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"Balancing of Movable Bridges: The Strain Gage Technique"

Disclaimer

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Introduction

Several moveable bridges were built in the United States during the mid and early 20th century. To prolong the life and reduce costly equipment replacement and refurbishing, the bridge should be maintained in a good operating balance state.

The two major bridge types considered here are vertical lift bridges and bascule span bridges. Vertical lift, much like an elevator, are raised by cables at each of the four corners of the span. The cables are suspended from pulleys supported by towers. The weight of the span are balanced by a counterweight attached to the cables on the opposite side of the pulleys.

There are two major types of bascule bridges. These are trunnion and roller types. A trunnion type consists of a deck supporting leaf and a counterweight that pivots about a fixed trunnion bearing. The roller type bascule bridge consists of a leaf and counterweight that pivot about the axis of a large roller. Roller bridges rotate and move horizontally during its operation.

Both bridge types can develop excessive imbalances caused by deck rehabilitation, addition of utilities, dirt accumulation, paint, and numerous other reasons. These imbalances can increase operating power requirements and machine wear, and in extreme cases cause equipment failure and create potential hazardous conditions.

Several methods exist to balance a bascule bridge, but most provide an incomplete picture of the full balance state of the bridge. This paper will present a method of determining the balance state of a bascule bridge using strain gages on the final pinion shafts. The gages are used to measure operating torque during the raising and lowering of the span. For vertical lift bridges the data can be used to determine the present balance state and trunnion friction. For bascule bridges the resulting data can be used to determine the horizontal and vertical eccentricity of the imbalance load, trunnion or roller friction, plus information on the performance on the mechanical drive components.

Test Method

This test method for balancing the movable bridge described here requires the installation of strain gages on the final pinion drive shaft. Four (4) strain gages are installed on each final pinion shaft in a full wheatstone bridge configuration. The orientation of the gages used in this test measures shaft torque and cancels out the effects of direct shear, moment and axial loading (See Figure 1). A full bridge is also temperature compensating. A four conductor individual shielded pair cable with a common wire connects the shaft gages to the strain gage signal conditioning system. The cable shielding is grounded at the signal conditioning system only.

On bascule bridges an inclinometer is mounted to the span to detect the angle of the bridge during its operation. The amplified strain gage output and inclinometer voltages are recorded on an analog tape recorder during the test.

Before testing of the bridge, the strain gage signals must be calibrated and then zeroed at a no load state of the pinion shaft. The gages are calibrated by the use of a shunt calibration resistor. The resistor is temporarily connected in parallel across one of the gages to simulate a strain in the shaft (typically 50 microstrain). The resistor can be connected at the gages which will account for the effects of lead wire resistance. The shunt resistor can also be connected at the signal conditioner and the effects of lead wire resistance manually calculated. The calibration strain signals are recorded for each strain gage bridge and is used as a reference when interpreting the actual shaft strains.

The gages are zeroed using the signal conditioning system when the pinion shaft is in a zero load state. To set a zero load state the span locking pins are engaged while the braking system is manually released. The operating machinery is manually rotated to take up the backlash in one direction, then the other. This will locate the mid-position so that the pinion can float between the drive rack or gear teeth. If the positioning is correct and the pinion is not loaded at this point the output of the gages will not respond to the passage of a live load.

Typically three tests are run with data being recorded during both the raising and lowering of the span. Especially in the case of bascule spans, it is advantageous to operate the bridge to its full limits of opening to collect as many data points as possible. The bridge should also be operated at a constant speed to reduce inertia effects. Testing under severe weather or with ice and snow accumulating should be avoided. A typical single leaf test trace is presented in Figure 2.

Data Reduction

To analyze the balance state of the bridge, shaft strain must be converted into operating load for vertical lift bridges or leaf moments for bascule spans. For both bridge types, this begins with determining pinion shaft torque during operation.

The equations to convert strain to pinion shaft torque are as follows:

Equation

No. 1: $\epsilon_{cal} = R_G / [(R_S + R_G) \text{ X G.F.})]$
No. 2: $\tau = \alpha G$
  2A: $\epsilon = \alpha/2$
  2B: $\tau = 2\epsilon G$
  2C: $\epsilon = E/[2 \text{ x } (1 + \mu)]$
  2D: $\tau = 2\epsilon E/[2 \text{ x } (1 + \mu)] = \epsilon E/(1 + \mu)$

No. 3: $J = \pi D^4/32$
  3A: $c = D/2$
  3B: $J/c = \pi D^3/16$

No. 4: $\tau = T_S \; c/J$
  4A: $T_S = \pi J/c$

Definition of Terms

ϵ_{cal} = Calibration strain for R^s
R_G = Resistance of Strain Gage (OHMS)
R_S = Resistance of Calibration Shunt (OHMS)
G.F. = Gage Factor for Strain Gages (provided by Manufacturer)
τ = Torsional Shear Stress (PSI)
α = Shear Strain (inch per inch)
G = Shear Modulus for Shaft Material
ϵ = Measured Strain (inch per inch)

E = Young's Modulus for Shaft Material = 30×10^6 PSI
μ = Poisson's Ratio = .3
J = Polar Moment of Inertia
D = Pinion Shaft Diameter (inches)
c = Distance from Neutral Axis to Strain Gage
T_S = Pinion Shaft Torque (inch pounds)
M = Bascule Imbalance Moment (inch pounds)
G.R. = Gear Ratio Between Pinion Shaft and Bascule Span Rotation or Lift Bridge Bull Gear Rotation
r = Radius of the Sheave Pulley (Lift Bridges)
L = Tension load on a cable group (Lift Bridges)

Solving Equation 2D: $\tau = \epsilon E/(1 + \mu)$
Where: $E = 30 * 10^6$
$\mu = 0.3$
Produces: $\tau = (23.1)\ (\mu\epsilon)$

Inserting that value into equation 4A: $T_S = \tau\ J/c$
Where: $J/c = \pi D^3/16$ (equation 3B)

For bascule spans, leaf moment is determined by;

$$M = T_S(\text{G.R.})$$

For vertical lift, lift load is determined by load;

$$L = T_S(\text{G.R.})/2\pi r$$

In both cases, strain can be converted into the desired load by a single conversion factor.

The strain gage output during operation is a complex wave form. Much of the low frequency signal (.5 Hz to 10 Hz) is generated by the individual teeth of the drive gears. The magnitude of the strain due to the gears can be greater than the strain due to the span imbalance. To extract the strain due to imbalance a smooth curve can be drawn through the total strain trace. The signal can also be played back through a low frequency filter when the signal is converted into a digital form. A computer can be utilized to filter the signal by several various criteria, most often by point averaging.

The operating friction of the bridge beyond the pinion shaft is determined by halving the difference of the raising and lowering load histories. To determine the imbalance loads without friction, the raising and lowering load histories are averaged.

For a vertical lift bridge the data reduction would be complete at this point. For a bascule bridge, the vertical and horizontal component of the imbalance must be determined. To do this resulting load histories from all pinion shafts in a leaf are added together. The cosine curve that best fits the data points must be determined. This is most often accomplished using a computer program.

The results of the program provide:

1. The theoretical maximum moment (the angle of the lift that this moment would develop at may be beyond the actual range of angles the bridge operated within).

2. The angle of lift that the bridge experiences the moment.

3. The vertical and horizontal component of the theoretical maximum moment when the bridge is in the closed position.

4. The operating friction.

5. The degree of fit of the cosine curve.

Refer to Figure 3 for items 1 - 5.

Adjusting the Balance State

Adjusting the balance state of a vertical lift bridge usually entail the addition or removal of weight from counterweight. This alone can produce the most desired balance states.

The balancing of a bascule bridge requires considering the vertical and horizontal components of the bridge imbalance and of the available balancing weight locations.

Operating load conditions can be predicted for any change in the bascule span balance state. This is performed by;

1. Calculating the total of the weights to be removed and added.

2. Calculating the center of gravity of the new in weight and its vertical and horizontal distanced referenced from the center of rotation of the bascule span.

3. Calculate the vertical and horizontal moments caused by the new weights.

4. Add these moments to the corresponding existing balance state moments.

5. Calculate the new maximum theoretical moment and its angle.

6. Construct a cosine curve in phase with the lift angles with a magnitude equal to the maximum moment and a phase shift equal to its angle.

This will produce a new balance curve. Friction can be added to produce the new opening and closing load curves. If the weight to balance the bridge is significant the friction can be adjusted by the factor of;

$$\frac{\text{New Dead Load}}{\text{Old Dead Load}}$$

These operating curves can them be examined to see if they fall within acceptable limits.

The Balance State

No set standard of bridge balance has been widely established with the condition of balance usually being determined by the Engineer. The factors considered in determining the best balance state are often:

Safety

When balancing the span, it is desireable that with the motor off and the brakes released the span should not raise from its lowered position. On most bridges, this usually entails making the bridge slightly span heavy. On many bascule bridges the counterweight is part of the deck structure. A live load passing over the counterweight will tend to lift the span. Increasing the leaf weight or reducing the counterweight may be necessary to counter this effect.

Machine Wear and Load

Much of the financial gains to be made by balancing a bridge are in increased equipment life. This is accomplished by reduced operating loads. Span loads can be made to lessen with opening or even made negative at the fully opened position if desired.

Structural Wear

When lowered, the spans should be well seated on the live load bearing to reduce pumping of the bearings. This minimizes an unwanted transmission of loads through the structure and the transmission of undue load to the drive machinery. The span lifting forces should be applied evenly to the structure to avoid torquing of the span.

Computerized Data Acquisition and Analysis System

The test method described in this paper involves the recording of an analog signal for playback during analysis. A computerized data acquisition and analysis system has been developed to collect the data and provide on-site results. The strain gage and inclinometer signals (where applicable) are entered directly to the system and converted to a digital form. At the end of each test, the system can provide the present balance state, predict the load curves for proposed weight changes, and recommend weight changes based on available weight locations.

The system has the advantage of producing instant results. The results are very repeatable and not subject to visual interpretation by the operator. The program will analyze thousands of data points for each test as compared to the tens of points typically analyzed during manual analysis. This means results are available soon after changes in the weights have been made. These can be used to verify the effects of the weight changes and if needed recommend further fine tuning of the weight placement.

The system is more compact and lighter than the current system and with some training, a non-engineer can run the test.

Case Study No. 1

The Route 52 Ocean City, New Jersey Bascule Span

Upon analysis, the span was found to have an extreme vertical imbalance moment. This would require placement of weight above the trunnion to a degree not possible with the available weight locations. Subsequent investigation found that the original wood and asphalt concrete deck was removed. A lighter steel grid deck is presently in place (See Figure 4). To correct this imbalance, major reconstruction of the span would be required. To minimize the effect until corrections are made, operating the span at full opening position can be avoided unless waterway traffic requires it.

Case Study No. 2

Route 52 Somerset, New Jersey Bascule Span

Incorrect wiring of one of the wheatstone bridges produced a gage configuration sensitive to direct shear in one plane. The result was an output cosine wave in phase with the pinion shaft rotation. The mistake was identified, corrected by re-wiring of the wheatstone bridge and the test was performed.

Case Study No. 3

Eastern Boulevard Bridge, New York Bascule Span

The Eastern Boulevard Bridge carries five lanes of interstate Route 278 traffic in both the east and westbound directions across the Bronx River in Bronx, New York City. THe bridge has a 118 foot 8¼ inch span between trunnion centerlines and a vertical clearance of 24½ feet at mean high water. The bridge is operated as four (4) independent trunnion bascule leafs with a north and south unit one each side of the river. Each leaf is comprised of two (2) separate leafs that have subsequently been bolted together to act as a unit. Therefore, each unit has two (2) sets of machinery including four (4) pinions and four (4) rack gears (See Figure).

Mechanical deficiencies were clearly evident from the results in certain machinery. One leaf had a defective differential. In general the load sharing of the separate shafts was widely scattered. When the torques for the four (4) separate shafts in each leaf were total, the resulting leaf moments were similar to the four (4) leafs. The leafs were generally span heavy by at least 200,000 foot pounds. Representative data from the tests are provided in Figure 6 and 7. The load verses angle traces before and after balancing are provided in Figure 8 and 9. Note the decrease of the operating moments due to the addition of 10,000 pounds to the counterweight.

Case Study No. 4

Route 1&9 Vertical Lift Bridge Over the Passaic River

The Passaic River Route 1&9 vertical lift bridge carries two (2) lanes of traffic in both the east and westbound directions across the Passiac River in Newark, New Jersey. Each end of the span is independently operated by separate machinery controlled by the bridge operator. There is a pinion-bull gear-sheave assembly over which wire ropes run attached at one end to the span and the other end to the counterweight.

A 2000 pound generator was left on the bridge during the test program. This condition was not noted until the completion of the test program. The generator load produce 0.07% of dead load error in the northwest cable group. This effect was accounted for during the final balance calculations.

The frictional forces were found to be substantially high on the east tower, several times higher than the balance goal.

The desired 1% span heavy condition was achieved when considering each end as a unit. Further attempts to improve the individual corners would be questionable considering that the frictional forces are substantially greater than balance goal.

Case Study No. 5

Devon Railroad Bridge, Stratford/Milford Connecticut

During data analysis the south pinion was developing torques that were 2.5 to 3 times greater than the north pinion. Subsequent testing determined that the north pinion reduction gear and transmission bearings were in disrepair and developing high friction. The bridge differential was distributing equal torque to each pinion's machinery, but the bearing friction of the north pinion machinery reduced the torque available to drive the pinion. Subsequent to this test the machinery was replaced. Tests on the new machinery revealed equal torques amongst the pinions.

Case Study No. 6

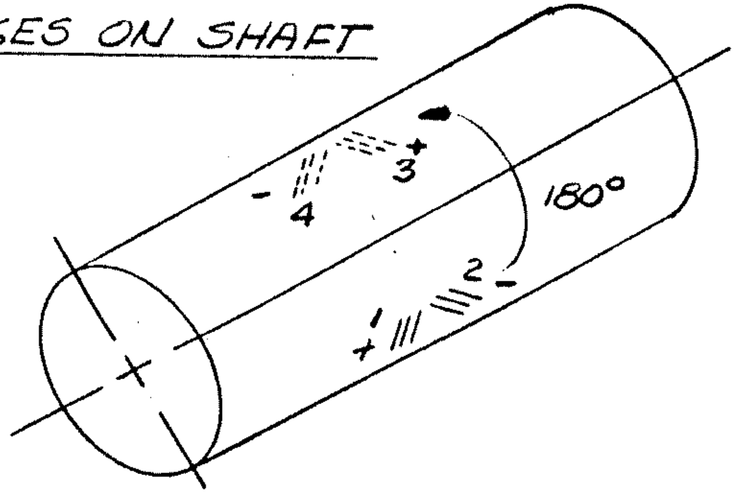
Meadowbrook State Parkway Bridge Over Sloop Channel

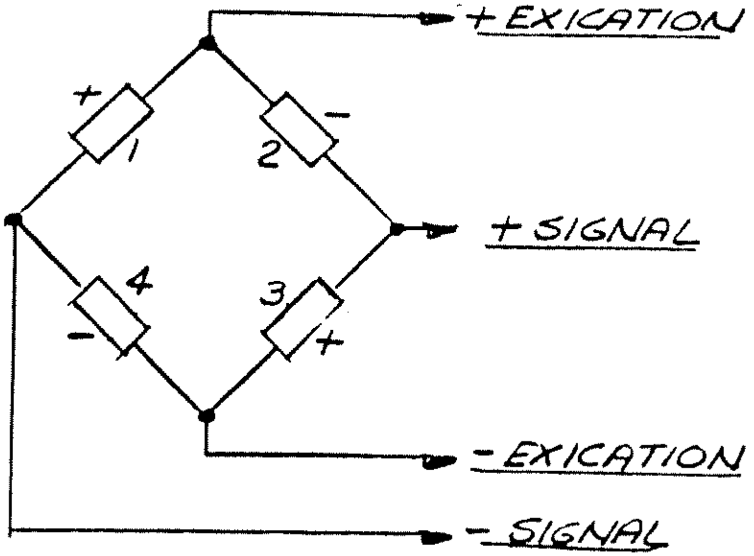
A balance test on the northwest leaf of the Meadowbrook State Parkway Bridge revealed extreme differences between moment of the east and west pinion during operation. The differential was inspected with the bridge in the closed position and found it to be well lubricated at points near the access door but dry and rusted at the difficult to reach locations. There was no relative movement between the ring gears and pinion gears except when the bridge was hard seated.

The bridge machinery is currently undergoing rehabilitation.

APPENDIX A
FIGURES

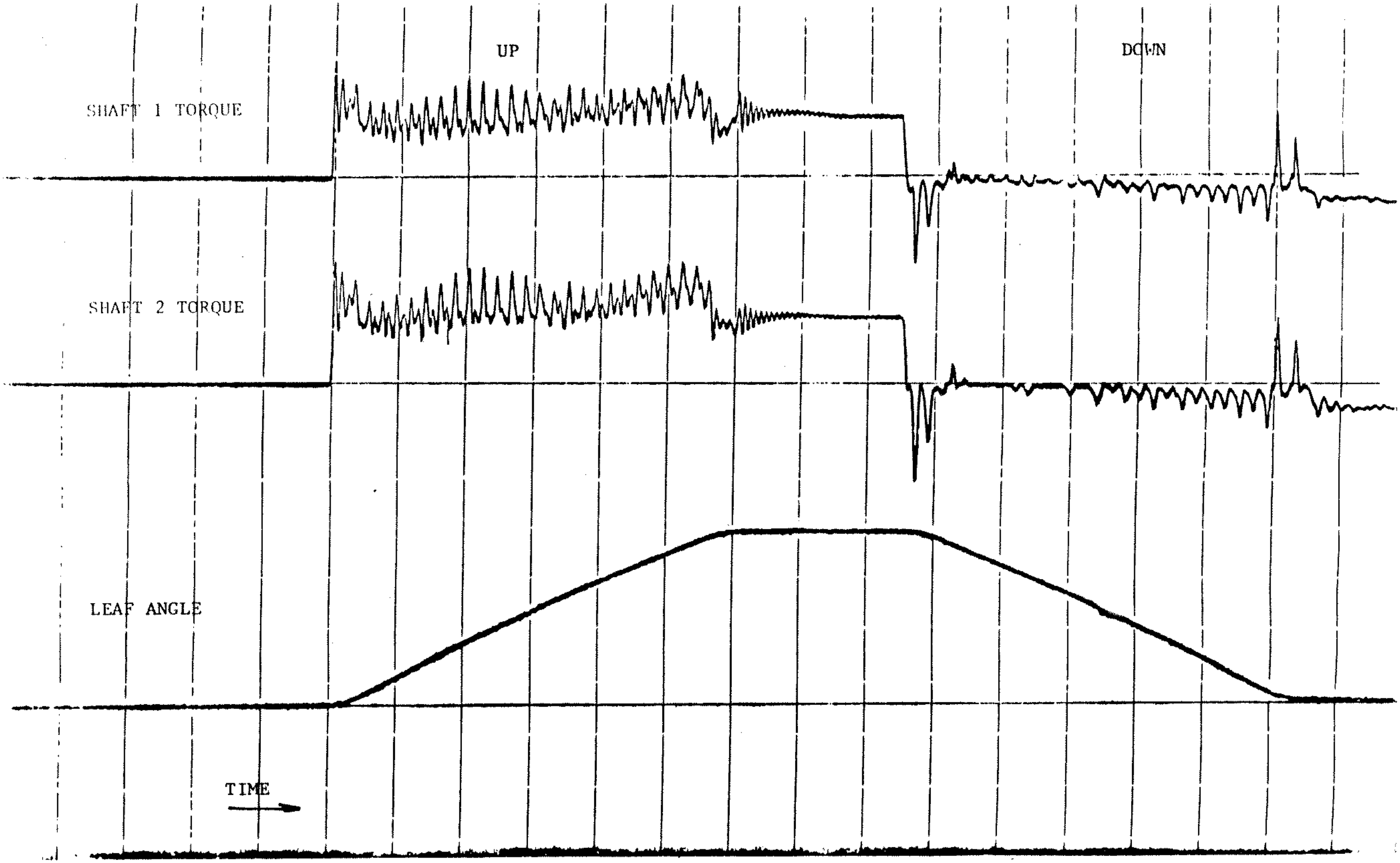
GAGES ON SHAFT





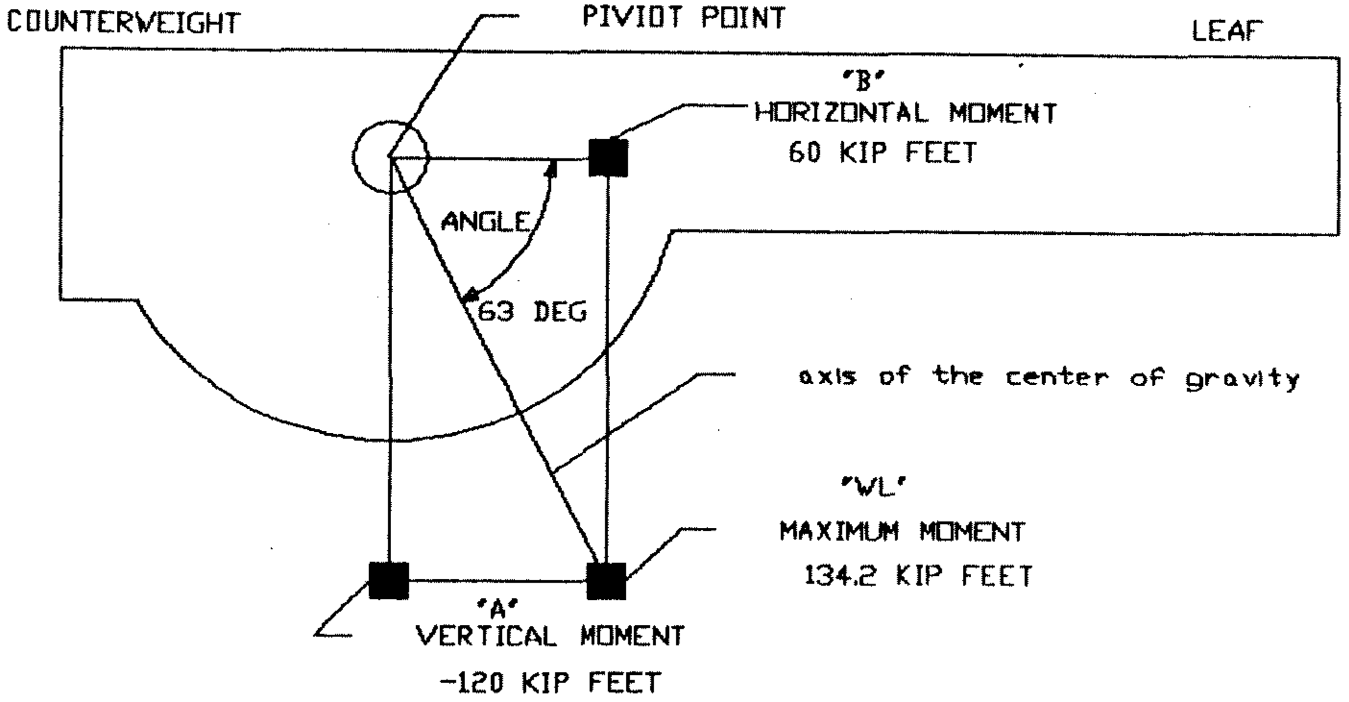
FULL WHEATSTONE BRIDGE

FIGURE #1



TYPICAL BASCULE BRIDGE

Figure 2



A = HORIZONTAL MOMENT
B = VERTICAL MOMENT
WL= MAXIMUM MOMENT

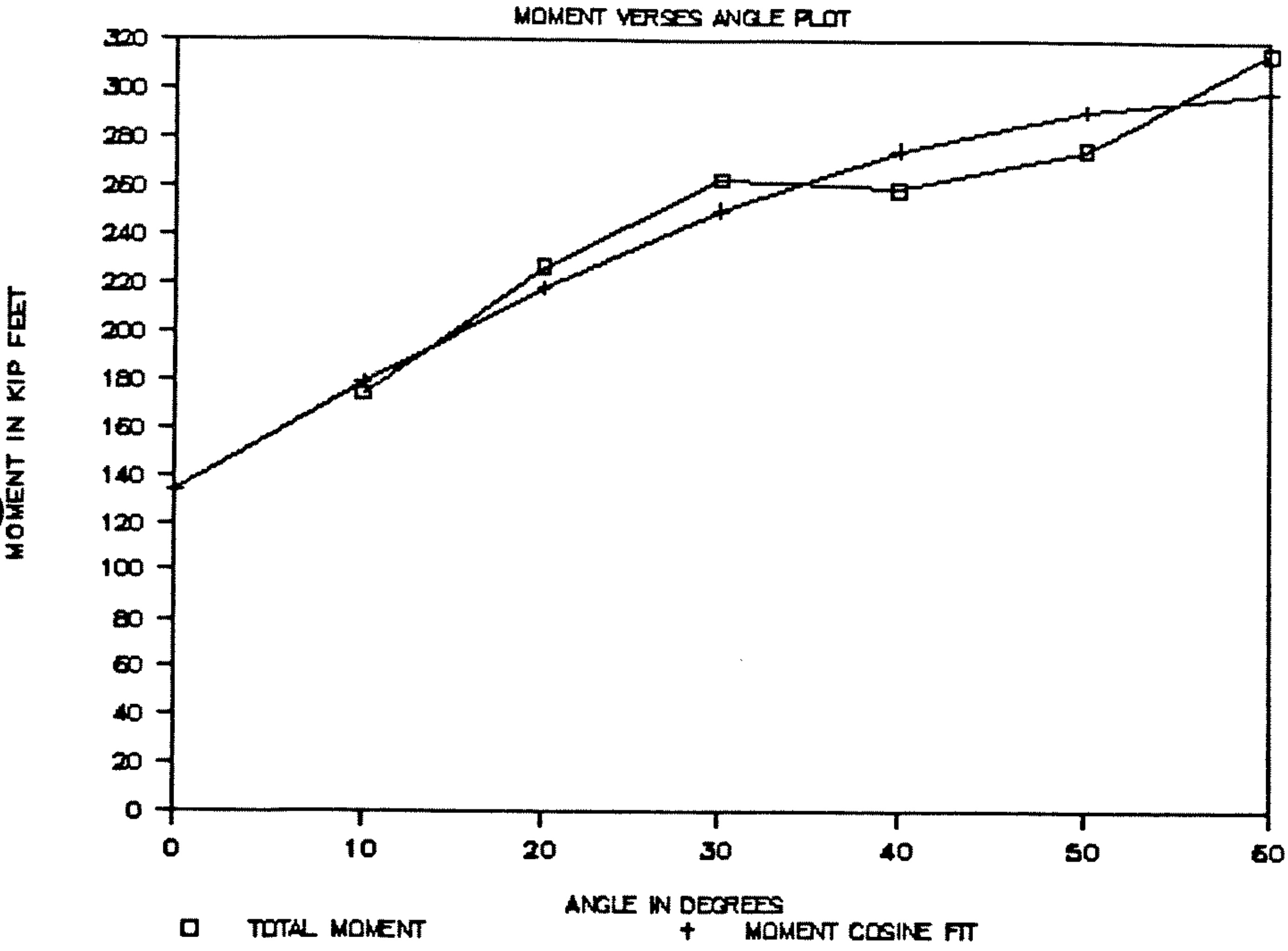
A= WL COS ANGLE

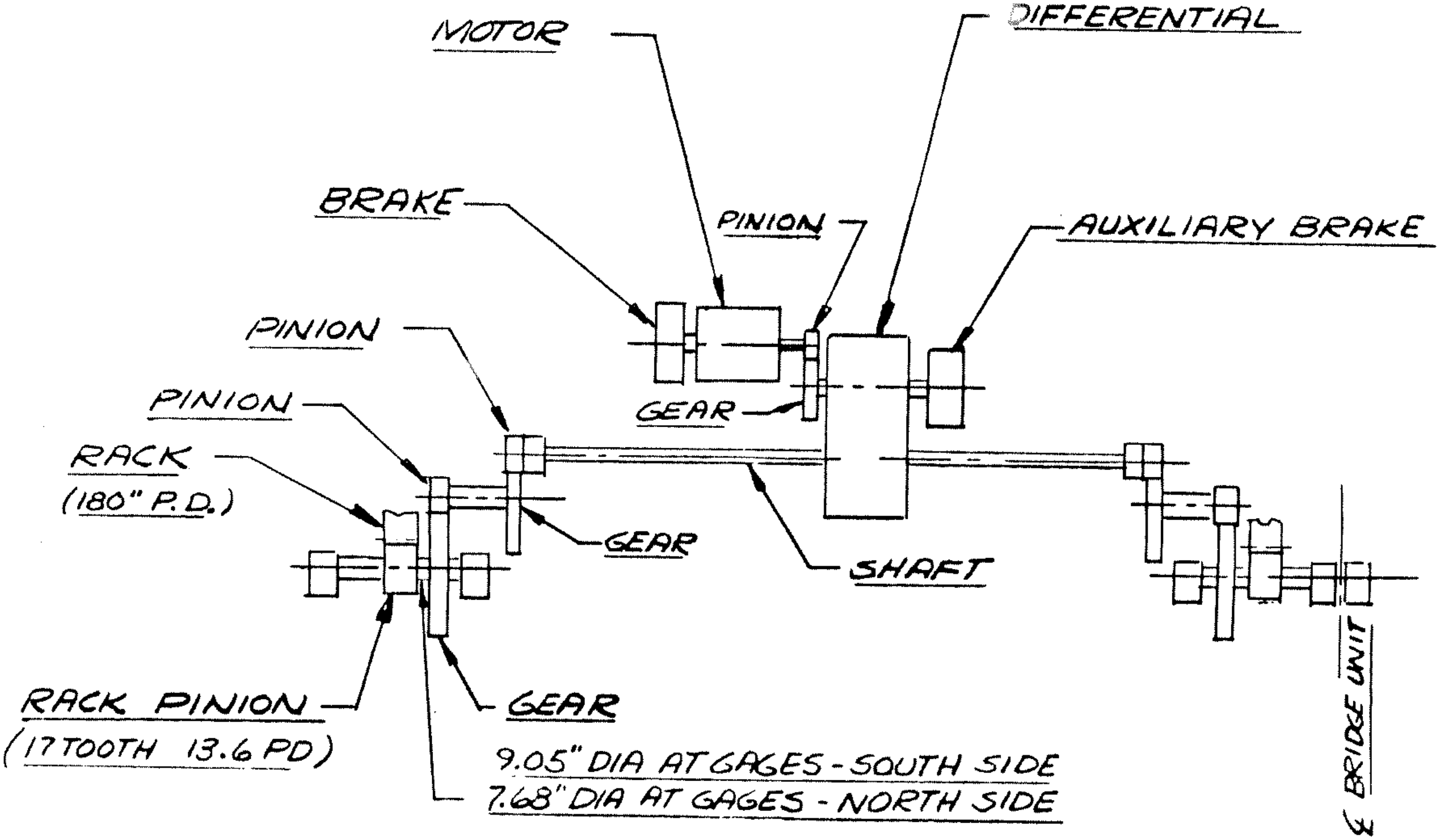
B= WL SIN ANGLE

figure 3. EXAMPLE BASCULE BALANCE STATE

FIGURE 4

OCEAN CITY





DRIVE DIAGRAM (PRIOR TO RECONSTRUCTION)

(EASTERN BOULEVARD BRIDGE OVER BRONX RIVER)

FIGURE # 5

LEAF NO. 4

BALANCE MOMENT (K-LBS-FT)

LEAF ANGLE (deg)	LOCATION 1				LOCATION 2				LOCATION 3				LOCATION 4			
	UP	DOWN	AVG.	COS REG	UP	DOWN	AVG.	COS REG	UP	DOWN	AVG.	COS REG	UP	DOWN	AVG.	COS REG
0.00				55.91				63.07				57.38				60.01
10.00	103.11	18.07	60.59	58.19	104.30	15.70	60.00	64.74	81.84	13.55	47.70	53.53	60.55	46.73	53.64	58.06
20.00	97.78	21.93	59.85	58.71	116.45	15.11	65.78	64.44	81.57	11.61	46.59	48.05	53.92	52.26	53.09	54.35
30.00	93.33	14.82	54.07	57.44	111.11	18.96	65.04	62.18	78.53	9.40	43.96	41.11	48.66	55.02	51.84	48.99
40.00	88.59	15.70	52.15	54.43	105.19	15.11	60.15	58.04	72.17	6.36	39.26	32.92	43.41	51.71	47.56	42.14
50.00	84.45	13.93	49.19	49.77	99.26	12.15	55.70	52.12	65.53	2.77	34.15	23.73	38.43	40.09	39.26	34.00
60.00	79.11	14.52	46.82	43.59	70.22	7.11	38.67	44.63	52.26	8.85	30.55	13.82	31.80	0.00	15.90	24.84
70.00				36.09				35.78				3.49				14.92

A = 55.91
B =-18.05
WL = 58.75
Frict = 37.28
Angle =-17.90
error =.04 WL
error = 2.39

A = 63.08
B =-15.12
WL = 64.86
Frict = 43.53
Angle =-13.48
error =.06 WL
error = 3.77

A = 57.38
B = 17.17
WL = 59.89
Frict = 31.61
Angle = 16.65
error =.13 WL
error = 8.00

A = 60.01
B = 5.96
WL = 60.30
Frict = 2.58
Angle = 5.67
error =.09 WL
error = 5.26

Figure 6

LEAF NO. 4

LEAF ANGLE (deg)	BALANCE MOMENT (K-LBS-FT)											
	MOMENT TOTALS 1 & 2				MOMENT TOTALS 3 & 4				MOMENT TOTALS 1, 2, 3 & 4			
	UP	DOWN	AVG.	COS REG	UP	DOWN	AVG.	COS REG	UP	DOWN	AVG.	COS REG
0.00				118.99				106.89				225.88
10.00	207.41	33.78	120.59	122.94	142.40	60.28	101.34	105.38	349.81	94.06	221.93	228.32
20.00	214.22	37.04	125.63	123.16	135.49	63.87	99.68	100.67	349.71	100.91	225.31	223.82
30.00	204.45	33.78	119.11	119.63	127.19	64.42	95.81	92.89	331.64	98.20	214.92	212.53
40.00	193.78	30.82	112.30	112.47	115.58	58.07	86.82	82.30	309.36	88.88	199.12	194.77
50.00	183.71	26.07	104.89	101.89	103.96	42.86	73.41	69.20	287.67	68.93	178.30	171.10
60.00	149.34	21.63	85.48	88.22	84.06	8.85	46.45	54.01	233.39	30.48	131.93	142.22
70.00				71.87				37.17				109.03

A =118.99
B =-33.17
WL =123.52
Frict = 80.82
Angle =-15.58
error =.02 WL
error = 2.17

A =106.89
B = -0.65
WL =106.89
Frict = 34.20
Angle = -0.35
error =.04 WL
error = 4.49

A =225.88
B =-33.81
WL =228.40
Frict =115.01
Angle = -8.51
error =.03 WL
error = 6.13

Figure 7

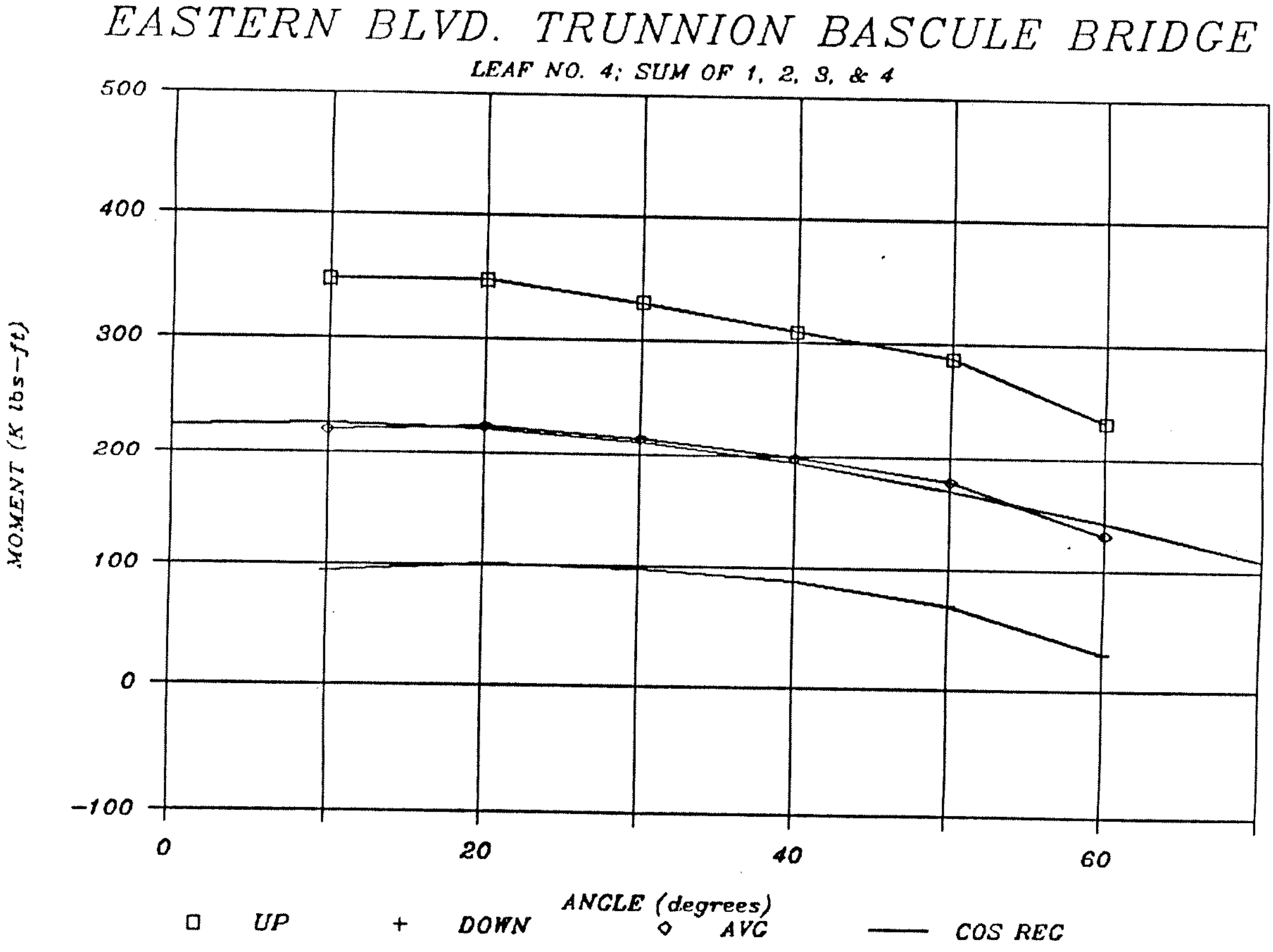

EASTERN BLVD. TRUNNION BASCULE BRIDGE
LEAF NO. 4; SUM OF 1, 2, 3, & 4
MOMENT (K lbs-ft)
500
400
300
200
100
0
-100
0
20
40
60
ANGLE (degrees)
□ UP
+ DOWN
◇ AVG
— COS REC

Figure 8

EASTERN BLVD. TRUNNION BASCULE BRIDGE

LEAF NO. 4; SUM OF 1, 2, 3, & 4

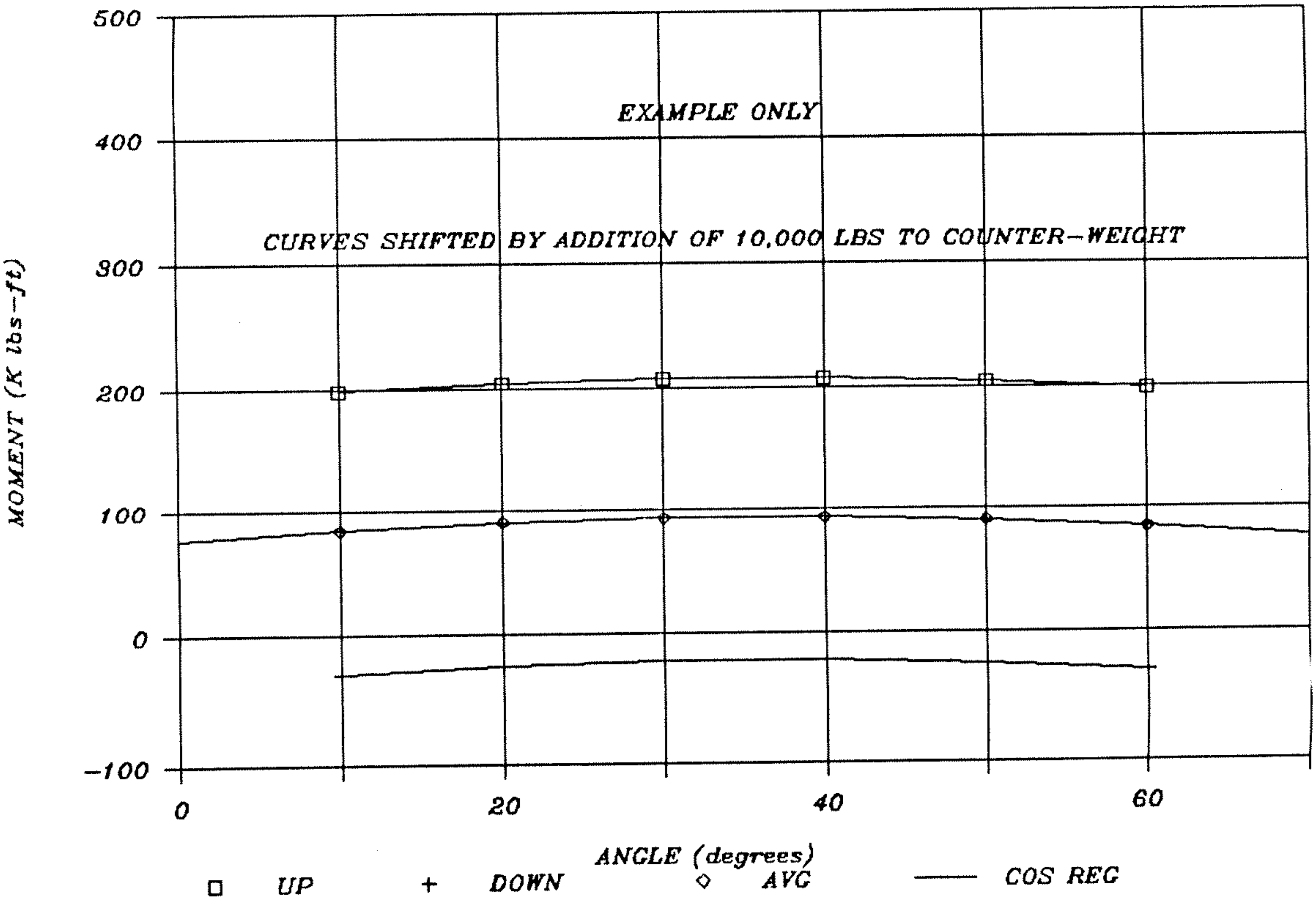


Figure 9