated to perform well. With one data diskette for each inspection trip, the system can accumulate all the data defining the current imbalance state. The field system programs can evaluate the bridge performance and imbalance state, and display the recorded opening and closing torque versus angle curve, as well as the fitted curve representing the imbalance state.

Another program can be run, which will predict the results of correction block placement and plot the basic imbalance curves (before and after the proposed correction) displayed together for comparison. Any graphical display on the screen can be copied by the printer. The parameters calculated to represent the imbalance state are stored on the diskette.

The continuous recording procedure, even with an xy-plotter instead of a computer, is a good procedure for determining the imbalance state. It is considered far superior to measuring the torque required to hold the stopped span at selected angles. There are two advantages to the continuous recording system, one technical and one political. The technical shortcoming of the static method is a consequence of the fact that the torsional friction is of the same order of magnitude as the imbalance torque (often as much as half of the imbalance torque). Because the static friction actually mobilized in the stopped position is unknown, large errors may be induced in the estimation of the imbalance moment by the static method. The political disadvantage of the static method quickly becomes obvious when you watch a long line of irate motorists caught in backed-up traffic while the static measurements are made. The continuous recordings can be made during regular openings for ship traffic without any additional openings or longer openings.

The continuous openings can also furnish information about span vibration, about the condition of the drive machinery, and about the adequacy of control operation by the bridge tender or by an automatic control device.

The computer system has some additional advantages. It is not dependent upon the judgment of the person who draws the smooth curves through the recorded xy-plots. This is especially advantageous when the analysis is done in the field where working conditions are seldom conducive to careful drafting. The computer can do the work and determine the imbalance state in a few minutes after the recording is made. It can also transmit the data quickly to the Tallahassee DOT office, where additional technical expertise can be called upon to decide upon correction procedures.

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