Louisiana Transportation Research Center

Final Report 643

Skew Detection System Replacement on Vertical Lift Bridges

by

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TECHNICAL REPORT STANDARD PAGE

1. Title and Subtitle
   Skew Detection System Replacement on Vertical Lift Bridges

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5. Report No.
   FHWA/LA.17/643

6. Report Date
   January 2021

7. Performing Organization Code
   LTRC Project Number: 20-2ST
   SIO Number: DOTLT1000343

8. Type of Report and Period Covered
   Draft Final Report
   March 2020 – December 2020

9. No. of Pages
   42

10. Supplementary Notes
    Conducted in Cooperation with the U.S. Department of Transportation, Federal Highway Administration

11. Distribution Statement
    Unrestricted. This document is available through the National Technical Information Service, Springfield, VA 21161.

12. Key Words
    Skew Detection System; Skew; Vertical Lift; Movable Bridges; Programmable Logic Controller (PLC); SMAR relays; Rotary Cam Limit Switch (RCLS); Selsyn System

13. Abstract

For a tower drive vertical lift bridge, failure to maintain level operation over its length or width is known as span longitudinal or transverse skew. When occurring, this can lead to jamming of the movable span in its guides and, without adequate protection, can lead to a catastrophic bridge failure. Vertical lift tower drive skew indication and monitoring was historically satisfied with the use of a differential selsyn. However, this legacy technology is nearly obsolete. This study included a review of alternatives for skew control, monitoring, and indication for tower drive vertical lift bridges based on effective management of skew and minimizing advanced electronic equipment. Based on this review, the preferred system for skew control combines the use of direct skew measurement with an inclinometer for skew monitoring and trip indication, and indirect measurement of skew using encoders for controlling skew during operation. To minimize maintenance, mean-time-to-repair, and to limit dependency on PLC systems, control integration should include the use of SMART relays that contains self-diagnostics and may easily be replaced in the event of an issue.

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Abstract

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Acknowledgments

The author wishes to thank the Louisiana Department of Transportation and Development (DOTD) for providing the resources necessary for this project and the Louisiana Transportation Research Center (LTRC) for the funding of this study. A significant portion of the work relies on owners' feedback and on the feedback of control systems vendors with regards to installation trends and the effectiveness of the skew control systems that have been installed. The author is grateful to all who have participated in this research.

Implementation Statement

This study provides an evaluation of skew indication and monitoring alternatives for use on tower drive vertical lift bridges. The results of this study should be considered in the design of skew control for tower drive vertical lift bridges, whether for new systems or for the rehabilitation of existing systems.

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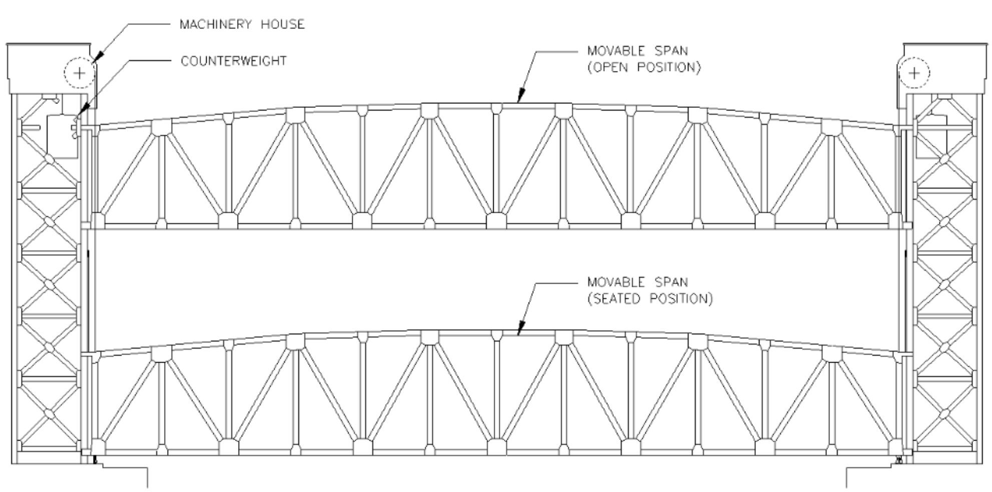
Introduction

Louisiana, by virtue of its extensive waterways, has more than 140 movable bridges with over 40 of them being vertical lift bridges. A vertical lift bridge is a type of movable bridge that provides navigational clearance by lifting the movable lift span vertically. Bearing supported counterweight sheave assemblies in the bridge towers support the lift span and its counterweights through wire rope assemblies. See Figure 1.

The two common types of vertical lift bridges are the span drive vertical lift bridge and the tower drive vertical lift bridge. For span drive vertical lift bridges, the drive machinery is mounted on the lift span and operation is achieved by reeling in and paying out operating ropes wound around operating drums with operating ropes coming off of the structure at all four corners. Uphaul operating ropes terminate in the towers and are loaded when raising the lift span. Downhaul operating ropes terminate near the base of the towers or at the piers, and are loaded when lowering or seating the lift span. Skew is not an issue for well-maintained span drive vertical lift bridges, as the bridge is powered by a single drive system and skew is normally effectively controlled by limiting or equalizing the slack in the operating ropes at each corner of the moving span.

For the tower drive vertical lift bridge, the span drive machinery is typically located in the bridge towers. See Figure 1.

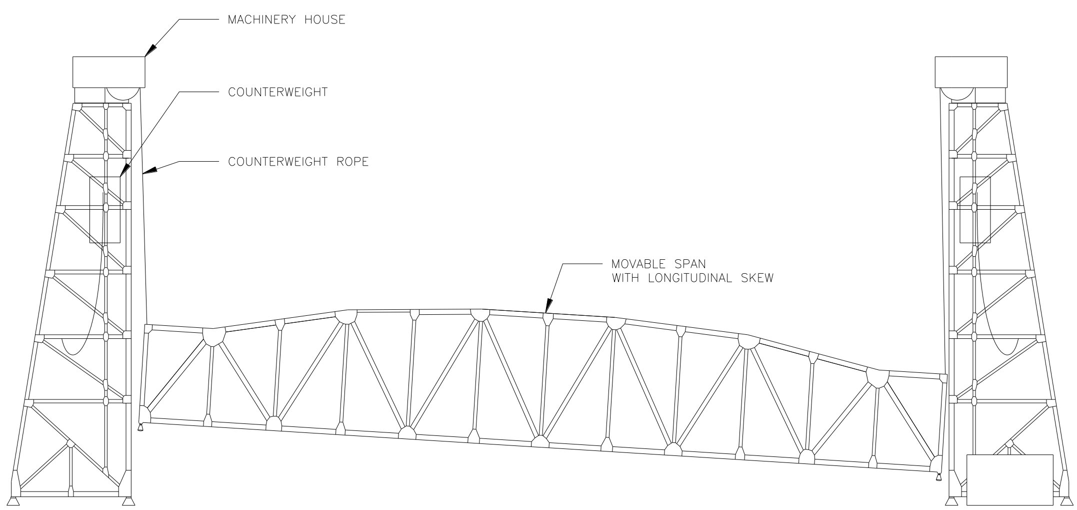
Figure 1. Tower dive vertical lift bridge schematic



A common arrangement includes separate drives located in each tower. The typical machinery arrangements are electric motor-powered mechanical power transmission equipment with the final drive pinions engaging ring gears that are secured to the counterweight sheaves. As the sheaves turn the lift span is raised and lowered.

For all types of vertical lift bridges, lift span and counterweight guides are used to maintain moving span position relative to the tower during operation. But these provide limited guidance. One inherent and critical function built into all tower drive vertical lift bridge control system is their ability to monitor that the moving span is maintained level throughout its operating travel. Failure to maintain level operation over its length is known as span longitudinal skew. See Figure 2.

Figure 2. Tower drive vertical lift bridge schematic, bridge in skewed position



When excessive longitudinal skew occurs, it can lead to interference of the movable span in its operating guides that hold the moving span in position during travel. Without adequate protection, excessive longitudinal skew can lead to jamming the movable span within the guide system, sometimes resulting in damage to the bridge guide system, the lift span structure, or the tower structure and may result in length periods with the bridge out of service.

A typical cause of longitudinal skew would be a failure to accurately measure the skew of the lift span, which may sometimes be attributed to a failure of a component within the monitoring and indication system, or a misapplication of a measurement device. Other inaccuracies may accrue over time. For indirect measurement using encoders or resolvers, the measurement of the tower-to-tower drive positions can be negatively affected by counterweight rope slippage of the sheaves. The slippage of counterweight ropes over sheaves is a common occurrence at tower drive vertical lift bridges, often occurring during high load events such as accelerations and decelerations, or sometimes when the movable span is seated following an operation. When ropes slip over the counterweight sheaves, it effectively changes the rotational position of the drive machinery. Because indirect skew measurements are coupled to the drive machinery, rope slippage can result in errors in the positions to the extent that indirect skew measurements show a skew problem between the towers, though one may not exist, or vice versa.

Failure to maintain level operation over the width of the moving span is known as transverse skew. This transverse skew condition occurs less frequently than longitudinal skew and provisions are not always made within the bridge control system to monitor this condition. It is often left to bridge maintenance personnel to periodically make the appropriate mechanical adjustments. Transverse skew tends to be a less significant issue as the drive arrangement for tower drive vertical lift bridges typically involves mechanically connected machinery quadrants within a given tower. The transverse skew, then, would tend to be limited to counterweight rope slippage over the counterweight sheaves. The measuring of transfer skew, when applied, is very similar to longitudinal skew but in this case the inclination across the width of the moving structure at its ends is measured. As with longitudinal skew, historically it was measured with the use of a selsyn differential system with indicators located on the operators control console to indicate transverse skew conditions at either end of the bridge.

Tower drive vertical lift skew indication and monitoring was historically satisfied with the use of a differential selsyn. A differential selsyn consists of a transmitter in each tower that monitors and transmits angular rotation of each tower drive to a differential receiver that produces a rotational output. This output is a measure of the difference in angular rotation of the two tower drives and hence a measure of longitudinal skew. This measure of skew is used to alarm skew and trip the bridge drive system.

In a similar way to longitudinal skew measurement, transverse skew has been measured in a similar way, using differential selsyns by monitoring the difference in angular rotation of the two sheaves of the ropes on each corner of each end of the moving span.

Hence historically, when monitoring skew on a tower drive vertical lift bridge, three selsyn differential indicators were used, one indicating longitudinal skew of the moving span and one indicating transverse skew at each end of the moving span.

Based on obsolescence, failures, and the limited availability of replacements of their existing selsyn components, alternative approaches to detecting and monitoring skew conditions for tower drive vertical lift bridges are necessary. Current industry practice is moving towards replacement of legacy selsyn and power synchro-tie systems with skew control, monitoring, and indication through the use of encoders, resolvers, inclinometers, or other devices, typically through programmable logic controller (PLC) systems and commanding necessary tower drive adjustments to mitigate skew conditions.

This document summarizes alternatives for skew monitoring and indication systems and provides recommendations to the DOTD for their consideration for replacement of the legacy skew technology.

Literature Review

There are few published documents that provide guidance or options for skew control systems for tower drive vertical lift bridges. The limited literature that is available is supplemented by information provided in governing design specifications and other documents related to the industry. Important guidance is also found in the experiences of owners, maintainers, and control system vendors.

The maintenance of lift spans to ensure reliable speed of operation and elevation is a necessary requirement. This is particularly true for tower drive vertical bridges that have separate operating machinery in each tower. Early tower drive systems were often controlled with the use of a selsyn system, which has been used in the United States as early as 1931 *[1]*. The selsyn, or synchro, is a device reminiscent of an electric motor with a pair of rotating windings that are utilized to provide an analog output of relative angular rotation of the shaft to which it is coupled.

Although not directly related to this study, a discussion on the synchro-tie system, a method used to control skew, is warranted. For tower drive vertical lift bridges, the differential selsyn principle was sometimes utilized as part of the bridge drive system. Additional drive motors were installed as part of a power synchro-tie system used to transfer power from one tower to the other in an attempt to control skew. Additional wound rotor synchro-tie motors, one in each tower, were connected electrically to achieve the power synchro-tie system goal. The system provides an immediate response with power transfer from one tower to the other to maintain equal elevation of the moving span during operation. Koglin notes that synchro-tie system has been the "…most common and least troublesome form ..." of control for this system *[2]*. Depending on the size of the synchro-tie motors, the system sometimes provides the added benefit of using these motors as back-ups to the main drive motors. The disadvantage of using synchro-tie motors is additional machinery cost, machinery design complications, and additional machinery installation space requirements and added maintenance.

In recent history, the maintenance and replacement of the selsyns as a means of skew measurement has become a significant issue as there are limited or no manufacturers available to provide this legacy technology component.

Koglin also describes an alternative direct measurement of skew, whereby sensors on the moving span pick up on control marker locations installed along the tower. These would be input into the control system to ensure a level moving span and are linear equivalents of the absolute encoder, with the advantage that they are not susceptible to errors caused by counterweight rope slippage.

In their publications, both Koglin and Birnstiel, Bowden, and Foerster outline alternative skew measurement devices such as encoders, inclinometers, and resolvers *[2], [1]*. Successful utilization of these devices requires some amount of processing to ensure a level span position without interference with typical deviations in normal operation. Feedback from owners and control specialists make it clear that skew control using one or more of these components is the current practice in the industry and will—with the addition of string potentiometers, lasers and similar devices—likely continue to be used for the foreseeable future.

In the United States, design specifications for movable bridge machinery include the American Association of State and Highway Transportation Officials LRFD Movable Highway Bridge Design Specifications (AASHTO) and Section 6 of Chapter 15 of the *American Railway Engineering and Maintenance-of-Way Association* (AREMA) *Manual for Railway Engineering [3], [4]*. In Canada, movable bridge machinery is governed by Section 13 of CAN/CSA-S6-14 of the Canadian Highway Bridge Design Code (CHBDC) *[5]*.

These three design specifications are similar in that they do not specify a required methodology for skew control, leaving that to designer discretion. All three design specifications provide some requirements for skew control design components and testing. As an example, AASHTO specifies a limit to the acceptable skew measurement (skew precision to be measured within 1 in. per AASHTO 8.4.5.1), and provides requirements for various skew control components (e.g., resolver, cabling, and housing specifications listed in AASHTO 8.4.5.4; absolute encoder requirements in AASHTO 8.4.5.5; skew control motor requirements in AASHTO 8.5.2.3). Compared with the CHBDC and AREMA, the AASHTO specifications provide more detailed technical requirements.

AASHTO also provides some direction and commentary that is useful in understanding the current philosophy for skew control within the movable bridge design industry. AASHTO commentary in articles C8.4.2.2 Relay Control Logic and C8.4.2.3 Programmable Logic Controller (PLC) effectively highlight the trade-offs when using PLC control versus relay control. These articles note the high reliability of relay control and its preference for limited maintenance, but also its limitation for continuous control of speed and skew of the operating bridge. Conversely, PLCs offer high reliability and skew control but are sometimes not preferred due to the requirements for specific training related to PLC maintenance and troubleshooting.

In commentary for the article Synchronous Systems, AASHTO C8.4.5.2, the specification notes an advantage of the selsyns is that they are “relatively immune to problems associated with electrical noise and distance between devices” but it also notes the industry’s trend away from these devices due to cost.

Commentary on the power synchro-tie system is provided in AASHTO C8.5.2.3, Skew Control or Synchronizing Motors. This part of the specification highlights the historical success of the power synchro-tie system for skew control but notes the movement away from these systems to simplify design and reduce costs. The commentary notes that this system is “rarely used in new system design” though it remains in use for a number of existing systems, often as a legacy installation.

AASHTO commentary regarding design selection for skew control using resolvers or encoders is provided in C8.4.5.4. A resolver is a rotating transformer with multiple windings on both its rotor and stator. Two of its windings are known as its Sine and Cosine windings and the ratio of the output voltage of these two windings is a measure of angular displacement to their drive shaft. An encoder is a device which outputs pulses based on angular rotation and consists of a disc with multiple holes which light is emitted through. A photo sensitive device receives the light as the disc rotates and transmits these light signals, or flashes, into pulses. For most movable bridge applications, encoders output 1024 pulses per revolution of the shaft that is driving them. AASHTO notes the advantages of resolvers to include: more precision, rugged construction, and a wider temperature range when compared with encoders. Today, with the advances in encoder technology, this is not strictly true and the performance of the encoder in all respects is comparable to the resolver. The disadvantage of the resolver is that it has multiple windings with increased possibility of a winding failure.

There are several published papers related to vertical lift bridge skew that are in symposium records for Heavy Movable Structures (HMS), a forum for the movable bridge industry designers, owners, and suppliers. The records are available for their biennial symposiums, dating from 1985 to 2018. On the whole, the published papers offer little guidance on the selection of appropriate skew control, monitoring and indication systems, but they do offer a reflection of the trends in the movable bridge industry.

In a paper published in 1990, Dlugosz, Culkowski, and Dubin outline updates to the drive system for the Ohio Street Lift Bridge in Buffalo, New York *[6]*. In addition to the need for repairs, the authors note the cost and difficulty getting replacement components as a reason for a necessary upgrade to the electrical system. The upgrades described include providing skew control such that it enables position registers in each tower drive to monitor rotation and input the bridge control system programmable logic controller

(PLC); the programmed PLC then determines the differential rotational displacement between the two tower drives and alters the output to the drives to take action to correct the PLC determined skew condition. A 1992 publication by Eldessoky documents a failure of a selsyn system to control the skew at Broadway Bridge over the Harlem River Ship Canal in New York City *[7]*. The original system used selsyns through an amplidyne with DC drives and a Ward Leonard DC drive control system. The recommendations included the implementation of direct skew measurement through an inclinometer. It is unclear if this inclinometer system was ever installed at the bridge.

A 1998 publication by McConnell summarized the implementation of skew control using absolute encoders and PLC control as part of the rehabilitation of the Arthur Kill Railroad Lift Bridge in Staten Island, New York *[8]*. The bridge was built in 1958 and was the longest vertical lift bridge constructed in the world (558').

With a lack of published information, it is important to get feedback from owners, maintainers, and control specialists in evaluating alternatives for skew monitoring and indication. A survey of owners and maintainers is provided in the Appendix. The feedback offers a picture of current industry practice that is supportive of the information found in the reviewed literature. The use of a differential selsyn, sometimes with a power synchro-tie system, was common at older bridges. These appear to be relatively reliable, but obtaining replacement parts, or necessary repairs, presents a significant challenge. Newer installations tend to utilize PLC-based systems using encoders, resolvers, or inclinometers. Most of the installations report good success but some issues have been encountered and reported by owners and contractors in the programming and setting up of these PLC based systems. Direct skew measurements have been used at a number of locations. The inclinometer installation has been successful at the Sir Ambrose Shae Lift Bridge in Placentia, Newfoundland (but with power supply issues) and at the Snohomish Southbound Bridge in Everett, WA. The inclinometer at the Burlington Canal Lift Bridge is currently undergoing a redesign (due to improper inclinometer specification for the length of the span, wireless communication design problems, and integration issues). Note one unusual installation is at the Sarah Long Bridge in Portsmouth, New Hampshire. Here, the owner describes magnets installed at the counterweight which are used to trigger switches as the counterweight moves. This is a similar concept to that described by Koglin, except the measurements are at the counterweight instead of the lift span *[2]*. In this case, however, the counterweight travel measurement is not used to control skew but simply to indicate lift height.

Control system vendors Panatrol Corporation (Burr Ridge, IL) and Faith Technologies (Menasha, WI) clearly indicate a transition away from selsyn and synchro-tie technology for new bridge design and for rehabilitations. Their recent construction experience includes direct skew measurement with inclinometers and indirect measurements with resolvers or encoders, typically within PLC control systems. Both provided valuable input into the benefits and limitations of the different components for use in skew control including inclinometer limitations for long spans, vibration impact on inclinometers, and some technical challenges in programming. Both highlight the impact that counterweight rope slippage has on indirect skew measurements, whether with selsyns, encoders, or resolvers. Some encoders allow for automatic zeroing to address the issue.

On the whole, there is little published guidance for the selection of skew control, monitoring, and indication in the movable bridge industry. It is clear from the available literature, and from interviews with owners, maintainers, and control vendors, that the industry is moving towards replacement of legacy selsyn and power synchro-tie systems with skew control through the use of encoders, resolvers, inclinometers, or other devices. Apart from the use of the inclinometers, there is very little experience in the industry with the use of other direct skew measurement technology such as string potentiometers or lasers to measure span lift heights. Control systems utilizing PLCs are common for the industry for both new design and for rehabilitation design, though many owners retain functional and effective hard-wired control systems. It is expected that a properly designed and integrated hard-wired control system would remain a viable solution.

Objective

The objective of this work was to provide a thorough evaluation of alternatives to provide a solution to the problem of replacing the legacy technology skew monitoring and indication systems for tower drive vertical lift bridges. The primary goal was to select an effective skew monitoring and indication system that either does not require additional training or minimizes the required training for existing Louisiana Department of Transportation maintenance personnel. In addition to minimizing additional training for operation, maintenance, repair or programming, the ideal system would provide the bridge operator with specific information as to the skew status of the bridge and means to address it with minimal disruption to bridge operation.

Scope

The scope for the research project included the research and evaluation of skew detecting and monitoring systems used on tower drive vertical lift bridges. The project included reviewing literature for existing skew systems in use: researching, modern skew control, monitoring, and indication alternatives (and a comparison between alternatives); and researching legacy technologies in terms of reliability and maintainability.

Literature and information were compiled from the principal investigator's experience, the experience of bridge operators and maintenance personnel on existing vertical lift bridges, the design documents from existing vertical lift bridges and from bridge control system vendors who have knowledge and experience providing skew systems for control, monitoring, and indication.

The scope did not include testing of the reviewed skew indication and monitoring components, but instead relied on the experience within the industry.

Methodology

Skew indication and monitoring systems were evaluated based on developed criteria to ensure that the project objective was met, including each system's impact on longitudinal skew limitations, transverse skew limitations, sensitivity to drive impact loads to limit counterweight rope slippage, motor speed inaccuracies, minimization of the effect on normal operation, technology selection, maintenance requirements, and availability of repair parts.

The industry review included a review of approaches that have been taken by others through a review of available literature and through interviews with tower drive vertical lift bridge owners and maintainers. Interviews included a review of potential solutions, their functionalities, advantages and disadvantages, cost, maintainability, rates of failures, spare parts availability, and mean-time-to-replace or repair. Additionally, the industry review included gathering information from control system vendors related to their available products and systems and where they have deployed them to detect and measure skew.

Discussion of Results

Indirect and direct lift span skew monitoring and indication have been reviewed as part of this research effort. Direct lift span skew indication is based on physical measurements of lift span elevation relative to the piers or to the towers or physical measurements of lift span tilt. Indirect lift span skew indication is based on rotational measurements of the drive machinery in each tower.

Direct Skew Indication Components

Examples of direct skew control measurement devices are summarized below.

- Direct measurement with spring-retracted string potentiometers. The primary question for this direct measurement is the suitability of the device for the environment and for the duty cycle. It is of primary importance that the device function properly over long periods of time with significant exposure to the elements, and that the installation provide some level of protection for the device. Further, it is important that the device remain functional after withstanding long periods of inactivity, as is common for movable bridges. The model shown in Figure 3 is constructed for "harsh environments" and can accommodate lift heights well over 100 ft. Although this appears to be a viable solution, there have been limited installations in the movable bridge industry. One known example is at the Michigan Street Bridge in Milwaukee, Wisconsin, where string potentiometers have been successfully installed and used for the last 18 months.

Figure 3. TE Connectivity PT9DN series digital string potentiometer

- Direct measurement with laser position sensors. As an alternative to the string potentiometers, lasers may be used to measure distances between the lift span and targets on either the towers or on the piers. See Figure 4. The challenges for this type of installation would be to ensure the quality of the signal, immunity to electromagnetic interference (EMI), and the integrity and location of the signal targets. Laser position sensors have not been widely used for movable bridge skew indication but have been applied in a number of other similar applications with success and is a recognized and widely used technology for distance measurement. One known application in the movable industry includes laser position sensors to indicate lift height at the Pretoria Lift Bridge in Ottawa, Ontario (though they are not integrated into their skew control methodology but simply height measurement.) Laser sensors are also used to provide clear channel indication for some remotely operated movable rail bridges owned by the Norfolk Southern Corporation and the SMART rail system in California.

Figure 4. SICK DX1000 long distance laser sensor

- Direct measurement using inclinometers. Inclinometers are used to measure the magnitude of an inclination angle or slope of a movable span with respect to gravity's direction. Inclinometers use a freely moving object or liquid within the housing to determine angular position. A span inclinometer may be mounted directly to the lift span to measure tilt and thus the out-of-level condition. Direct measurement using inclinometers has been successfully implemented at a number of bridges since at least the mid-1980's, including the Sir Ambrose Shae Lift Bridge in Placentia, Newfoundland and the Hood River Bridge in Hood River, Oregon.
Some control vendors note that inclinometers do not have sufficient resolution to maintain adequate skew control "for long bridges", however the investigation shows that high precision inclinometers are available and suitable for most, if not all, tower drive vertical lift bridge applications. It is critical that the design of monitoring using an inclinometer ensure sufficient accuracy and precision for the application. Note that

the accuracy of the inclinometer can be affected by temperature if it is not specified with a means of temperature compensation. This issue has been noted on some bridges where inclinometers have been used. Additionally, it is important that inclinometers should only be active when the moving span is being operated to limit false indications due to vibrations caused by vehicular traffic over the bridge. Limiting the skew systems to periods of operation is good practice for all skew detection systems.

An inclinometer installation requires that the signal be transmitted to the control system, which is typically off the movable span and in the operator's house. This may include using a wireless transmitter and receiver, or physical wiring in the form of a droop cable arrangement or a cable reel to transition the signal from the moving span to the bridge fixed structure.

With a wireless transmission, the challenge is to ensure consistent signal integrity throughout the range of motion of the lift span. This may require iterative adjustments during the installation and commissioning process to locate components properly and ensure line-of-sight between the transmitter and receiver (one must ensure that the signal is unaffected by the structural steel of the moving span during bridge operation). In some installations, localized electromagnetic interference may make wireless transmission impossible; this maybe the case where a bridge is located in close proximity to high voltage transmission lines or where the electric power and control system has not been designed to fully respect electromagnetic compatibility of the various bridge subsystems.

An inclinometer is sometimes susceptible to vibration, though this is an issue that can be overcome with a properly selected inclinometer and a properly designed system. In the seated position, the control system should not review inclinometer readings and any vibration or fluctuation at the sensors would be disregarded. During operation, this vibration may be addressed with a suitable control algorithm with filters or delays that would limit and eliminate phantom skew triggers. See Figures 5 and 6 for schematics that show inclinometer installations. As with other direct measurement systems, the inclinometer will be exposed to the environment. One additional attribute of the inclinometer is its ruggedness and its reliability. A properly specified inclinometer can stand up to the harshest environment and it is extremely reliable with a mean-time-between-failures of more than 150 years.

Figure 5. Direct measurement with inclinometer, wireless transmission

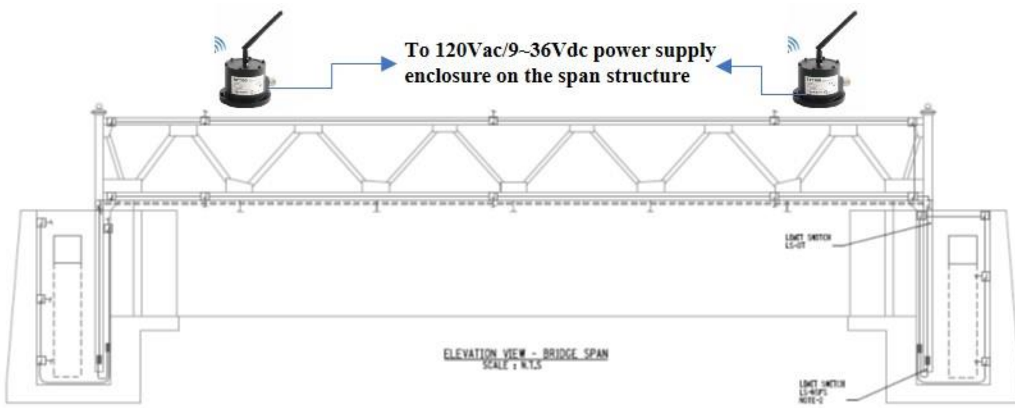
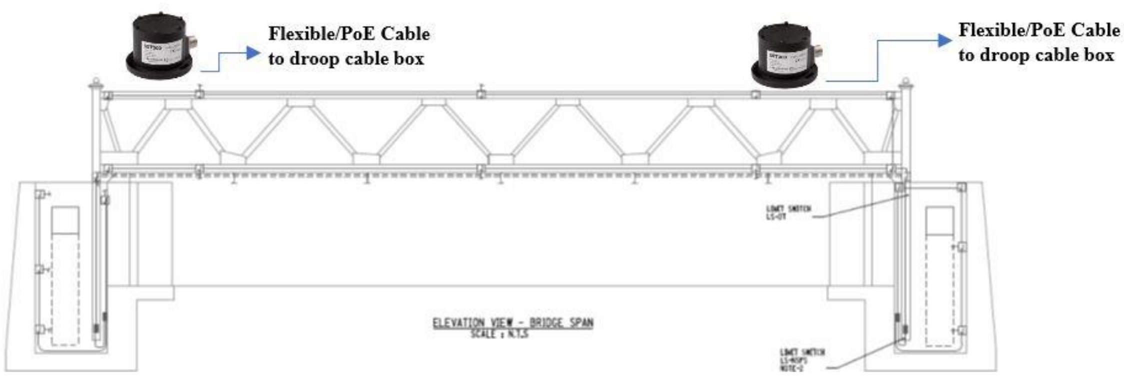


Figure 6. Direct measurement with inclinometer, direct transmission



- Direct measurement along towers. As Koglin notes, it is possible to provide incremental targets along the tower legs *[2]*. Sensors installed on the lift span can be used to count targets along the tower legs, thereby determining the lift height at a given location. It is not clear if this type of installation has been used in the industry. The challenge for this type of installation would be to ensure accurate readings while allowing for typical movement of the lift span in the lift span guide system and expansion and contraction of the lift span. The accuracy of this method would be proportional to the number of targets or pulses emanating from the sensor. A sensible spacing for accurate measurement would be a target every 6 in. of moving span height or 200 targets for a 100 ft. lift. This number of targets may not be feasible in practice.

Indirect Skew Indication Components

For indirect skew indication control, measurements of rotational measurements from each tower are compared with one another within the bridge control system to provide the appropriate adjustments to each tower's span drive to eliminate the measured skew. The following devices are common components that are utilized in indirect skew control measurement.

- Indirect measurements with synchros (selsyns). A synchro, or selsyn, is a transformer with a pair of rotating primary and secondary magnetic couplings that vary based on relative rotational orientation of their windings. The selsyn takes advantage of this variation as a measurement of changes in angular rotation. When used in a differential configuration to provide a measure of the relative difference in angular position of two selsyns, there is one on each tower and they are electrically connected to a differential receiver to provide an indication on the differential receiver indicator of the difference in the angular position of the two tower drives. See Figures 7 and 8. For tower drive vertical lift bridges, this has historically been used for indication and skew control.

Figure 7. Selsyn equipment outboard of reducer at Bridgeport, CT vertical lift

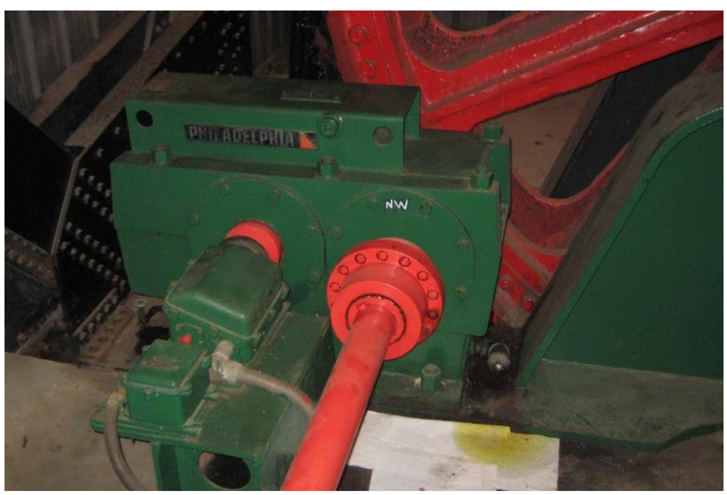
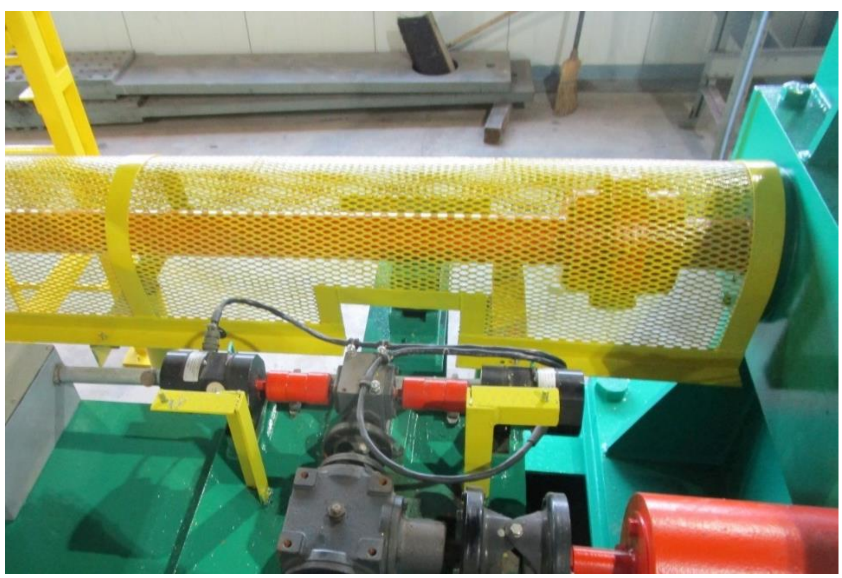


Figure 8. Selsyn equipment at Bridgeport, CT vertical lift

(a) Bridgeport selsyn opened for inspection (b) Bridgeport selsyn receiver at control desk

- Indirect measurement with resolvers. A resolver is effectively a rotating transformer that provides a true analog output which is proportional to angular displacement that can be used to determine relative angular rotation of a shaft. For tower drive vertical lift bridges, resolver readings from each tower are compared and the delta between them provides a measure of skew. See Figure 9.

Figure 9. Skew control resolvers installed at Route 88 in Point Pleasant, NJ



- Indirect measurement with encoders. An encoder is a sensor that converts rotational motion to digital electrical pulses. See Figure 10. When encoders that are arranged to monitor the angular rotation of a drive shaft in each tower are compared with one another, the delta between them provides a measure of skew. The two main types of encoders are the absolute encoder and the incremental encoder. The former can indicate absolute angular position, while the latter can only determine a *change* in angular position.

Figure 10. Encoder secured to motor housing

Both incremental and absolute encoders are subject to cumulative errors due to wire rope slippage. The application to movable bridges requires that the tracking be reset following operating cycles, thereby eliminating this cumulative error. The absolute encoder has an additional advantage when compared with the incremental encoder, as it retains position information in the event of a loss of power (through a mechanical gear train used to store the number of revolutions).

- Rotary Cam Limit Switch (RCLS). The RCLS, when used as part of a skew control system, is primarily used as an over-skew alarm and trip function, the cams being set to trigger associated switches. See Figure 11. The switches are used to indicate discrete rotational positions of the connected shaft. In detecting skew, rotary cam limit switches with cams and switches are mechanically connected to the drive shaft in each tower, and the two rotary cam limit switches are electrically connected such that as long as the two tower drives are in synchronism, and the span is level, there is an output from the combined rotary cam limit switches. But when they are out of synchronism with one another, as in a skew condition, the output from the combined rotary cam limit switches is lost and this loss of circuit continuity is used by the control system to trigger an alarm or trip the span drives. This form of measurement is simply digital and only outputs when continuity is lost between the two RCLSs which occurs when the tower drives become out of synchronism with one another. The arrangement triggers within a range based on the number of individual cam switches used, direction of rotation, and direction of skew. This form of monitoring does not provide necessary information to be used for skew control purposes but is only used for alarm and trip purposes.

Figure 11. RCLS for ultimate skew indication, Route 88 in Point Pleasant, NJ

RCLS have been used for at least 50 years to indicate a moving span skew condition. Because they only provide a means of alarming and tripping in the event of a skew condition, and are not used as a skew control function, they are not evaluated as a form of skew control. Note that they are relatively reliable in alarming and tripping a drive system in the event of a skew condition but do require regular maintenance to reset them due to rope slippage and to periodically reset their cams that tend to slip.

Existing Installations and Current Industry Practice

Current industry practice may be determined based on interviews with bridge owners and maintainers, which were pursued through a questionnaire. Responses to the questionnaires are provided in the Appendix. In addition, recent tower drive vertical lift bridge designs were reviewed to determine the method of skew control, monitoring, and indication. Note that this included a review of bridge design documents but did not include a verification of final installation. To the extent that information was available, it is summarized in Table 1. Note that the table includes a column to indicate if the owner/maintainer had provided a response to the questionnaire.

Table 1. Survey of recent rehabilitations and questionnaire responses

Bridge	Location	Quest. Response	Date	Skew Control	Equipment
Wittpenn	Jersey City, NJ	No	2020+	Indirect	Selsyn, Resolvers, PLC
Rio Vista Bridge	Rio Vista, CA	Yes	2020+	Indirect	Encoders, PLC
Hood River	Hood River, OR	No	2018	Direct	Inclinometers, PLC
Sarah M. Long	Portsmouth, NH	Yes	2018	Both	Encoders, PLC, Cwt Travel Sensors
Portage Lake	Houghton, MI	Yes	2015	Indirect	Selsyns, Resolvers, Encoder, PLC
Burlington Canal Lift Bridge	Burlington, ON	Yes	2013	Both	Inclinometers, resolvers, PLC
Galveston Causeway RR	Galveston, TX	No	2013	Indirect	Encoders, Resolvers, PLC
Chelsea Street	Boston, MA	No	2012	Indirect	Encoders, Resolvers, PLC
Sir Ambrose Shea	Placentia, NL	Yes	2013	Direct	Inclinometer, PLC
Danziger Bridge	New Orleans, LA	Yes	2011	Indirect	Synchro-tie, selsyns, relays
Route 88	Point Pleasant, NJ	Yes	2010	Indirect	Resolvers, PLC
Willow Ave.	Cleveland, OH	No	2009	Indirect	Encoders, PLC
New Young's Bay	Astoria, OR	Yes	2008	Indirect	Encoders, PLC
South Park Ave.	Buffalo, NY	No	2008	Indirect	Encoders, PLC
Stickel Memorial	Newark, NJ	Yes	2006	Indirect	Encoders, PLC main drive; synchro-tie aux
Tomlinson Lift Bridge	New Haven, CT	No	2002	Indirect	Synchro-tie, selsyns, relays
1&9T over Passaic R.	Newark, NJ	Yes	2002	Indirect	Synchro-tie, PLC, relays
Howard Ave.	Houma, LA	Yes	2000	Indirect	Synchro-tie, selsyns
Arthur Kill	New York, NY	No	1996	Indirect	Encoder, PLC
Ohio Street	Buffalo, NY	No	1993	Indirect	Encoder, PLC
SR529 Snohomish Southbound	Everett, WA	Yes	1995	Direct	Synchro-tie, inclinometer, PLC, relays
1&9T over Hackensack R.	Newark, NJ	Yes	1995	Indirect	PLC, selsyns, resolvers

Bridge	Location	Quest. Response	Date	Skew Control	Equipment
Route 7	Belleville, NJ	Yes	1987	Indirect	Synchro-tie, encoders, PLC
James River Bridge	Newport News, VA	Yes	1982	Indirect	Synchro-tie, selsyns, relays
Riverside Ave.	Hoquiam, WA	Yes	1970s	Indirect	Synchro-tie, selsyns, relays
Stratford Ave.	Bridgeport, CT	Yes	1973	Indirect	Synchro-tie, selsyns, relays
Judge Seeber	New Orleans, LA	Yes	1955	Indirect	Synchro-tie, encoders
Snake River	Clarkston, WA	Yes	1939	Indirect	Synchro-tie, selsyns, relays

The information in the table provides a picture of current industry practice. Indirect skew monitoring and indication remains the most often used skew control system for tower drive vertical lift bridges. The use of a differential selsyn, sometimes with a power synchro-tie system, is common at older bridges. Based on the responses, selsyns appear to be relatively reliable, but obtaining replacement parts, or necessary repairs, presents a significant challenge. Newer installations tend to utilize PLC-based systems using encoders, resolvers, or inclinometers.

Direct skew measurements have been used at a number of locations, mostly in the form of inclinometers. Recent inclinometer installations have been successful at the Sir Ambrose Shae Lift Bridge in Placentia, Newfoundland (but with power supply issues) and at the Snohomish Southbound Bridge in Everett, WA. The inclinometer at the Burlington Canal Lift Bridge is currently undergoing a redesign (due to improper inclinometer for the length the span, wireless communication design problems, and integration issues).

In conversations with control system vendors Panatrol Corporation (Burr Ridge, IL) and Faith Technologies (Menasha, WI), they indicate a transition away from selsyn (and synchro-tie technology) for new bridge design and for rehabilitations. Their recent construction experience includes direct skew measurement with inclinometers and indirect measurements with resolvers or encoders, typically within PLC control systems. Both provided valuable input into the benefits and limitations of the different components for use in skew control which are discussed further in the following section of the report. Both highlight the impact that counterweight rope slippage has on indirect skew measurements, whether with selsyns, encoders, or resolvers, and indicate that some encoders allow for automatic zeroing to address the issue.

Evaluation of Direct and Indirect Skew Methods

Direct and indirect skew measurement and indication alternatives were evaluated against the following criteria: accuracy for limitation of longitudinal and transverse skew, minimize the susceptibility to counterweight rope slippage due to drive acceleration and deceleration, minimize susceptibility to tower-to-tower motor speed inaccuracies (mismatches), technology selection, maintenance requirements, and the availability of repair parts.

With regards to accuracy for measurement of longitudinal and transverse skew, all of the skew measurement technologies reviewed are sufficiently accurate to be successfully used for skew indication on tower drive vertical lift bridges. It is in the application of the components where advantages and disadvantages become clear.

There is a clear advantage to all direct skew measurement devices versus indirect measurement devices in that they are not susceptible to errors due to counterweight rope slippage over the counterweight sheaves. Modern variable frequency drives (VFDs) are capable of providing well-controlled acceleration and deceleration of drive machinery and thus the use of indirect skew measurement is less of a concern with regards to counterweight rope slippage. Direct skew measurement offers a distinct advantage when it is applied to bridges with more rudimentary controls, as acceleration and decelerations may be more likely to cause counterweight rope slippage.

Similarly, there is an advantage to direct skew measurement devices versus indirect measurement devices because they are not susceptible to tower-to-tower motor speed inaccuracies. Again, it is expected that modern VFDs would control speed accurately and provide precision and smooth speed ramp functions that would reduce rope slippage. In contrast, older drive systems, particularly wound rotor motors with switched external resistors, would be less accurate and indirect skew measurements would be far less effective due to the crudeness of the speed control.

There is a clear advantage in direct skew measurements compared with indirect measurements as they eliminate errors associated with rotational differences between the two towers. The additional review of skew components that follows provides comparisons with regards to accuracy and application, control technology, and maintenance.

Direct Skew Indication Components

Of the direct skew measurements, an inclinometer provides the most accurate form of longitudinal or transverse skew measurement as no calculations are necessary to obtain an output proportional to angle of inclination. Inclinometers are readily available, so replacement with spares is not an issue, but there are issues in using inclinometers for skew measurement. These consist of their susceptibility to electromagnetic noise and vibration, transmission of inclinometer output to the controlling system, and the ability of the inclinometer to provide usable data for extremely long span bridges. Unless the specifier or engineer is aware of these potential drawbacks and accounts for them in their design and specification, the inclinometer may not achieve accurate and reliable results. The inclinometer must be specified to be immune from noise and vibration, its output must be suitably damped to eliminate transient and meaningless momentary events, and it must be provided with a reliable and signal transmission means that is immune to EMI. While there is some risk to the installation as it is exposed to the elements, when properly specified and installed, the inclinometer will require little or no maintenance and provide reliable service in the long term.

Based on the analysis of the direct skew measurement options available and used today, the inclinometer has significant advantages. When properly specified and applied, inclinometers achieve the desired accuracy, reliability, and maintainability. In addition, because they provide direct measurements of skew and do not require real-time calculations, they are best suited for relay-based control.

Two indirect forms of skew measurement that have been considered as replacements for the historically used differential selsyns. Resolvers and encoders provide monitoring, detection, and are sufficiently accurate to enable them to be used in conjunction with the bridge drive motors to control movable bridge skew. Resolvers and encoders are similar in that they are used to determine the difference in rotational displacement between the two tower operating machinery systems and output a signal proportional to skew. Both are readily available for purchase and thus there are no issues providing spares. Both offer advantages over direct measurements in that they are typically located in protected machinery spaces in the towers. They both have a similar drawback in not being as accurate as direct forms of skew measurement, given potential inaccuracies that stem from counterweight rope slippage as previously described.

Resolvers are pure analog devices whose output is proportional to the angular displacement of its shaft from a known reference. Due to its multiple fixed and rotating windings, its reliability is also questionable. A failure of a resolver will necessitate its direct replacement but determining a failure may be time consuming for maintenance personnel.

Encoders are digital devices that output pulses with the number of pulses being a measure of rotation of the driven shaft that connects it to the operating machinery. The encoder consists of a disc that contains multiple holes that light passes through which is received by a photo-sensitive device that generates the pulses as the disc rotates. This device is very simplistic but does rely on its light source and electronics which converts the photo sensitive pick-up to pulses. Failure of either the light source or the photo sensitive device electronics will result in the failure of this method of skew indication, though the published mean-time-between-failure of an encoder is very high, of the order of 4,500,000 hours which makes it very durable.

Additionally, encoders are provided with colored light emitting diodes (LED's) that indicate the status of the encoder for ease of troubleshooting. It should also be noted that in the case of an absolute encoder, the encoder can be reset at the end of each operating cycle, which eliminates the cumulative effect of rope slippage and skew error.

Of the two alternatives to selsyns, the encoder offers advantage for skew measurement. It is proven, current technology and the resolver is more susceptible to reliability issues.

Control Methodology

In general, the control methodology of a tower drive vertical lift bridge is very similar to any other movable bridge. The main difference is the form of the bridge moving span drive system. Unlike most movable bridges, the tower drive vertical lift utilizes two independent drives to operate the movable span, one in each of the bridge towers. The added complexity of this type of movable bridge operation is maintaining the independent drives in synchronism with one another and accounting for variations in rope slippage between the tower drives to maintain the moving span level.

This bridge control functionality was achieved for many years using differential selsyn system configured to monitor rotation of each tower drive and to translate it into degree of levelness (skew) of the moving span.

In conjunction with relay-based logic systems, this form of skew control, monitoring, and detection was widely adopted in the industry for many years. With the emergence of programmable logic controllers and lack of availability of selsyn type systems, the industry was forced to reassess the form of skew control to be applied to tower drive vertical lift bridges. Today, several different approaches have been developed and applied with varying degrees of success. Additionally, applying PLCs in place of bridge control system relay logic is not always an appropriate option for some owners due to the additional training required for maintenance personnel.

PLCs do lend themselves to providing the necessary computation power to enable skew conditions to be determined based on tower rotation inputs and provide the required indication and control which is beyond the capability of a conventional relay logic system.

Given the trained maintenance staff issue of maintaining and repairing PLC based systems, a compromise is the use of a relay logic control system for the bridge with a standalone skew control micro-PLC. This micro-PLC consists of a “SMART” relay with limited computing capability that is relatively inexpensive and easily replaced with a pre-programmed spare in the event of failure. See Figure 12. Note that the example relay shown is approximately 5 in. x 3 in. x 3 in.

Figure 12. Schneider Electric SMART relay

The SMART Relay can be considered as an effective control system that does not require specially trained personnel in the use of PLCs but does provide a reliable form of monitoring and controlling skew.

Although all skew measurement alternatives would have sufficient accuracy to measure longitudinal and transverse skew, there are clear advantages in direct skew measurements compared with indirect measurements as they eliminate errors associated with rotational differences between the two towers. There are small disadvantages in that the direct measurement systems are exposed to the elements. Of the direct skew measurement technologies, the inclinometer provides distinct advantages with regards to expected reliability, durability, and maintenance. Of the indirect skew alternatives, the encoder offers an advantage in reliability compared with resolvers. A comparison of the alternatives with regards to performance, maintenance, and technology restrictions is outlined in Table 2.

Table 2. Summary of skew indication component evaluation

Component	Reliability and Durability Risk	Cost	Frequency of Maintenance	Maintenance Description	Parts Availability	Track Record	Application Technology
String Potentiometers	Moderate	High	Moderate	Monitor and maintain	Good	None	PLC
Laser Position Sensors	Moderate	High	Low	Periodic adjustments	Good	Limited	PLC
Hardwired Inclinometers	Very Low	Moderate to High	Very Low	Minimal maintenance	Good	Proven	SMART Relay
Wireless Inclinometers	Low	Low to Moderate	Low	Minimal maintenance	Good	Proven	SMART Relay
Selsyns	Low	High	Moderate	Adjust for rope slippage	Poor	Proven	Relay or PLC
Resolvers	Low	Moderate	Moderate	Adjust for rope slippage	Good	Proven	Relay or PLC
Absolute Encoders	Low	Low	Low	Adjust for rope slippage	Good	Proven	SMART Relay or PLC

Conclusions

For a tower drive vertical lift bridge, failure to maintain span longitudinal or transverse skew can lead to jamming of the movable span in its guides and, without adequate protection, can lead to a catastrophic bridge failure. Tower drive vertical lift bridge skew indication and monitoring was historically satisfied with the use of a differential selsyn; however, this legacy technology is nearly obsolete.

This study included a review of alternatives for skew control, monitoring, and indication for tower drive vertical lift bridges based on effective management of skew and minimizing advanced electronic equipment.

There are few published documents documenting tower drive vertical lift bridge skew monitoring and indication options, but maintenance personnel, operating personnel, and control vendors all confirm obsolescence of differential selsyn technology. The movable bridge industry is moving towards replacement of legacy selsyn and power synchro-tie systems with skew control through the use of encoders, resolvers, inclinometers, or other devices. Apart from the use of the inclinometers, there is very little experience in the industry with the use of other direct skew measurement technology such as string potentiometers or lasers to measure span lift heights. Encoders and resolvers are both indirect skew measurement tools that are commonly used in the industry. Control systems utilizing PLCs are common for the industry for both new design and for rehabilitation design, though many owners retain functional and effective hard-wired control systems and prefer it to PLCs for ease of maintenance.

All of the reviewed skew monitoring and indication alternatives are sufficiently accurate, but there is a clear advantage to direct skew measurement devices versus indirect measurement devices as they are not susceptible to errors due to counterweight rope slippage over the counterweight sheaves, though they are subject to environmental conditions. Of direct skew alternatives, the inclinometer has significant advantages in reduced maintenance, improved reliability, and durability. When properly specified and applied, inclinometers will achieve the desired accuracy, reliability, and maintainability without any required calculations to determine movable span skew. Of the alternatives for indirect skew measurements, the encoder offers an advantage compared to the resolver as it is less susceptible to reliability issues.

Consideration may be given to combining the indirect and direct measurement of skew into an integrated control system, and the use of modern drive systems would provide for redundancy and an accurate and reliable form of skew control, indication, and system protection.

The industry has moved towards PLCs as they provide the necessary computation power to enable skew conditions to be determined based on tower rotation inputs, and provide indication and control functionality beyond the capability of a conventional relay logic system. But the preference for conventional relay logic systems does not preclude the use of inclinometers and encoders, as this may be achieved using a “SMART” relay, which has limited computing capability, is relatively inexpensive, and may be easily replaced with a pre-programmed spare in the event of failure.

Recommendations

For the replacement of legacy longitudinal and transverse skew control for tower drive vertical lift bridges, the following solutions are provided for consideration:

1. Direct skew measurement using inclinometers and SMART relays. The inclinometers would be used for control and for indication and alarm purposes as well as back-up trip functionality for an ultimate skew condition. For control, the inclinometer output would be used to control the independent tower drives to correct and eliminate a skew condition by providing minor adjustments to the drive outputs based on any instantaneous differential between the motor output feedback. A properly specified inclinometer would be specified for harsh environments, a means of temperature compensation, sufficient precision for the length of the movable span, properly protected from EMI where wireless systems are used, and specified and integrated to account for expected vibration.

   The inclinometer should only be functional during bridge operation, eliminating the effects of vibration and transient physical noise from vehicular traffic. Further, the inclinometer should be provided with a damping algorithm to damp out short duration transient events during operation.

2. Indirect skew measurement using absolute encoders and a SMART relay to provide skew control. This control function would be used to control the independent tower drives to correct and eliminate a skew condition by providing minor adjustments to the drive outputs based on any instantaneous differential between the motor output feedback. This indirect measurement may be used to provide indication of the span position and to alarm and trip the system in the event of an over skew condition. The installation should be provided with an automatic means of resetting the absolute encoders at the end of each bridge operating cycle, thereby eliminating the accumulative effect of rope slippage during multiple bridge operations.

3. A hybrid solution would utilize two independent forms of skew monitoring in the form of direct inclinometer measurements and indirect absolute encoder measurements. These would be combined to provide the desired functionality but also used as a check of one against the other, redundancy, and to enable them to be utilized for bridge auxiliary or emergency drives to enhance operating reliability.

Acronyms, Abbreviations, and Symbols

Term	Description
AASHTO	American Association of State Highway and Transportation Officials
AREMA	American Railway Engineering and Maintenance-of-Way Association
CHBDC	Canadian Highway Bridge Design Code
DOTD	Louisiana Department of Transportation and Development
EMI	electromagnetic interference
ft.	foot (feet)
in.	inch(es)
LED	light emitting diode
LTRC	Louisiana Transportation Research Center
PLC	programmable logic controller
RCLS	rotary cam limit switch
VFD	variable frequency drive

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Appendix

Responses to a skew questionnaire for vertical lift bridge owners and maintainers can be accessed by contacting the principal investigator Gareth Rees at (215) 340-5830 or grees@wje.com. Interested parties may also contact the LTRC publications department at 225-767-9150 for a PDF copy of the full appendix as well.

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