Long-Range Inspection of Suspender Ropes in Suspension Bridges Using the Magnetstrictive Sensor Technology

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ABSTRACT

The applicability of a long-range guided wave inspection technique called "magnetostrictive sensor (MsS)" for inspection of suspender ropes was field-evaluated on the George Washington Bridge (GWB) in New York City. From a test location above the sidewalk of the bridge, a pulse of 10-kHz longitudinal guided waves was launched along the length of the suspender and the reflected signals from geometric features and defects in the suspender were detected without requiring any paint removal. The test results showed that, from a single test location and without scanning the sensor along the rope, the MsS technique could examine the entire length of the suspender rope (from the socket to the main cable including the region over the main cable band) that was up to more than 100-meters (330-feet) long. The field tests indicated therefore that the MsS technique has good potential for providing a very cost- and performance-effective method of inspecting suspender ropes including areas that are remote and difficult to access, such as the socket end of the rope below the sidewalk and the region over the main cable band.

INTRODUCTION

In the United States, there are 46 suspension bridges with main spans of 213 meters (700 feet) or greater [1]. Most of these bridges have 50 years or more of service (30 were built before 1950). They are also subjected to increasingly higher usage and heavier traffic loads that exceed the original design limits. Because of their importance in the national infrastructure and their high replacement cost, maintaining structural integrity for safe and prolonged operation of these bridges is a serious concern for bridge engineers.

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Three ingredients are necessary to maintain the structural integrity of these bridges: (1) accurate condition assessment of primary load-bearing structural components, particularly the main cables and suspender ropes, (2) structural analyses of their safety, and (3) establishment of a proper maintenance and rehabilitation plan and its performance.

The primary method presently used for condition assessment of steel suspender wire ropes is a routine visual inspection, which involves walking along the bridge and looking for visible outward signs of corrosion and wire breaks. Although useful for finding gross damage and inexpensive to perform, the routine visual inspection cannot detect hidden interior damage. Also its results are too qualitative and subjective to be useful for condition assessment and safety analysis. To improve the inspection, a deep visual inspection technique is sometimes used that involves jacking the suspender rope to release the load, pulling the socket out and away from the bearing plate, cleaning and twisting in the opposite direction to the natural lay of the rope, and visually examining conditions of interior wires at that location [2]. This approach is time consuming and expensive to perform and, therefore, is applied to a limited number of locations and segments of suspender ropes. Conventional inspection techniques such as radiography, ultrasonics, eddy current, and magnetic flux-leakage have potential for inspection of steel cables. However, because of various limiting factors including radiation safety concern, accessibility problems, and high cost of inspection, they are rarely used for suspension bridge suspender inspection.

To achieve the condition assessment of aging suspension bridges in a cost- and performance-effective way, better ways of inspecting steel cables are needed; for example, methods that can inspect a long length of steel cables quickly and/or can inspect remotely from an accessible location difficult-to-access areas (such as cables around strand shoes at the main cable anchorage and the suspender ropes near sockets).

LONG-RANGE GUIDED WAVE INSPECTION AND THE MsS TECHNOLOGY

One approach that has good potential for providing an answer to steel cable inspection need is guided-wave inspection. Guided waves refer to elastic waves in sonic and ultrasonic frequencies that propagate in a bounded medium (such as rods, pipes and plates) along the direction parallel to the plane of the boundary [3]. With this approach, a guided-wave pulse is launched along a structure, and signals reflected from defects such as corrosion damage or cracks are detected from the same launching position. The location and severity of the defect are determined from the occurrence time of the defect signal and the signal amplitude. Since guided waves can travel a long distance (e.g., 100 feet or more), a large area can be examined quickly. Guided waves could also be used to examine inaccessible areas by launching waves from an accessible location and detecting, from the launching area, signals coming from inaccessible areas.

At Southwest Research Institute (SwRI), this guided-wave inspection approach is achieved by using a patented sensor and technique called “MsS [4,5],” that generates and detects guided waves electromagnetically in the material under testing without direct physical contact to the material surface. For wave generation, it relies on the magnetostrictive (or Joule) effect that refers to a small change in the physical dimensions of ferromagnetic materials – on the order of several parts per million in carbon steel – caused by externally applied magnetic field. For wave detection, it relies on the inverse-magnetostrictive (or Villari) effect that refers to a change in the magnetic induction of ferromagnetic material caused by mechanical stress (or strain).

A schematic diagram of the MsS and associated instruments for generation and detection of guided waves in steel cables or strands is illustrated in Figure 1 [6,7]. In this case, the MsS is ring-shaped and consists of an encircling coil in a biasing DC magnetic field that is typically provided using permanent magnetic circuits as illustrated. For guided wave generation, a short pulse of electric current is supplied to the transmitting MsS coil. The time varying magnetic field produced by the transmitting coil in turn expands and contracts the cable material underneath the sensor via the magnetostrictive effect, thus generating the guided waves that travel along the individual wires comprising the steel cable in both directions from the coil. Detection of guided waves is achieved by the reverse process, where the guided waves arriving at the sensor location cause the magnetic induction of the cable material underneath the sensor to change with time. The changing magnetic induction, in turn, induces in the receiving MsS coil an electric voltage, which is detected.

As mentioned above, the waves generated by a single transmitting coil propagate in both directions and a single receiving coil detects waves coming from both sides of the coil. In inspection, this bi-directional wave transmission and detection produces very complex signals that are difficult to interpret. To simplify the detected signals and data analyses the MsS system (Model MsSR 1000), developed by SwRI for field inspection, is equipped to control the direction of the transmitted wave and the detected waves primarily in one direction (instead of both directions). This directionality control is achieved by applying the phased array principle using two sets of transmitters and receivers, that are built into the system, and dual transmitting and receiving MsS coils.

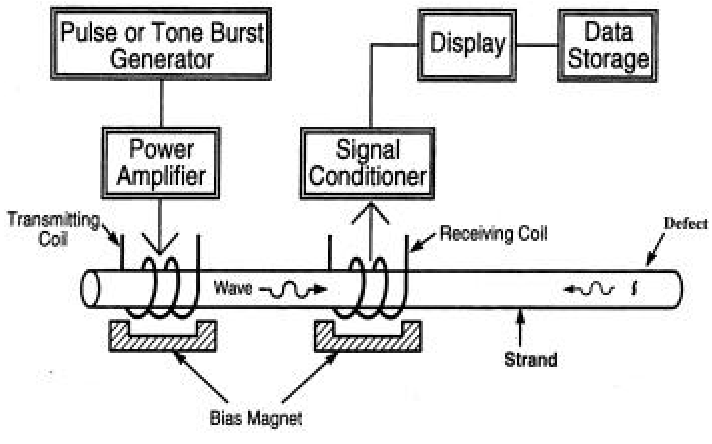


Figure 1. Schematic Diagram of the MsS and Associated Instrumentation.

MsS FIELD TESTING OF GWB SUSPENDER ROPES

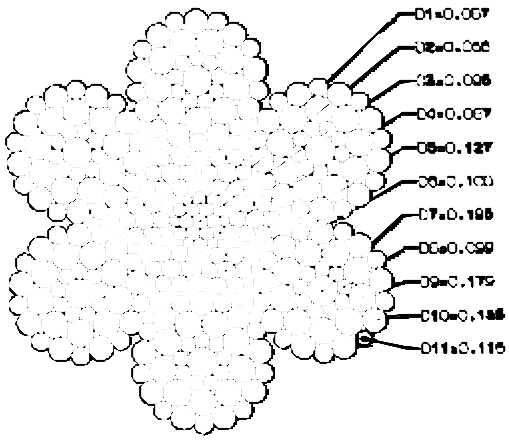
Objective

The primary objective of the field test conducted on the George Washington Bridge (GWB) was to evaluate the capability and practical applicability of the existing MsS technology for inspecting the steel cables, particularly suspender ropes, in suspension bridges. The existing MsS instrument and inspection and data analysis techniques have been used primarily for long-range inspection of piping in refineries and chemical plants.

The GWB and Configurations of its Suspender Rope

The GWB, on Interstate Highway 95, connects New York and New Jersey over the Hudson River. It is almost 1-mile long with approximately 3500-ft.-long main span. It has four main cables that support two levels of roadway with a total of 14 traffic lanes (8 upper and 6 lower level lanes). It was opened for traffic in 1931, and the lower roadway was added in 1962. The GWB has the highest load-bearing strength and is the most highly traveled suspension bridge in the U.S.A. and is operated and maintained by the Port Authority of New York and New Jersey.

The suspender rope on the GWB is 2-7/8 inches in diameter and consists of 6 strands around an independent wire rope center (IWRC), as shown in Figure 2. The overall arrangement of the suspender ropes on the bridge is illustrated in Figure 3. There are two suspender ropes at each suspender location on the bridge. Each rope is looped around the main cable band, and its two socket ends are fastened to the floor beam at approximately 6 feet 4 inches below the sidewalk of the upper level of the bridge. The two straight vertical sections of the suspender rope between the main cable and the socket are held parallel using a gatherer and a collar-and-sleeve arrangements. For suspenders whose height exceeds 250 feet, a cross-shaped separator is placed between the gatherer and the collar to prevent adjacent ropes from rubbing and to control rope vibrations. The suspender ropes are painted for protection from environmental weathering.



6 strands + 1 IWRC, total # of wires = 283 (37/str and and 61/IWRC). Total metallic cross section = 4.048 in^2

Figure 2. Typical Cross Section of 2-7/8-inch-Diameter Suspender Rope.

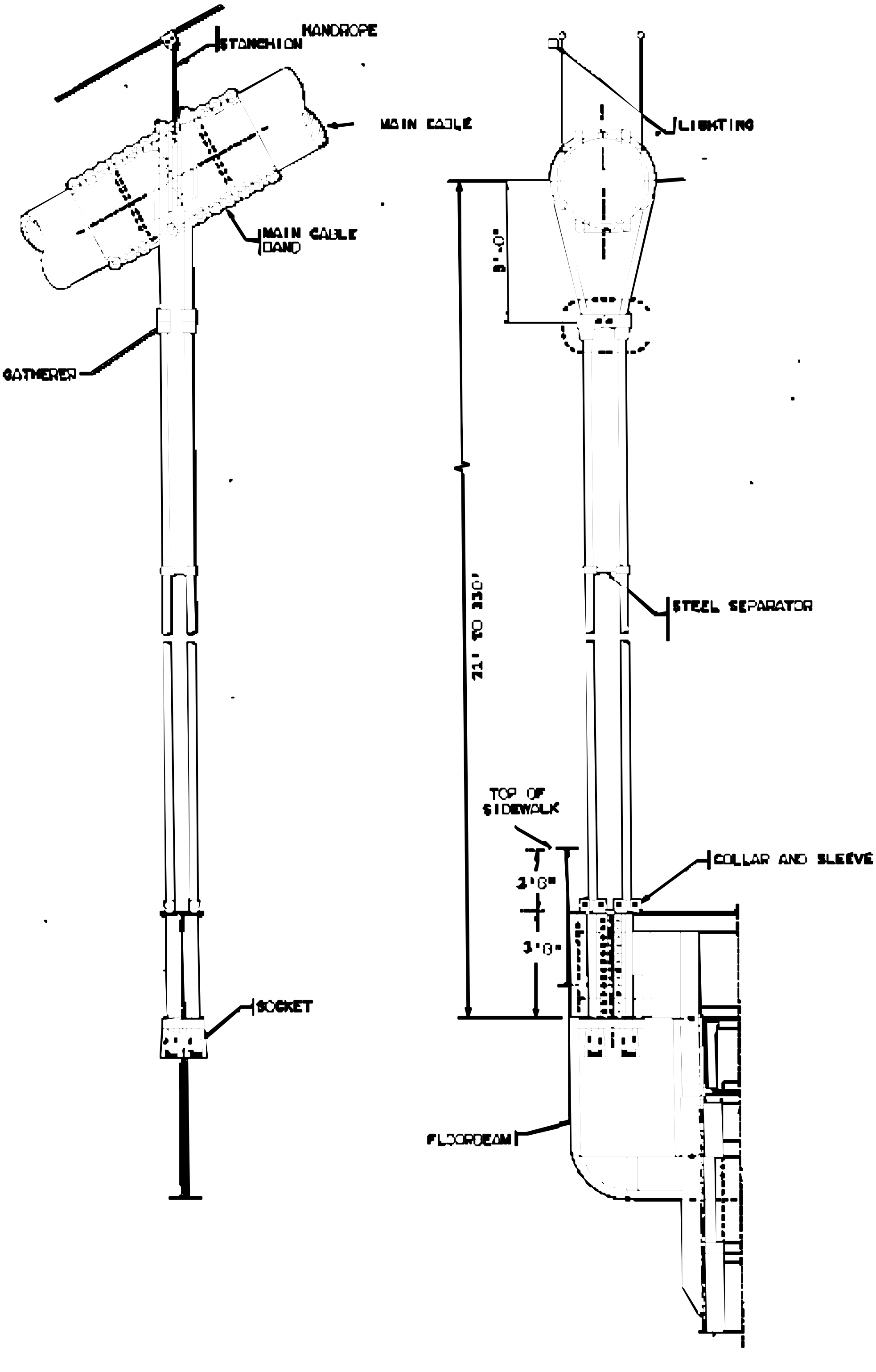


Figure 3. Configuration of Suspender Rope on the George Washington Bridge.

Test Procedures

The transmitting and receiving MsS coils were installed on a suspender rope at approximately 9- and 5-ft. heights from the sidewalk, respectively. The DC bias magnetic field required for MsS operation was supplied by using permanent magnetic circuits. By utilizing the wave direction control in the MsS instrument, a pulse of 10-kHz longitudinal guided waves was launched along the suspender toward its socket end and the signals reflected back were detected. The direction of wave propagation was then reversed toward the main cable end and the data acquisition was repeated. In addition, the amplitude of the transmitted wave signal that propagated from the transmitting MsS to the receiving MsS was also measured separately for a reference. The MsS is a non-contact device and, therefore, did not require clamping onto the rope or any paint removal.

The above measurements were then repeated after moving down the receiving MsS coils by a few feet. By correlating the two sets of data taken from two receiving sensor locations, the signals from the geometric features such as collar, separator, and socket as well as those from defect indications were identified. The above correlation process provides a self-calibration and facilitates the data interpretation by separating the signals reflected from real features in the structure from other signals such as those caused by imperfect wave direction control or other extraneous wave modes. The above procedures have been found to yield very high accuracy of defect detection and, therefore, are utilized routinely with the MsS technique.

Examples of Test Data and Discussions

Figure 4 shows data from the socket side of suspenders that were obtained from a newly installed suspender rope (top trace) and three existing suspender ropes (2nd through 4th traces). Similar data from the main cable side of suspenders are shown in Figure 5. Symbols used to describe and indicate the signals in the data are as follows: SK – socket, C – collar, Si – separators, Gi – gatherers, Di – defect indications, where i = 1, 2, 3, etc. The transmitted signal detected by the receiving MsS is indicated as TR. The signals from the opposite side that were detected because of the imperfect wave direction control are indicated by parentheses with the symbol; for example, (TR) and (SK).

The defect indications marked in the data were those detected through the data correlation process mentioned in the previous subsection that was applied only to signals exceeding a certain threshold level. In this case the threshold level was chosen to be, after compensation for wave attenuation, 1-percent of the transmitted signal amplitude that is equivalent to the reflection coefficient (R) value of 0.01. Assuming that the guided waves examine the entire 283 wires in the rope, the above threshold level is equivalent to signals from approximately 3 wire breaks.

The defect indications in Figure 4 were minor except for D2 in the 3rd trace whose R-value was approximately 0.05 that corresponds to approximately 15 wire breaks. The D2 indication may be caused by defects in the collar area that altered

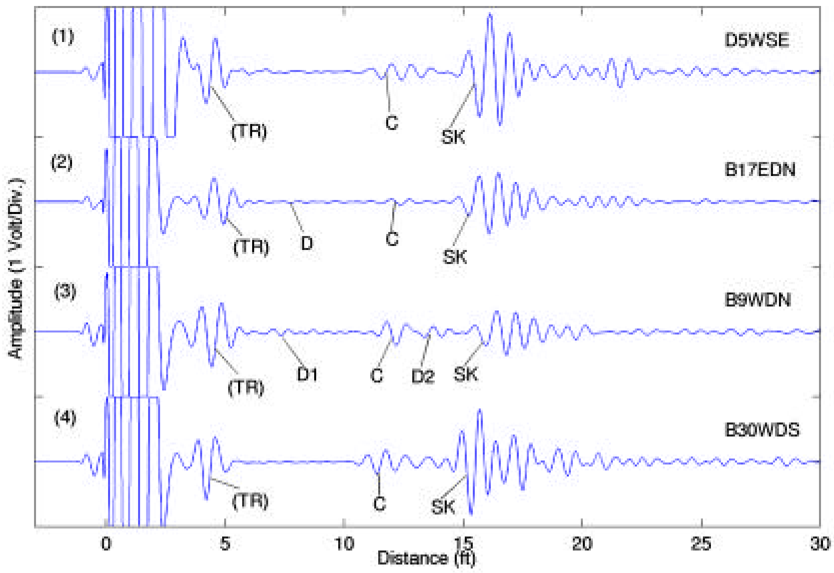


Figure 4. Examples of Data From Socket Side of Suspenders. Top Trace was from a Newly Installed Suspender and the rest were from Old Existing Suspenders.

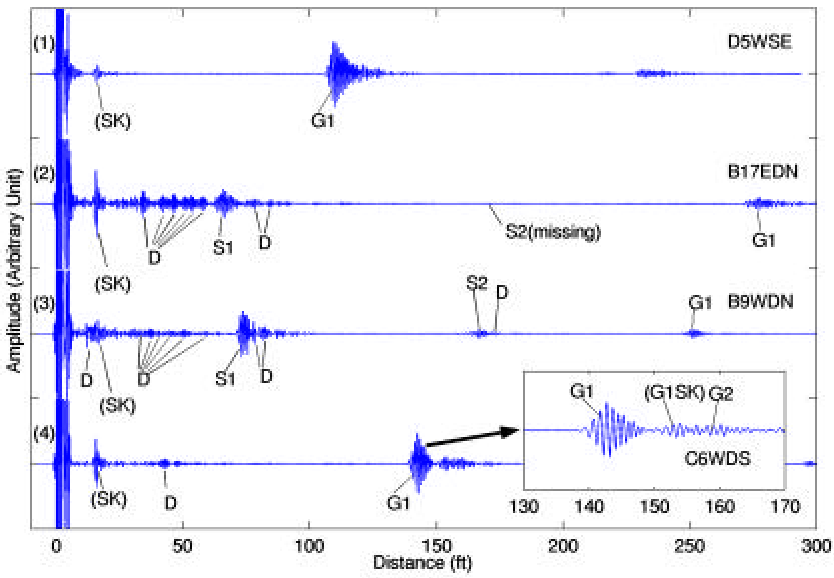


Figure 5. Example of Data from the Main Cable Side of Suspenders. Top trace was from a Newly Installed Suspender and the rest were from Old Existing Suspenders.

the normal waveform of C. The data in the 4th trace were similar to those from the new suspender with no defect indications, indicating that that rope is in good condition. Compared to the data from the new suspender, the signal from the collar area in the 2nd trace was significantly smaller in amplitude, suggesting that either the collar is loose or the presence of corrosion damage in that area.

The data in Figure 5 show signals from the gatherer that was at a more than 250-ft distance, demonstrating the capability of inspecting a long length of suspender. The defect indications marked in Figure 5 were also minor. Of the three existing suspenders from which the data in the 2nd through 4th traces were taken, it was found that the 2nd one was in the worst condition, followed by the 3rd one, and, then, the 4th one that was in almost as good a condition as the new suspender, except for a small defect indication with R ~0.01. Additionally, the signal from the 2nd separator was missing in the 2nd trace data, indicating a loose separator. Also in the 4th trace, the signals reflected from the front gatherer (G1) and the rear gatherer (G2) over the main cable band were detectable. The expanded view of the data from that region is also shown in the figure. Except for the signal indicated as (G1SK) which was the G1 signal reflected back from the socket, there were no detectable defect indications between G1 and G2. By further refining the MsS system and procedures so that interfering signals such as (G1SK) would be minimized, it is believed that more accurate inspection of the suspender region over the main cable band is achievable from the sidewalk level of the bridge.

The data given in Figures 4 and 5 clearly demonstrate the capability of the MsS technique for inspecting the entire length of suspender ropes (from the socket to the main cable including the region over the main cable band) from the sidewalk of the suspension bridge.

Although not described in this paper, the MsS technique was also found to be applicable for long-range inspection of main suspension cable elements, especially the anchorage strand where inaccessible areas around the strand shoes are impossible to inspect by visual or in-depth visual inspection by wedging.

CONCLUSIONS

The results of the field evaluation on the GWB show that the existing MsS technology is applicable for long-range inspection of suspender ropes in suspension bridges. With further refinement and tailoring of the MsS technology for the cable inspection, a very cost- and performance-effective inspection of suspenders and other bridge cables that is suitable for structural condition assessment, can be achieved using the technology.

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