HEAVY MOVABLE STRUCTURES, INC.

EIGHTH BIENNIAL SYMPOSIUM

NOVEMBER 8 – 10, 2000

Grosvenor Resort
Walt Disney World Village
Lake Buena Visa, Florida

"Digital Data Acquisition for Strain Gage Bridge Balancing"

by John L. Williams
Stafford Bandlow Engineering, Inc.

DIGITAL DATA ACQUISITION
FOR
DYNAMIC STRAIN GAGE BRIDGE BALANCING

Prepared by:

John R. Williams

STAFFORD BANDLOW ENGINEERING
573 Main Street
Doylestown, PA 18901
(215) 340-5830

Prepared for:

HEAVY MOVABLE STRUCTURES
8th BIENNIAL SYMPOSIUM
LAKE BUENA VISTA, FLORIDA

NOVEMBER 2000

Introduction:

The strain gage method of bridge balancing has been proven through years of use to be an accurate and effective means of assessing the balance condition of bascule and vertical lift bridges. It has only been in the relatively recent past that digital data acquisition equipment has outmoded analog hardware (i.e. strip chart recorders). This change in technology presents new technical challenges and has brought about changes in the tools and methods that are required to process bridge balance data.

This paper focuses on the issues related to acquiring digital strain data and processing this information to yield balance results. This will include a brief discussion of the current hardware and software technology and a comparison of this technology to the analog technology, how to determine an appropriate sampling rate, and methods used in processing digital data to ensure the accuracy of results. Examples will be presented using actual data collected during the balancing of bridges of different types.

While this paper focuses on the subject of the data acquisition and analysis, there are myriad potential sources of error involved in balance testing of movable bridges by the dynamic strain gage method. A discussion of these other topics, from the proper selection and application of strain gages to an understanding of the mechanical systems and engineering mechanics involved, is beyond the scope of this paper.

Background:

There are many different types of instrumentation available for the collection of dynamic strain gage data. The earliest systems consisted of a signal conditioner/amplifier unit that provided an analog signal to a strip chart recorder. While these systems remain effective, they require the user to manually read a strip chart to determine data points to be used in the analysis. This introduces a degree of human error and can also be quite tedious, effectively limiting the number of points used for analysis. In the relatively recent past, it has become much more common for the analog output from the signal conditioner/amplifier to be converted into digital form and recorded. This enables the user to utilize a computer to efficiently and accurately process and analyze the results. However, it is important to understand the differences between dealing with data in digital form versus on a strip chart if accurate results are to be obtained.

The Technology:

A generic system for recording digital dynamic strain data consists of an arrangement of strain gages mounted on a specimen and wired in a full Wheatstone Bridge, a signal conditioner/amplifier that provides an excitation voltage across the bridge and amplifies the resulting output, an analog to digital converter (ADC) and a recorder that provides the user with a permanent record of the indicated strains. There are many different types of instruments available based on this architecture that fall into two general categories: The first requires a connection to a computer (PC) while the second operates as a stand alone unit. PC based data acquisition units couples a PC with an ADC. This combination converts to digital, filters and saves the analog data output from the signal conditioning unit. A stand alone strain recorder combines the signal conditioner and ADC with a built in processor to take care of these functions and can acquire, convert, filter and save data without the use of a PC. The type of system that is employed is of little importance. Of primary importance are the capabilities of the system in terms of sampling rate. Sampling rate is defined as the total number of useful data points per unit time for each signal channel. This is similar to the frequency response of an analog system. If the signal is undersampled during a test, the data collected will be insufficient to reconstruct the signal later.

A system that is suitable for movable bridge balancing will have features that enable the user to easily transport and set up the instrument in the field. It is also important that the hardware include a shunt calibration feature. This allows the user to test the instrument by applying a known load across one leg of the Wheatstone bridge to obtain a specific output. This is the only way to verify that the instrument is providing the correct voltage to the gages and is properly amplifying the resulting output from them short of applying a calibrated load to the instrumented test specimen. Systems that do not provide for shunt calibration should not be used as they provide no means to verify that the instrument is set-up correctly at the time of the test.

The final component of a digital data acquisition system is software. This software can either be built in to the operating system of a stand alone strain recorder or may be an application that is run on a PC during PC based data acquisition. The software enables the user to control the acquisition and may also include features to perform signal conditioning functions to reduce noise to complement the filtering of the signal that is performed by the ADC hardware.

Sample Rate:

It is critical that the data be sampled at the appropriate rate to ensure that the signal can be accurately reconstructed. The Nyquist sampling theorem says that if a signal only contains frequencies less than f_c (called the cutoff frequency), all the information in the signal can be captured by sampling at $2f_c$. In the case of a movable bridge driven by rotating machinery, the highest frequency of interest is the speed of the motor driving the machinery. For a motor rotating at 900 RPM, f_c is 15 Hz (15 rotations per second). The minimum sample rate in this case is 30 Hz. If the information contained in the signal at or near the cutoff frequency is of importance, it is common to sample at a rate up to ten times f_c. This is generally not required for movable bridge balancing but may be helpful when performing other types of movable bridge drivetrain analysis.

Data Processing:

When the data being processed is recorded on a strip chart, it is relatively straightforward to process. The user selects "by eye" what points on the chart to use for the analysis. This is illustrated in Figure 1. The data presented represents the closing half of the lift cycle for the subject bridge. Subsequent test runs require the user to repeat the process of selecting data points. The advantage of this method lies in its simplicity. However, it requires the user to make subjective choices about the data that will ultimately influence the results. Also, the number of points used in the calculation must be kept to a minimum because each point must be manually read from the chart. In this example, the bridge being tested is a vertical lift bridge with balance chains that fully compensate for the change in balance due to the counterweight ropes passing over the sheaves. The imbalance remains constant through the entire range of motion. The analysis required to convert the strain data to imbalance is the simplest of any bridge type, as evinced by the brief hand calculations on the chart that determine the imbalance state of the bridge. It is of interest to note that the data does not remain constant, but appears to follow a step function. This is entirely due to the fact that the bridge has significant sources of friction acting externally, due to contact between the lift span and the guide rails during some portions of the lift. The potential for these sorts of problems with the operation of the bridge highlights the need for testing to be performed by personnel that are experienced and have a good understanding of the operating machinery of movable bridges.

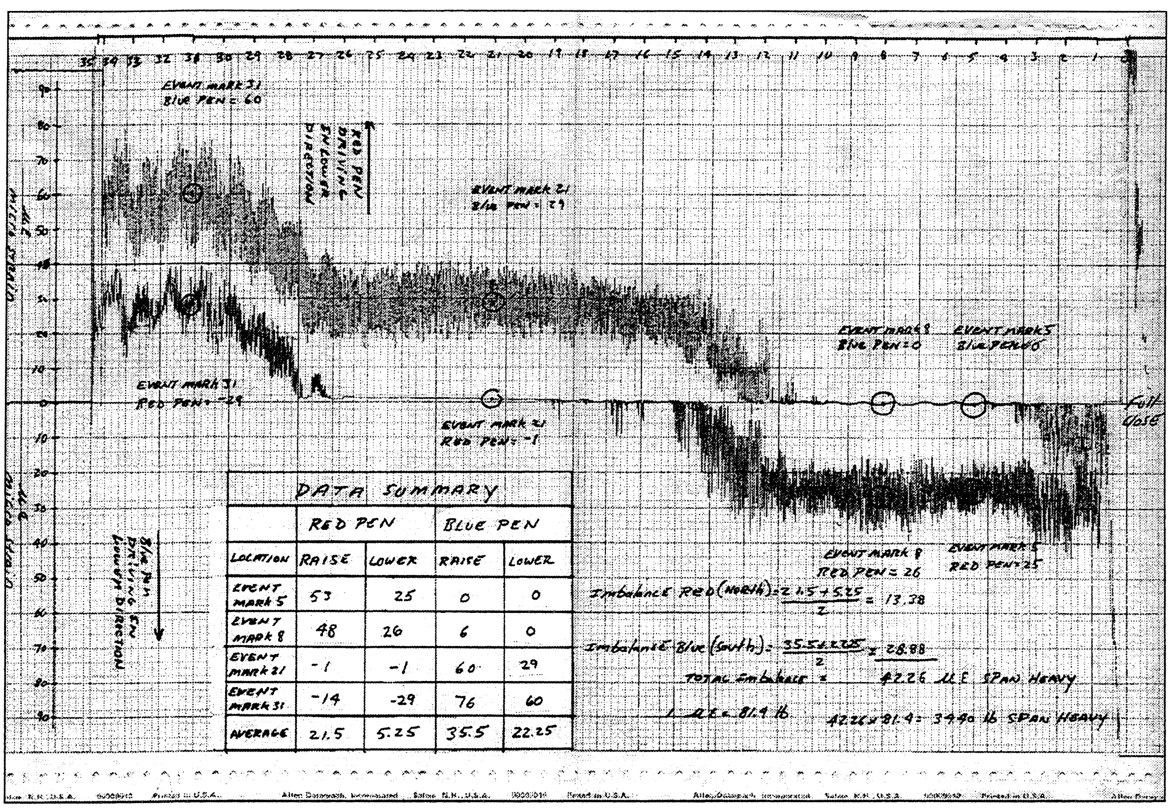


Figure 1: Analog Strip Chart And Manual Data Analysis For A Vertical Lift Bridge Equipped With Balance Chains (Closing Trace Only)

If the benefits of using digital data acquisition are to be realized, software must now perform the task of selecting the appropriate points to be used for analysis. The selection of points "by eye" will be replaced by a more exact method that can be codified. This will become increasingly important for bridge types that require a more complex analysis.

In Figure 2, a single channel of strain data from a trunnion bascule bridge collected using a PC based data acquisition system at 50 Hz is plotted versus time (in this case the minimum sample rate was defined by the Engineer for the project). A second channel records the output from an electric clinometer to provide a relationship between torque and bridge opening position. The individual points identified are selected at regular 5 degree intervals from the raw data.

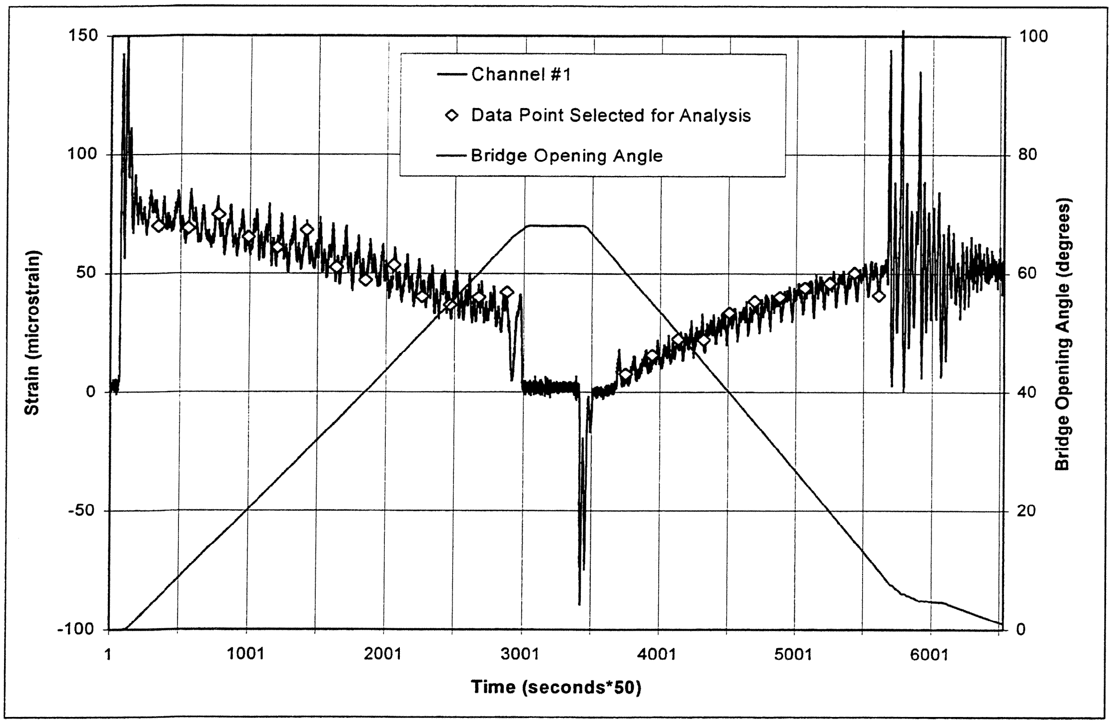


Figure 2: A Plot Of Digitally Acquired Data From A Trunnion Bascule Bridge Balance Test

As evinced in Figures 1 and 2, the torque signature from a gear-driven movable bridge is full of peaks and valleys that occur at regular intervals. These periodic fluctuations are a result of physical phenomena such as impacts from gears meshing and sliding friction between gear teeth. If a single point is selected to represent the data, as is the case in Figure 2, it is possible that the selected point may fall on a peak or in a valley, introducing some error into the analysis.

A simple method for reducing the error associated with periodically fluctuating data is to average the values of multiple data points. The number of data points averaged must be greater than the period of the fluctuating data. In Figure 3, 20 seconds of data is plotted starting at t=20 seconds. It is easily determined by counting peaks that there are 11 cycles within this duration of data. Since the data was sampled at 50 Hz, the number of points to be averaged should be at least:

$$\text{time} = 20 \text{ seconds}$$

$$\text{cycles} = 11$$

$$\text{period} = \frac{\text{time}}{\text{cycles}} \qquad \text{period} = 1.82 \text{ seconds/cycle}$$

$$\text{sampling rate} = 50 \text{ Hz}$$

$$\text{period} * \text{sampling rate} = 91 \text{ samples}$$

The length of time between peaks in the data corresponds to the rate at which the rack pinion teeth enter the mesh with the rack. Thus, an alternative method for determining the correct averaging interval is by calculation. Since the actual motor speed is not known, and may vary throughout the test, the nameplate data is used:

$$\text{motor speed} = 900 \text{ RPM} \qquad \text{ratio} = 539{:}1 \qquad \text{teeth} = 18$$

$$\text{rack pinion speed} = \frac{\text{motor speed}}{\text{ratio}} \qquad \text{rack pinion speed} = 1.67 \text{ RPM}$$

$$\text{period} = \frac{60 \text{ seconds}}{\text{teeth} * \text{rack pinion speed}} \qquad \text{period} = 1.996 \text{ seconds/cycle}$$

$$\text{sampling rate} = 50 \text{ Hz}$$

$$\text{period} * \text{sampling rate} = 100 \text{ samples}$$

Therefore, averaging 100 points of raw data should be sufficient to minimize the error associated with the fluctuations in the data.

To illustrate the effect of averaging, points were selected from the raw data shown in Figure 2 by averaging 100 samples. 20 seconds of raw data and the 10 points determined by averaging are plotted in the chart below. It is clear that the values generated in this manner more accurately reflect the trend of the data versus the solitary points selected in Figure 2.

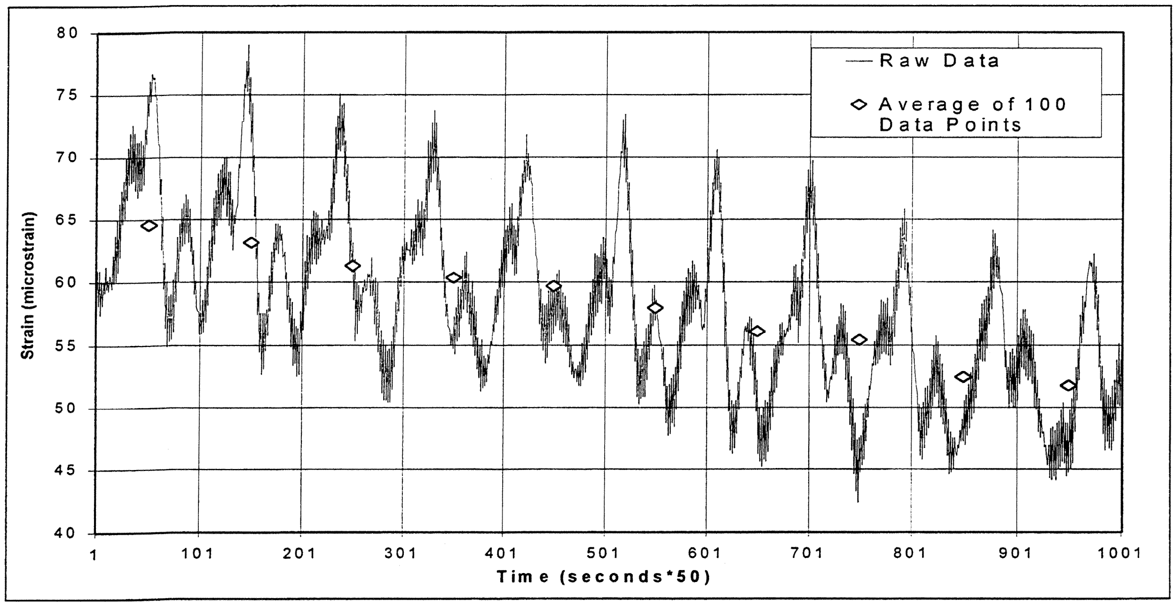


Figure 3: 20 Seconds Of Data Plotted With Points Selected By Averaging 100 Points Of Raw Data

Calculations:

Once the data collected during a test has been processed, calculations must be performed to determine the imbalance condition of the bridge with the bridge closed. For a trunnion bascule bridge, the data will fit a cosine function that is defined by two coefficients relating to the angular location of the center of gravity and the magnitude of the imbalance. A cosine curve is fit to the data from the constant speed portion of the opening, and the coefficients that define the curve are determined. The angular location of the center of gravity and the magnitude of the imbalance of the bridge at any opening angle can then be determined.

Whenever a curve must be fit to data, one factor that greatly enhances the accuracy of the results is the number of points used in the calculation. The accuracy almost always increases with the number of points used. The exception to this rule is that some algorithms used for curve fitting become unstable when large numbers of points are used. A great benefit of processing digital data on a PC is that any number of points can be generated during processing for any number of channels without any additional effort. This can result in a considerable time savings when the testing involves multiple channels and multiple tests.

In order to illustrate the effects of properly processing strain data for a balance analysis, The data from a single balance test was processed three different ways. The points selected were then used as inputs in a program that performs the tasks of fitting the curve to the data and extrapolating to determine the imbalance condition with the bridge fully closed. The different data points used in each of the three cases are presented in Figure 4 alongside the raw data. Note that this plot of strain versus opening angle contains two traces. The upper trace is from the portion of the test when the bridge is opening. The lower trace is from the closing portion of the test.

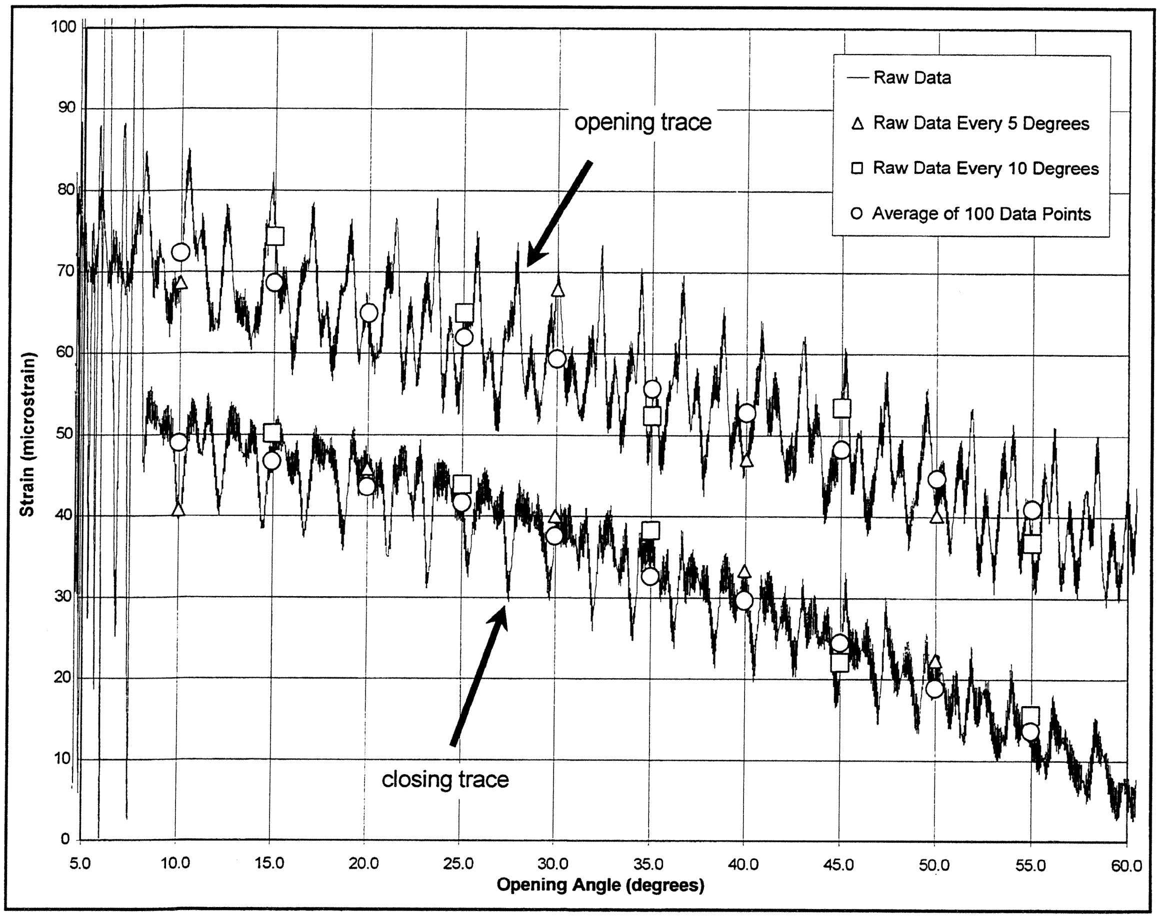
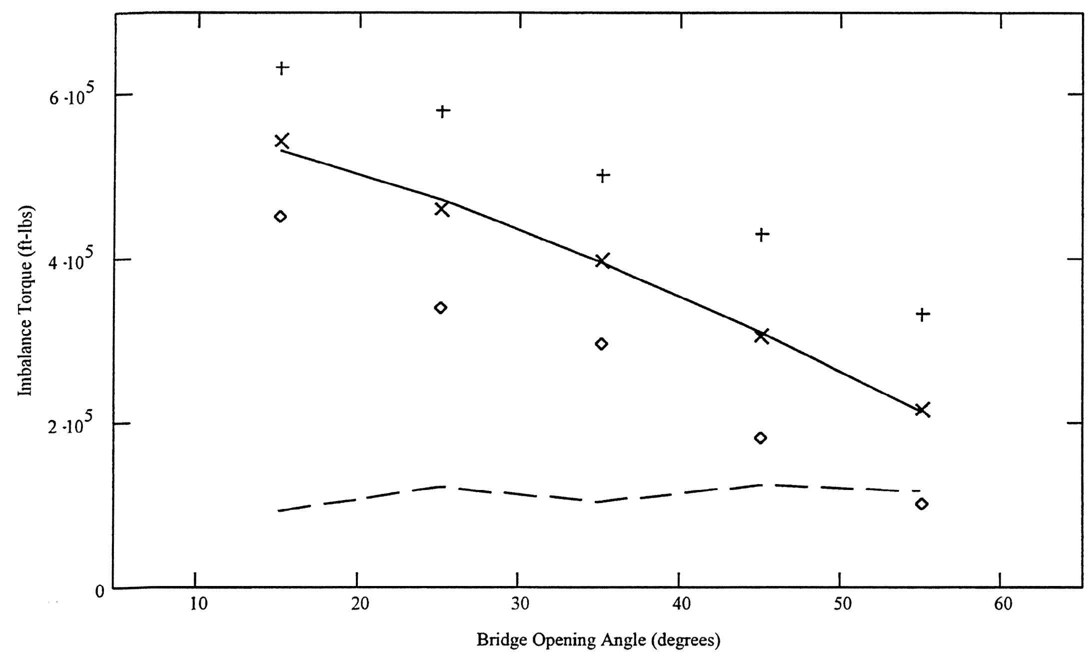


Figure 4: X-Y Plot of Strain Versus Opening Angle With Data Points Used For Calculations Identified

Results

The first set of calculations was based on selecting 10 single points from the raw data at regular 10 degree intervals from 15 to 55 degrees (5 points from the opening portion and 5 from the closing portion of the data) as shown in Figure 4. The results of the calculations are presented in Figure 5.

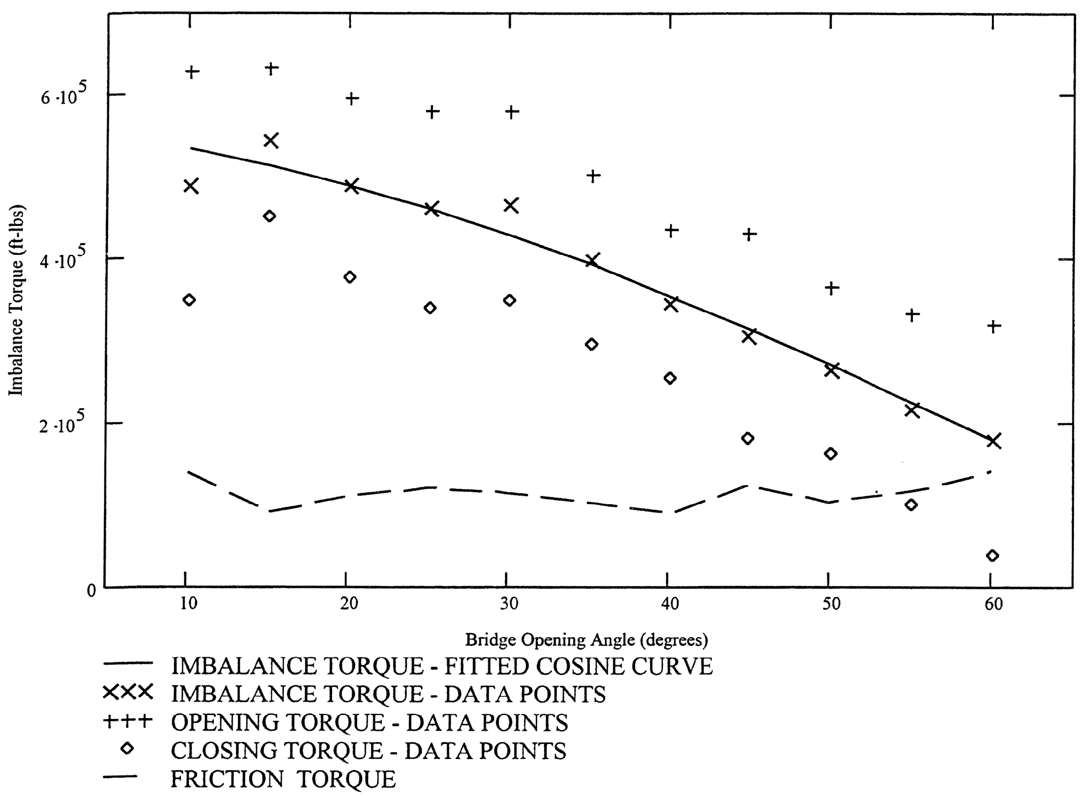


$\theta := 0$ $\quad\theta =$ leaf angle

$\text{Torque}_{\text{Imbalance}} = 588822.056$ FT-LBS with the span fully closed

Figure 5: Calculated Imbalance Torque Using 10 Points Selected From The Raw Data At 10 Degree Intervals (Case 1)

The second set of calculations was performed with the same 10 points used in the initial set of calculations plus an additional 12 points were selected at regular intervals. The data used in the calculation now represents 22 single points selected from the raw data at 5 degree intervals, from 10 to 60 degrees as shown in Figure 4. The results are presented in Figure 6.



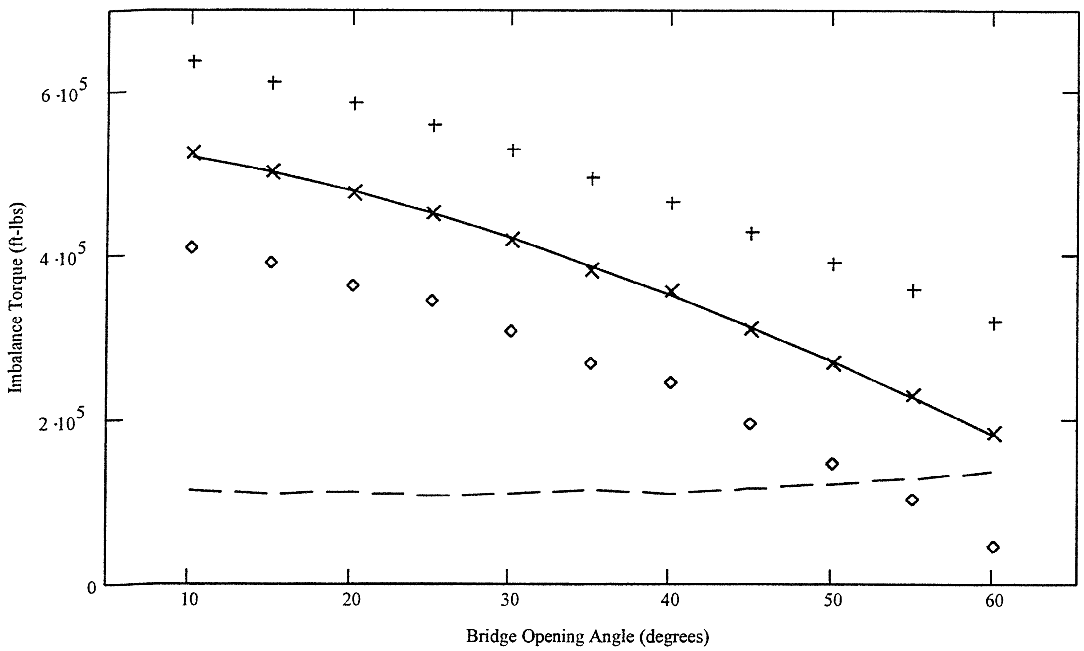
$\theta := 0$ $\quad\quad$ $\theta =$ leaf angle

$Torque_{Imbalance} = 561123.945$ FT-LBS with the span fully closed

Figure 6: Calculated Imbalance Torque Using 22 Points Selected From The Raw Data At 5 Degree Intervals (Case 2)

When comparing the chart in Figure 5 versus Figure 6, note that as additional data points have been added to fill in the gaps, several of the points now lie outside of the path of the fitted cosine curve. The curve still appears to fit to the data reasonably well.

The final set of calculations used points that were selected by averaging the raw data to reduce the error caused by using a solitary point. 100 points of raw data were averaged based on the results of the earlier calculations. Points were selected at the same 5 degree increments used in the second set of calculations. The results of these calculations are shown in Figure 7.



—— IMBALANCE TORQUE - FITTED COSINE CURVE
XXX IMBALANCE TORQUE - DATA POINTS
+++ OPENING TORQUE - DATA POINTS
◇ CLOSING TORQUE - DATA POINTS
— FRICTION TORQUE

$\theta := 0$ $\theta =$ leaf angle

$\text{Torque}_{\text{Imbalance}} = 545644.838$ FT-LBS with the span fully closed

Figure 7: Calculated Imbalance Torque Using 22 Points Selected By Averaging 100 Points Of The Raw Data At 5 Degree Intervals (Case 3)

With the error resulting from the fluctuations in the data removed, the curve neatly fits to the data, with no outlying points. This is a good indication that the curve accurately represents the trend of the data.

Conclusions

The results from the three different sets of calculations are summarized below.

Data Set Used To Calculate Imbalance	Calculated Imbalance Torque	Percentage Change Versus Case 3
Case 1: 10 Points From Raw Data	588822 ft-lbs.	8%
Case 2: 22 Points from Raw Data	561124 ft-lbs.	3%
Case 3: 22 Points from Averaged Data	545645 ft-lbs.	----

Table 1: Summary of Results From Imbalance Calculations

In the example used, the leaf was significantly span heavy and the test results were used to calculate the additional counterweight required to achieve the proper balance condition. The error resulting from improperly processing the data from the test would have resulted in adding hundreds of pounds of unnecessary weight to the counterweight. This may be a small number relative to the total mass of counterweight required, but the refined analysis clearly provides the user with improvements in the reliability and repeatability of results.

While the use of digital data acquisition technology presents an opportunity to harness computers to accomplish many of the tasks required to calculate movable bridge imbalance from strain data, many decisions must be made that can have a significant impact on the outcome of the analysis. When the capabilities of the available hardware and software are combined with informed decisions about how to properly use the technology, superior balance results can be efficiently and reliably obtained in comparison to capturing, processing, and analyzing data with analog systems.