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Electronic Bridge Span Monitoring

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Introduction
As quickly as it is becoming the standard in movable structure balance measurement, electronic data acquisition is also beginning to prove its viability in a much wider array of efficiency testing. Reaching far beyond simply documenting the reaction of a structure to gravity during an opening/closing sequence, additional information is being produced that highlights the performance of individual drive and control components as well. With the increased flexibility of RF communication replacing hardwired sensors, improved accuracy and ease of operation of the acquisition equipment and specialized acquisition personnel, more information than ever before is being made available for the benefit of bridge inspection, maintenance and design.

This paper will demonstrate various applications of installing electronic data acquisition sensors and logging equipment for the monitoring of electrical, hydraulic and mechanical subsystems and components on heavy movable structures. All of the instances cited in this paper refer to actual situations taken from a study of tests performed by West Brook Industries, Inc. on 15 movable roadway and railway bridges over the last 5 years. Through a demonstration of the general concepts of this technology we hope to provide the audience with a springboard for thought in recognizing its potential in his/her individual applications. Additionally, and just as importantly we have included recording samples, photographs and data processing results that indicated areas with existing problems or noticeable potential for failure that would have otherwise gone undetected.

Electronic Monitoring Overview
In general, electronic monitoring amounts to the attachment of an electronic sensor at a location specific to obtaining data from the target element; providing an electrical source of power that the sensor can convert to a signal that reflects changes in loads placed on the target element; conveying the signal to an acquisition device; storing the data and finally processing the data and interpreting its meaning. As it applies to balance testing of a bridge span the process has become quite dependable and extremely accurate. Through proper application of equipment and computer software the whole concept is losing its shroud of

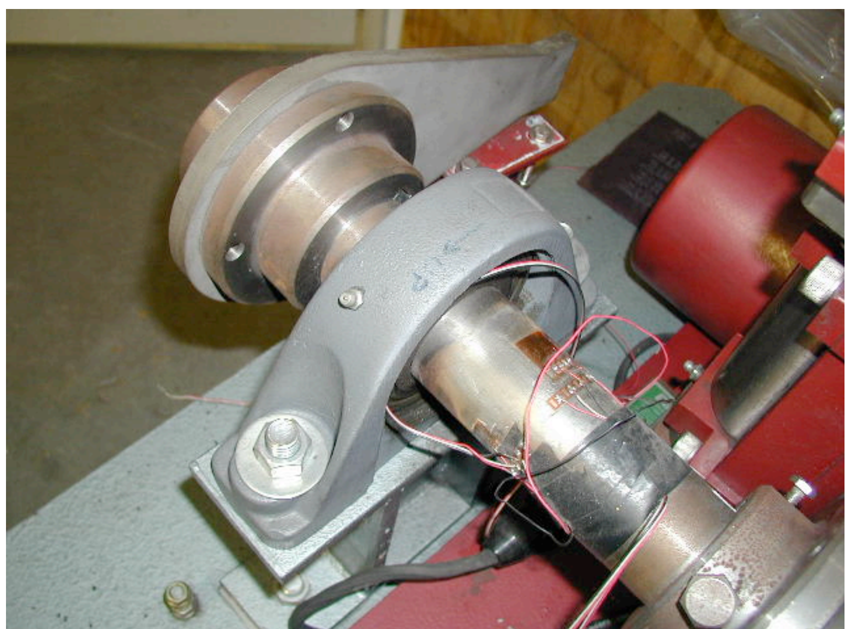

Figure 1 - Foil type strain gauges are mounted on an in-house test unit used for equipment calibration prior to field trips. This fixture also provides the means for studying the effects of shaft deflection, gauge limitations and system hysteresis among others.

mystery and can be viewed in terms of basic mathematics, something all of us can better appreciate.

When balance testing a gear-driven structure the sensor is typically a Wheatstone Bridge strain gauge (**Figure 1**) that senses stress exerted on a shaft. A mathematical conversion of the signal from this sensor changes the shaft strain to torque values providing the basis of determining the structure's reaction to gravity at various positions. In drives involving hydraulic cylinders as the primary mover strain gauges can be placed in the clevis pins but a much more widely accepted method is the sensing of fluid pressure on both ends of the working cylinders. The data is processed somewhat differently but the result is the same, balance of the structure is determined from electronic monitoring devices.

This paper is not meant to focus on monitoring equipment or software selection nor will it look at the intricacies of sample rates or data processing. The primary purpose here will be to reveal a natural next step being taken in the use of this technology in bridge maintenance and design. Once the basic process of monitoring the change in stress on driveline components has been applied to a particular structure for balance testing purposes a whole realm of information has been placed at the disposal of the contractor, engineer and owner. This information gives an in-depth look at the efficiency, effectiveness and even safety of a number of systems operating each time the bridge runs and most of this information cannot be accessed by any other means.

The accurate dissemination of this information requires very close adherence to some basic rules of electronic data collection. Only through proper understanding and application is this data valuable for any interpretation including span balance determination. There are procedures and guidelines currently being prepared for print that outline the responsibilities and minimum qualifications of personnel conducting this type of testing and are offered under separate cover.

Applications for Electronic Monitoring

Individual Component analysis

As with any practice, the more time spent in analysis of the subject matter the more it can be understood. This certainly applies to the electronic monitoring of bridge operations and two particularly useful applications have emerged as a result. First is the ability to quantify loads placed on individual components during normal operations and second is being able to accurately document the reaction of the components to these loads. When a bridge is set up to operate at given speeds, accelerate and decelerate at specific rates and operate within certain ambient parameters what is known about the actual effect of each variable on the structure itself? In support of theoretical stress predictions the attachment of strain sensing devices during and following the construction process can provide many of the answers with a high degree of accuracy.

Over time it has been noted that several components of the structure, particularly within the drive train, provide unique, recognizable electronic patterns when reviewing the monitor charts of bridge operations. Brakes, drives, reducers and others, when operating properly, repeatedly fit certain individual patterns. It's when there is an abnormality whether within the component itself or in the force acting on it externally that the patterns begin to alter. Close observation of the electronic readout, if undertaken live while the bridge is operating can highlight a potential for failure or possibly link an errant pattern to other audible or visible indicators. This can be a significant aide in identifying the problem source.

A brief look at several of these components follows. In it, specific examples are given showing observations made in the field while conducting routine span balance testing. The importance of understanding and applying this technology can be seen in each case as the owner and contractor both benefited directly by being provided this additional information.

Brakes

How effective are the brakes on your last project? Even if set up according to specifications it is only an assumption that the retarding of movement each brake is designed to accomplish is actually being provided. With variables like control timing, set/release time adjustment, spring pressure adjustment and friction surface efficiencies the likelihood that any one brake is functioning precisely as designed is very low. Put up to 4 brakes on a single drive train and the uniformity of function becomes even more important.

A prime example of a multiple-brake system recently monitored can be seen in Figure 2. This is a 2 motor drive feeding a single center-mounted pinion with 2 brakes for each motor. Readings taken before and after a leaf rehab can be seen in Figure 3. The areas highlighted in Figure 3L show brakes being applied as the leaf reached the Near-Open position. Typically any unexpectedly sharp change in strain readings is an attention getter and this one had an additional

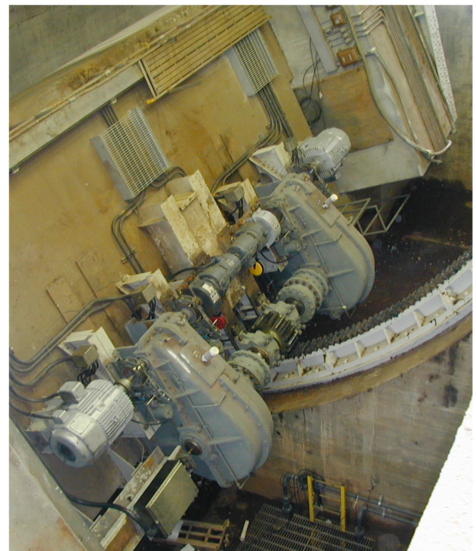

Figure 3- Here, a single pinion is powered by two drives each with a machinery and a motor brake.

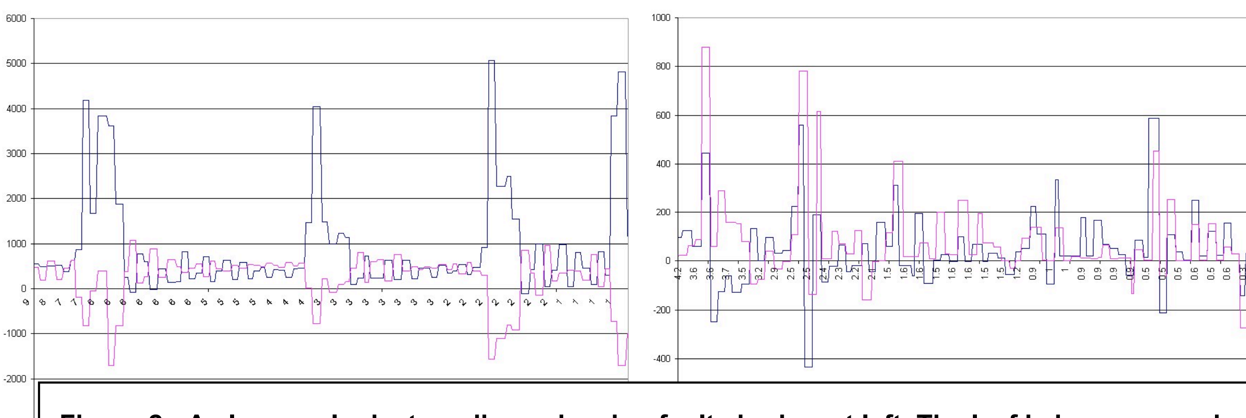

Figure 2 - A close-up look at readings showing faulty brakes at left. The leaf is in creep mode approaching full closed position and each time the brakes are applied only one brake on Drive A (blue line) operates while Drive B (red line) has no braking of its own. At right is the same leaf following rehab. The brakes are working much more as intended and with additional adjustment will exert almost identical effort when applied.

twist to it. The lines representing the strain readings from the individual drives separated radically each time the brakes were applied providing an additional warning sign.

This sudden change in torque readings is attributable to the brakes since the drive system in use here is not capable of producing this deceleration without reversing and the overall pattern is consistent with those generated by brake application. What looks like an increase in torque on the north shaft is actually the south brake slowing the north drive train through the pinion. This reading was corroborated by the fact that only one of the four brakes was operational prior to the rehab project.

Figure 3R is a printout of readings taken following completion of the rehab. In the area highlighted the same deceleration period is depicted and the results are much more as expected. There are four new brakes on this drive and while final adjustments had not been completed the braking effectiveness was much more uniform between the brakes. A subsequent check performed immediately upon finishing this run indicated an increased temperature of the lining and wheel on one brake compared to the other three. After being informed of the situation the contractor was able to make the changes necessary to correct the problem.

Reducer Efficiency

An obvious application for strain gauge sensing is the assessment of gearbox efficiency. Placing a sensor on the input and output shafts of a reducer will accurately indicate how much torque is being consumed within the reducer itself. Until recently connections between sensors and the acquisition device had to be hard-wired preventing the exploitation of this source of valuable information. As we move into the use of radio frequency data transfer this procedure will become more viable and initial testing has already begun in this area.

Normally strain balance testing requires two measurement points on a two motor system driving a single pinion, a single motor driving two pinions or a two-motor/pinion combination. This practice insures that load share between motors and/or pinions is being accurately evaluated. To test reducer efficiency an additional sensor would be located on the upstream side of each reducer and this data can be compared to the existing sensors placed downstream from the reducer, typically on the main pinion shaft.

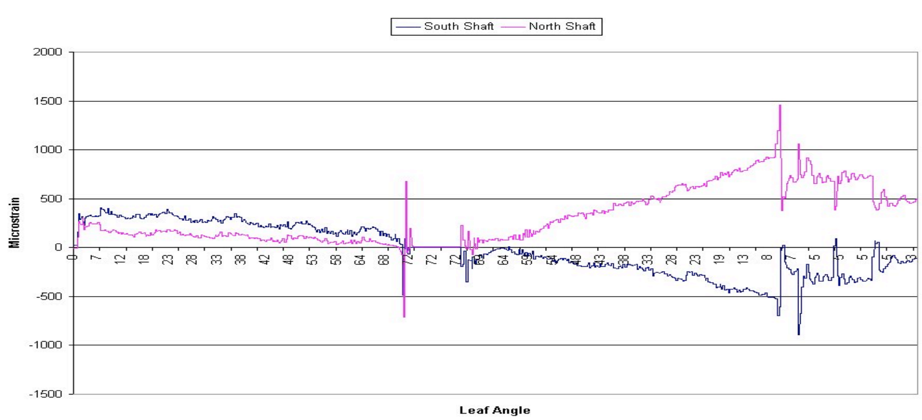

Figure 4 –This reducer spun a bearing while span balance tests were being made. As the leaf started to lower the display showing real-time readings indicated a serious problem taking place as seen by the separating traces tracking to the right.

Friction

A basic concern in bridge operation is the understanding of how friction affects span balance testing as well as equipment operation. It seems like a simple process to isolate the effects of friction on readings taken for the calculation of span balance however it may not be as clear cut as averaging raise and lower readings. On the first run of a balance test following a rehab project it was noticed immediately that one drive was inoperative and the other drive was lifting the span by itself. The run was completed and a search revealed that a motor overload was tripped. It was unclear how long it had been operated this way prior to our arrival but after resetting the overload it operated without failure.

An interesting discovery was made when the processing of the data with the second drive operating compared to when it was not. It would have made sense to see torque readings somewhere close to double when the good drive performed all the work of raising the leaf as compared to when it was sharing the load with the faulty drive. This was not the case.

A look at the raw data readings for the lift when only the south motor was running, **Figure 5**, shows what we saw as the leaf was opening. It was immediately apparent that a problem existed and after verifying that the logging equipment was operating correctly it was determined that the North motor was not operating. The leaf was lowered and the inspection of the MCC revealed the problem. **Figure 6** shows the raw data from the next operation. While not exactly aligned the drives were operating much closer to normal.

Figure 5

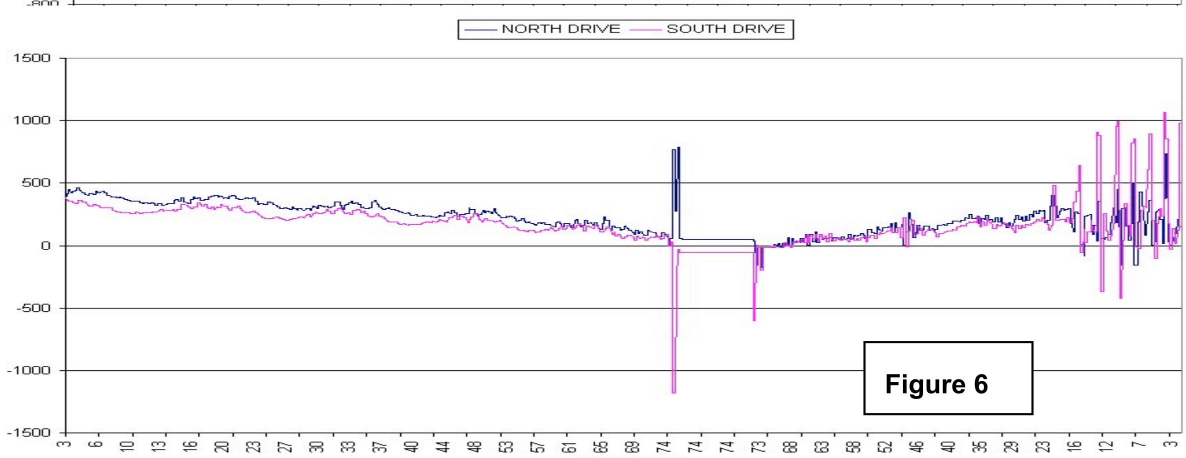

Figure 6

Figure 7 shows an overlay of the two runs using the averaged data with the friction values removed. This is typically the data that is then fitted with a cosine curve to establish balance conditions. A comparison at this point provides an apples-to-apples look at the two runs. It was expected that the torque readings for the single-motor operation would close to those for the two-motor operation. Not only are values not the same, the effort used in operating the leaf appears to be less when the south motor operated alone. The resulting balance calculations would be impacted directly by this difference. A closer investigation of parasitic losses within each drive would be necessary to identify the reason for this apparent anomaly but the lesson is that assumptions concerning friction should be made with care.

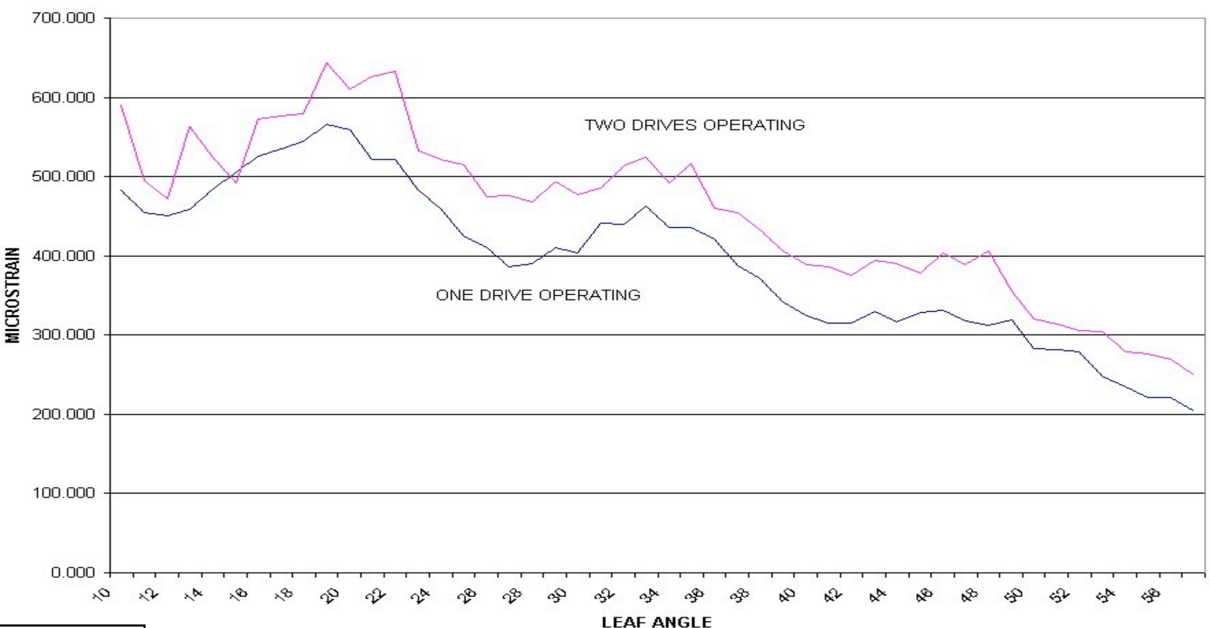

Figure 7

Drive load sharing

As seen when discussing friction, drive load sharing is another valuable tool provided by electronic data acquisition. Not only can sustained periods of movement be illustrated, acceleration and deceleration rates and durations can be documented as well. This function applies to hydraulic cylinder operations as much as it does motor drives.

Even with load-share testing performed at the time of manufacturing a whole new set of variables has been introduced once the equipment has been installed. Electrical and control connection quality, real-time load dynamics, ambient conditions and friction variations are just a few of the variables that can affect the ability of the drives to satisfactorily share the effort of operation. With all systems operating as designed testing can aid in making final adjustments to drive controls or cylinder pressures.

Subsystem integration

The same way individual components can be tested for effectiveness any of a bridge's subsystems can be evaluated as well. This is particularly important when the proper operation of a bridge depends on the seamless orchestration of systems being provided by various suppliers. A control cabinet from manufacturer 'X', the electrical drive system from manufacturer 'Y' and the installation abilities of subcontractor 'Z' may each represent the best in their respective fields but how well are the products and services actually working together on this project?

Electronic data received from key operation points will without question speed up the integration process. There are times when it is not clear why the leaf does not perform as expected at the same time each vendor insists that their system is operating correctly. This is when it comes down to clarifying what commands are being generated and sent at the control level, whether or not the signals are being received by the device and what functions are being undertaken as a result.

In **Figures 8 and 9** a hydraulic cylinder operated bridge was the subject of balance testing. Cylinder pressure readings were obtained and prepared for balance calculations and a comparison of readouts showed great dissimilarities from one leaf to the next. These charts show the differences between two leafs that were intended to be acting as twins leading the opposite pair into locking position. There were pressure differences at all phases of the operating sequence and time-lapse differences particularly at creep to full open

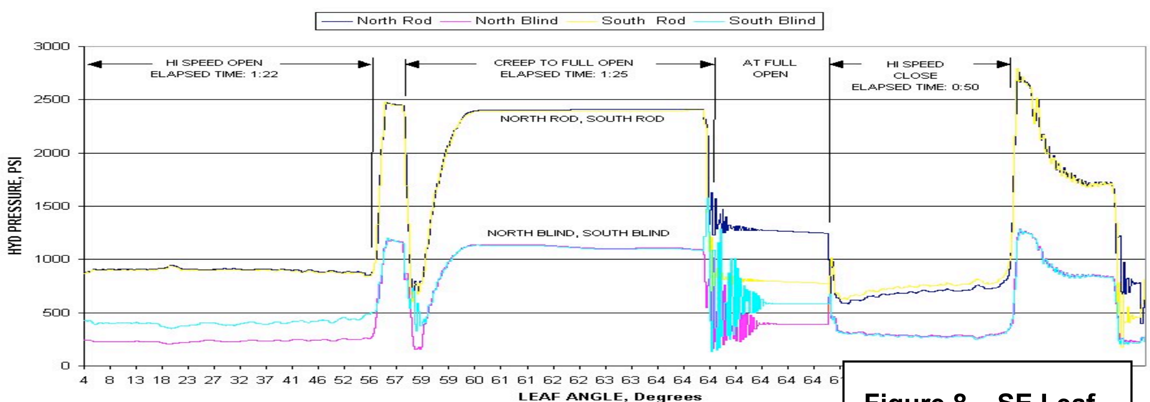

Figure 8 – SE Leaf

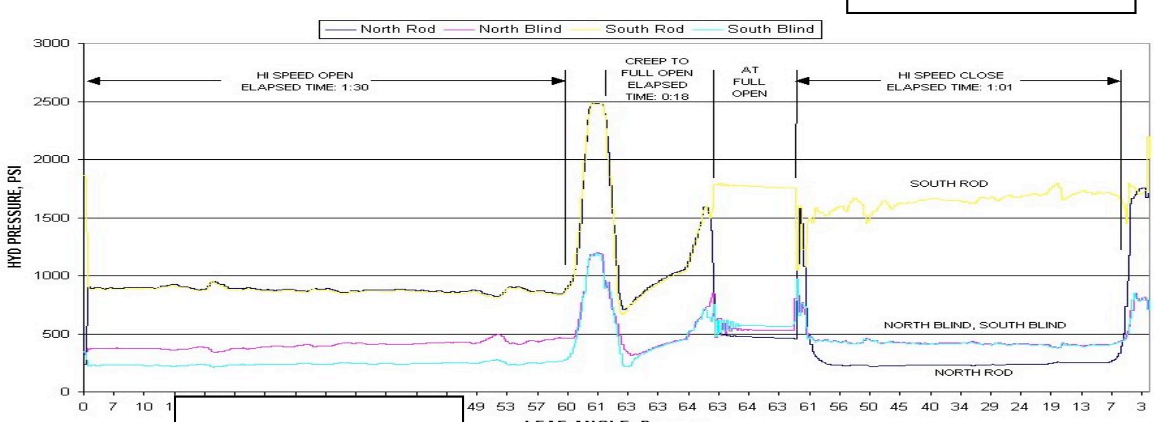

Figure 9 – SW Leaf

Mapping of specific control signals was provided and the results can be seen in **Figures 10 and 11**. The leaf operation on the nearly completed rehab project was erratic and there were serious pressure spikes recorded when balance testing was conducted. These spikes happened so quickly they were imperceptible without electronic monitoring. No two leafs behaved the same and there seemed to be little indication what was at fault. The result was a lot of frustration on the part of the contractor as well as the owner.

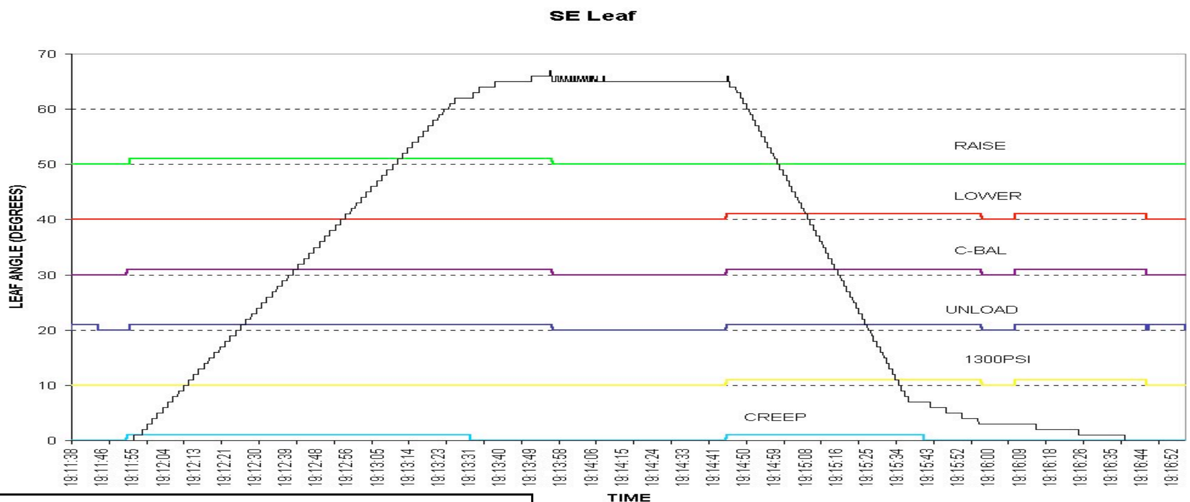

Figure 10 – SE Leaf Control Signal Map

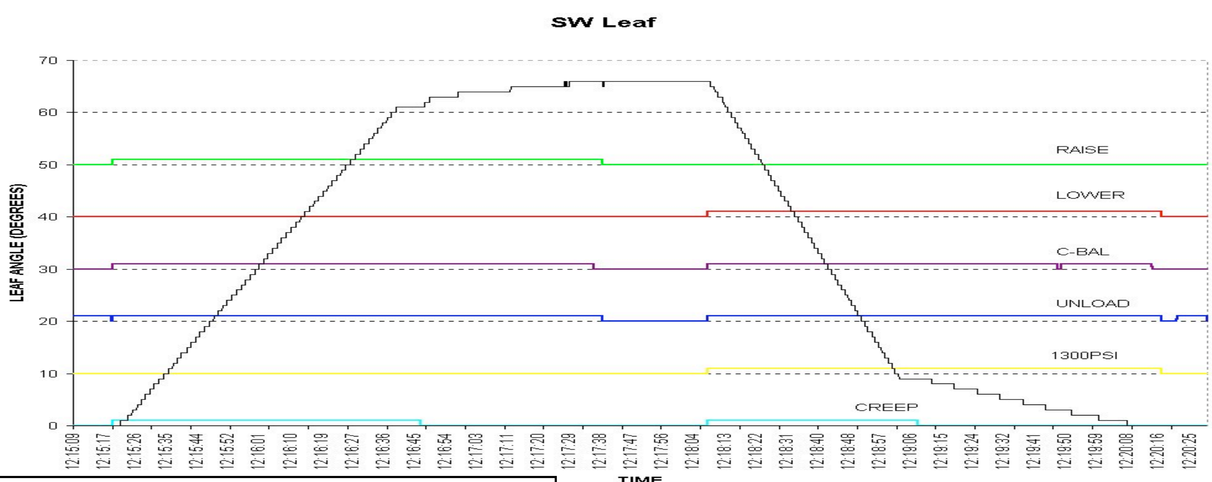

Figure 11 – SW Leaf Control Signal Map

Once the charts were produced it became clear that the control system and hydraulic pressures were primary deterrents to satisfactory operation. The power units were receiving control signals at dissimilar time intervals and even in varying sequence. After a few changes to the PLC control program as well as some pressure adjustments at the power units more consistency between each leaf and the elimination of some serious pressure spikes were realized.

External force evaluation

Another area of interest for collecting data on movable structures is to track the effects of forces external to the bridge itself. These would include wind, weather conditions and live loading among others. It is easy to spot the effects wind as it applies pressure to the exposed surface of a leaf at full open when monitoring for span balance. Even a light breeze shows up on the charts emphasizing the need to establish guidelines for maximum wind velocities allowable for testing. Even with these in place careful attention should be paid to note any variation in readings that might be due to wind.

FIGURE 12 – A weather station that logs wind speed and direction provides addition information about the influence of wind while balance testing.

Recently, the addition of a weather station to the data acquisition equipment has increased the level of confidence. The wind speed and direction data is logged and compared to strain readings in order to remove any question of wind influence.

Live loads like rain, snow and ice can have serious effects on balance directly influencing stresses on a number of systems. Monitoring the bridge operation through a series of weather events can provide valuable information concerning what to expect during adverse conditions in the future.

Roadway and construction debris have shown up on drive load readings as well. Rolling bascules are especially vulnerable as material can collect on the track and produce fluctuations in the load readings. Settling and deformation of the track foundation and tread steel have similar effects of the freedom of movement and balance readings as a result.

Another unfortunate source of external forces are collisions, both on the roadway and on the waterway. Affects that these may or may not have on operations can be determined to some extent by comparing force data obtained previous to and following such an event. By concentrating on the areas determined to be most vulnerable to damage (trunnions, lock bars, etc.), changes in force or friction can be documented for careful analysis.

Conclusion

Most of the topics discussed here are currently available as part of normal balance testing procedures and very little additional set up is required to gather and analyze the data needed to learn a great deal more about the operation of a movable structure. The most significant hindrance to using this data more effectively is experience on the part of the testing personnel. The application is new enough that trained personnel are not readily available as yet.

Even though electronic data acquisition has been used for specific machinery function testing for some time the notion of making it an integral part of balance testing is just now becoming feasible. Wireless transmission radios capable of high-speed data transfer enable sensors to be attached to components where rotational movement had prevented it previously. As a result the specialist who is on-site to take balance measurements has access to information like no one else. As thorough as an annual inspection may be there is no comparison to direct communication between a PC and specific internal elements of the structure. Additionally, just having a trained individual watch repeated operations of the bridge at close proximity should be taken advantage of from an inspection standpoint. There have been numerous occasions that specific problems have been observed only because of the time spent performing balance testing.

Obviously the task of providing additional analysis of bridge equipment is not a light one. It calls for a specialist to pay close attention to live chart readings; to listen and watch for abnormal indicators; fully understand machinery operation and to apply a lot of common sense. A significant investment in time spent studying recordings in the field and on the test bench is necessary to learn what constitutes 'normal' and 'abnormal' readouts. In the end, the right combination of people and equipment can make major contributions in preventative maintenance programs, inspection procedures as well as bridge design criteria.

The benefits only start with the savings to owners and contractors. In terms of prolonged equipment life and the additional safety factor they go much farther. Any steps taken to reduce risk to the public, employees and equipment are well worth the negligible cost of these measures. By simply specifying reports and recordings relating to machinery operation the engineer has increased the information base for evaluating the integrity of the structure many-fold.