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Review Article

A Laser-Based Noncontact Vibration Technique for Health Monitoring of Structural Cables: Background, Success, and New Developments

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Structural cables are susceptible to the effects of high stress concentrations, corrosion, and wind-induced and other vibrations. Cables are normally the most critical elements in a cable-supported structure and their well-being is very important in the health of the structure. The laser-based vibration technique discussed in this paper is a means for health monitoring of cables and therefore the entire cable-supported structure. This technique uses a noncontact remote sensing laser vibrometer for collecting cable vibration data from distances of up to several hundreds of feet and determines its dynamic characteristics including vibration frequencies and damping ratios. A formulation specifically developed for structural cables capable of accounting for important cable parameters is then used to calculate the cable force. Estimated forces in the cables are compared to previously measured forces or designer's prediction to detect patterns associated with damage to the cable itself and/or changes to the structure elsewhere. The estimated damping ratios are also compared against predefined criteria to infer about susceptibility against wind-induced vibrations and other vibrations. The technique provides rapid, effective, and accurate means for health monitoring of cable-supported structures. It determines the locations and elements with potential damage and the need for detailed and hands on inspection. To date, the technique has been used successfully for evaluation of twenty-five major bridges in the US and abroad. Though originally devised for condition assessment of stay cables, it has been developed further to include a variety of systems and conditions among them structural hanger ropes in suspension, truss, and arch supported bridges, ungrouted stay cables, cables with cross-ties, and external posttensioning tendons in segmental bridge construction. It has also found a valuable place in construction-phase activities for verification of forces in tension elements with minimal efforts. Future endeavors for automation and aerial delivery are being considered for this technique.

1. Introduction

Despite all the advantages associated with structural cables and ropes, their use has not been without concerns and questions. These include consequences of high stress concentrations in anchorage zones, corrosion, and susceptibility to wind-induced vibrations and other vibrations. Because of these concerns, structural cable systems are being continuously modified and standard cable systems have yet to be established. Monitoring the health and performance of existing structural cable systems can help in determination of advantages and shortfalls of various systems and identification of proper remedies for problems observed for cable-supported structures. Incidents of major damage to cables in some cable-supported bridges [1–4] have created enough concern for the owners to initiate a series of investigation resulting in development of health monitoring systems and preventive measures.

General inspection of cable structures provides useful information but can only reveal visible and/or highly advanced damage that normally necessitates extensive repairs and remedies. This is because, normally, main tension elements of structural cables, especially in the case of stay cables of cable-stayed bridges, are covered by layers of corrosion protection elements and their condition is hidden from inspectors using traditional methods of inspection.

Therefore, availability of nondestructive testing methods for detection of damage early in the service life of the structural cables is essential for health monitoring of structures that rely heavily on these elements for their integrity and load carrying capacity. Owing to the unique structural system in cable-supported constructions, cables and tension members are very suitable as surrogate sensors for reliable structural health monitoring adaptation for detecting damage and deterioration. Variation of forces and other dynamic characteristics of cables not only are indicative of their condition but also can be indication of damage at any other location in the structure. Damage and changes at any location on the cable-supported structure do induce a change in the force distribution of all members, including the cables. It is also understood that the intrinsic damping of structural slender elements such as cables is normally very low [5], making them vulnerable to large oscillations in presence of wind-induced vibrations and other source of excitations.

A rapid, laser-based vibration technique for force and damping measurement, along with numerical algorithms developed through federally and privately funded research, has provided a practical, cost-effective tool to address immediate concerns and determine the need for action in relation to structural cables and cable-supported bridges [6, 7]. As described above, force estimation in time provides an excellent means for detection of damage in structural cables and cable-supported bridges. Figure 1 shows the laser vibrometer targeting cables and a sample comparison of estimated forces. To also address vulnerability of structural slender elements against wind-induced vibrations, damping ratios can be estimated using the laser-based technique and compared to predefined thresholds for verification of susceptibility to excessive vibration. The damping measurement is also employed to verify the damping provided by external devices designed to suppress large oscillations. In all, the laser-based vibration technique provides an excellent tool for damage detection, determination of susceptibility to damage, and verification of design of mitigation methods.

To date, this technique has been used successfully for twenty-five cable-supported bridges and has continuously been adapted and evolved for new applications. With the advent of new wave of technological advances in delivery of testing and inspection methods in the form of automated aerial and ground vehicles, an entirely new endeavor has opened for novel application of this already tested technique.

2. Background

As part of a research project sponsored by the Federal Highway Administration to develop a quantitative condition-assessment technique for cable-stayed bridges, an innovative noncontacting, laser-based vibration technique was developed to measure vibration, forces, and damping in structural slender elements [6]. With this technique, cable vibration from ambient sources can be recorded from a distance by targeting the cable with the laser beam. The laser can then turn to the next cable and continue measurement for all cables in direct view. By analyzing the vibration record, the cable vibration characteristics including fundamental vibration frequencies and damping ratios are calculated. Using this information and a formulation specifically developed for structural cables, tension forces in the cables are calculated. The resulting force distribution array in cables is used to make much more refined judgments about the condition, aging, reliability, and maintenance of critical facilities than previously possible. The innovation was so practical and effective that it was put to work right away as the NDT (Nondestructive Testing) tool of choice for assisting evaluation of cable-supported bridges nationwide and abroad. Since its development, this technique has been used successfully for condition evaluation of twenty-five landmark bridges in the US, including thirteen cable-stayed bridges, five suspension bridges, and seven arch bridge.

Furthermore, one of the primary parameters which affect the susceptibility of the cables to aerodynamic vibration problems is the cable damping. Structural cables have minimal intrinsic damping that is not normally adequate to suppress wind-induced vibration in the cables. They can potentially be driven to large amplitude oscillations by a variety of wind-related mechanisms. Of the various wind-related mechanisms, the structural cables are generally susceptible to three main phenomena, namely, rain-wind-induced vibrations, galloping of various types, and vortex excitation [1, 5]. Of these, the rain-wind phenomenon is a widespread problem for stay cables resulting in large amplitude vibration of the cables under moderate wind and light rain and has been reported on several bridges around the world. Formation of water rivulets under such conditions is related to this phenomenon.

In recent years, there has been new developments on application of various types of noncontact sensors to vibration measurement. One such promising method is holographic interferometry with ability to target several moving objects from a single view point [8, 9]. Vision-based monitoring devices have also been used with some success for vibration measurement applications [10, 11]. Regardless of the type of technology, it is essential ensure assure adequate accuracy and to avoid object identification errors during field measurement. A comprehensive QC/QA for field measurement processes as well as for postprocessing is critical for viable data. Noncontact sensor devices are only the tool for collecting the vibration data from slender tension elements. The major task for force and damping estimation still remains with postprocessing and employment of simple yet accurate formulation.

3. Field Implementation and Procedure

Field application of vibration-based methods normally poses problems related to attachment of sensors (accelerometers) to measurement points and interruption of bridge function and traffic flow. For periodic cable force measurements, the manual method of sensor attachment involves additional cost and difficulty. The use of laser-based sensors therefore offers many advantages. The laser technique includes the use of a noncontact laser vibrometer aimed at cable from a distance. It eliminates the need for accessing cables for sensor installation and normally avoids major interruption to traffic.

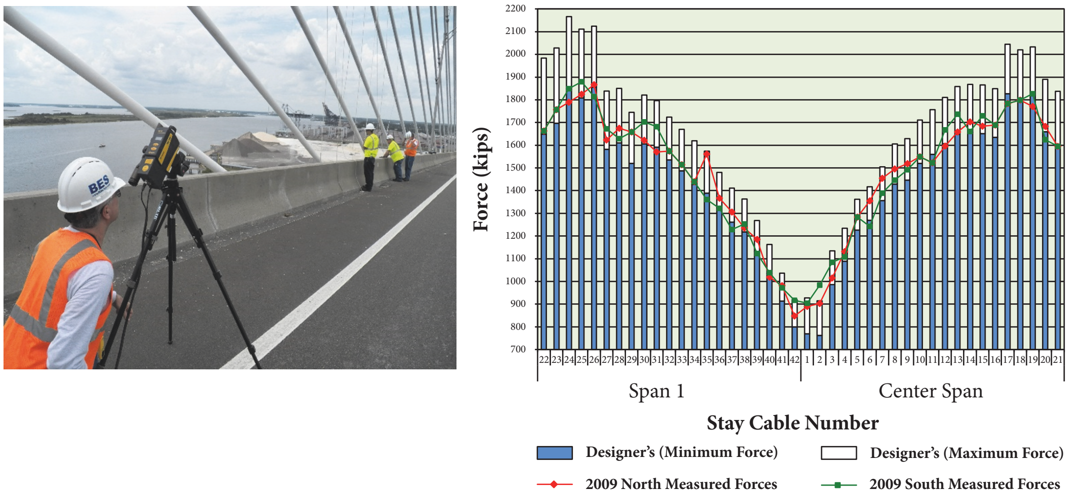

FIGURE 1: Laser vibrometer targeting cables (left), sample force comparison (right).

The laser-based measurement technique provides a noncontact remote sensing ability, and for periodic measurements and for cables with a more difficult accessibility, the technique has proven to be an extremely useful tool in reducing the time and efforts required for measurements. In most cases, ambient excitations sources such as traffic and wind induce enough vibration and there is no need for manual excitation. However, if these sources are not present or not adequate, cables are excited manually. Depending on accessibility and cable stiffness and size, manual excitation can be performed with slight impacting or the use of ropes, where a rope is passed around the cable and pulled repeatedly with a rhythm in concert with cable's natural vibration frequencies [2].

3.1. Procedure. Prior to field measurements, physical properties of the cables including length, cross-sectional area, mass per unit length, and mechanical properties are sought and gathered from design or as-built drawings and other sources. This information is utilized for sensor selection and utilization planning, and for the selection of cable excitation methods and means of safe access to the cables. Normally, minimum traffic interruption is desired by the owners. Therefore, employing lift equipment to install contact sensors (e.g., accelerometers) needs to be avoided, and the use of laser vibrometer is definitely preferred. Depending on the roadway shoulder width and other access limitations, the field measurement can be performed with only one shoulder or one shoulder and a lane closure. In some instances, for cable-stayed bridges with one plane of stay cables, the roadway median has been used for measurement operation without any lane closures. For cables with customary mechanical and geometric properties, e.g., those with first-mode frequencies of up to 2 Hz, ambient sources normally provide adequate excitation and there is no need for external sources. For stiffer cables that either have large cross-section or shorter lengths, manual excitation may be required. For measurements, the laser vibrometer is stationed on the bridge deck and cables are targeted. For construction-phase measurement, when proper location is not available on the bridge, the laser vibrometer can be stationed off the bridge within the effective range. The effective range of laser vibrometer, depending on the type of the equipment, can be from 100 to 300 ft (30 to 100 m). Usually, several cables are targeted from one laser station. Although the high sensitivity of the laser vibrometer allows flexibility in laser positioning and targeting, the ideal is to have the laser beam as perpendicular to the cable chord as possible. Also, targeting the 1/3 of the cable length from the deck provides better clarity and at the same time better participation of first and second mode of vibration in the recorded response.

The vibration time history of each cable is recorded in this manner which contains data showing the amplitude of velocity with respect to time for a predefined time interval. Using Fast Fourier Transform (FFT) analysis, the frequency spectrum for each cable vibration is calculated and the fundamental vibration frequencies are identified. Sampling rate and duration of vibration measurement are selected to provide the required frequency resolution and preventing the aliasing effects. For example, a 100 second recording duration will offer 0.01 Hz resolution in the calculated frequency spectrum. Also, to avoid the aliasing effects the data needs to be sampled at a rate at least twice the expected frequency (Nyquist Theorem). Figure 2 shows a sample time history record and results in frequency domain. The force versus frequency relationship described later in this paper is then used to calculate the force corresponding to each frequency for cables. The accuracy of the force estimation using this formulation is dependent on the accuracy of geometric and physical/mechanical properties of cables provided for measurement process, as well as on the consideration and knowledge of the actual boundary conditions for cables. Although higher accuracies are achievable, the sampling rate and recording duration are normally selected to limit the maximum error in frequency measurement to one percent, equivalent to about two percent error in the force measurement. For damping measurement, an excitation source

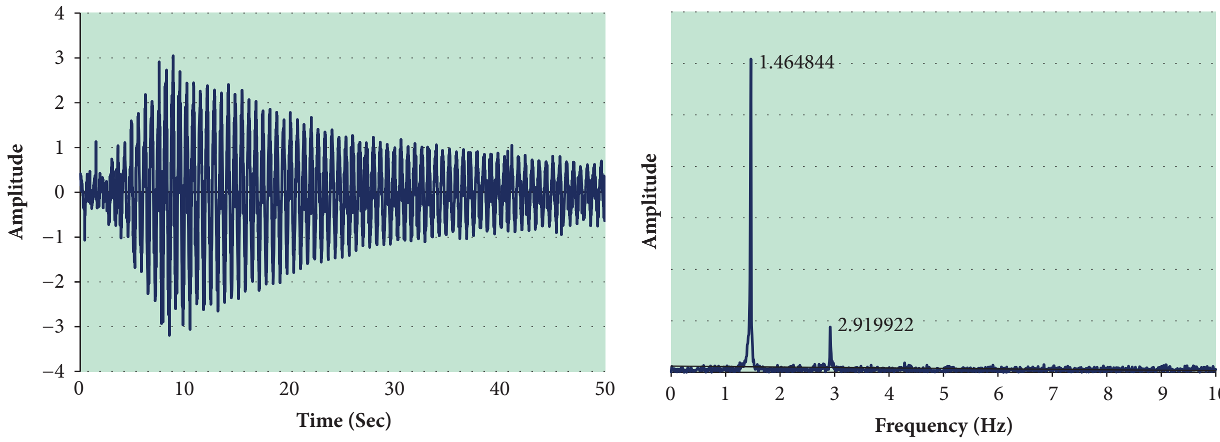

Figure 2: A vibration time history (left) and result in frequency domain (right).

is required to generate a "considerable" movement in the cables. It is realized that the damping ratio calculated for a cable may be dependent on the initial excitation amplitude; however, to this end there is no guideline or standard as to what this amplitude should be. The common way of exciting the structural cables for damping measurement is manual excitation such as impacting with rubber mallet or using rope to apply resonating motion in the cable. Mechanical shakers have also been used as source of excitation, but because of concerns for damaging the cables, their application has not been favored by the owners. In any case, the damping ratios are calculated from the free vibration time history recorded after releasing cable using available methods.

Following steps are normally ensued for a typical force measurement program:

(i) To properly characterize physical properties of the cable, data related to its mass, length, geometry, stiffness, and component materials are sought and gathered from the client.

(ii) The attachment condition of the cable to other components of the structure is obtained and studied, as are results of previous measurement programs for comparison.

(iii) The data from steps one and two above are reviewed to assess their specific relevance to force measurement procedures and accuracy, and the test data analysis protocol is defined for each individual cable variant on a structure.

(iv) The structure's configuration is reviewed, permitting sensor selection and utilization planning and selection of cable excitation techniques and safe access methods.

(v) Laser vibrometer is stationed in appropriate location on the deck (or off the bridge) and the cables are targeted under ambient (wind or traffic), or if necessary manual excitation, and time history of cable vibration is recorded.

(vi) All datasets for cables tested are stored and identified uniquely with cable numbering. Other relevant information such as date/time, wind, and temperature is also recorded.

(vii) The time domain vibration data are transformed to a record of amplitude versus frequency by Fast Fourier Transform processing. Dominant (fundamental) modes of frequency are identified and recorded for use in computation of tension force for each individual cable.

(viii) Individual cable forces are computed based on the test data analysis protocol and mathematical formulation developed specifically for cables of various characteristics.

(ix) Time history records are also used for estimation of cable damping ratios and compared to predefined thresholds for verification of susceptibility to wind-induced vibration.

The structural significance of cable array force distributions is studied through comparison of measurements with design-estimated cable forces, construction records, and/or previous measurement results. Comparative assessment seeks cursors for cable force redistribution from the prior measurement or from baseline data. Significant changes of forces, e.g., lower-than-anticipated forces in a cable element, can be indicative of potential deterioration or damage. Additionally, the pattern of force changes in cable array can also indicate damage or changes in other elements of the bridge structure. Estimation of damping ratios and comparison to predefined thresholds also determine the need for additional damping or adequacy of existing damper devices.

4. Theoretical Background

Due to the complex nature of the problem of free vibration of structural cables with vibration characteristics that are significantly different from strings, accurate yet simple analytical relationships that take into account all pertinent parameters are needed. In many cases (such as stay cables), the use of the string equation leads to excessive oversimplification and unacceptable increased errors in force predictions.

4.1. Force Measurement. The laser-based technique developed for health monitoring of structural cables is a vibration-based method. It has been completed and enhanced by development of mathematical formulation and simplified relationships that take into account the effect of parameters not considered in the taut string equation [6]. This technique has been validated by extensive laboratory experimentation and field verification, and has been used successfully for evaluation of dozens of bridges.

Formulation—For the tension members that deviate from a taut string by their different dynamic characteristics, the taut string theory needs to be augmented to be able to account for the differing characteristics of cables from those of theoretical taut string. Mehrabi and Tabatabai [6] introduced a finite difference formulation for vibration analysis of structural cables. This formulation incorporated the effects of bending stiffness of cable and its sag-extensibility characteristics into a unified solution and provided a tool for accurate determination of vibration mode shapes and frequencies. Various cable end conditions, variable cross sections, and intermediate springs and/or dampers were taken into account. Using a nondimensional form of this formulation, a parametric study was conducted on the effects of sag-extensibility and bending stiffness. Figure 3 shows variation of the first-mode inplane vibration frequency of a cable with respect to sag-extensibility and bending stiffness parameters. This formulation was verified with available theoretical solutions and compared with finite element analyses. A simple relationship among nondimensional cable parameters was also introduced for the range of parameters applicable to stay cables in cable-stayed bridges. This simple relationship provides an accurate tool for measurement of tension forces in stay cables using the vibration method.

The simple equation introduced by Mehrabi and Tabatabai [6] is expressed as

$$\frac{\omega_n}{\omega_{ns}} = \alpha\beta_n - 0.24\frac{\mu}{\zeta} \tag{1}$$

where

$\beta_n = 1 + 2/\zeta + (4 + n^2\pi^2/2)/\zeta^2$ [12],

$\omega_{ns} = n\omega_{1s} = n\pi/L\sqrt{H/m}$,

$\lambda^2 = L((WL\cos\theta/H)^2/(HL_e/EA))$,

$\zeta = L(H/EI)^{1/2}$,

W = cable weight per unit length,

ω_{1s} = First mode frequency as a taut string,

$\mu = \lambda^2$ for n = 1 (in – plane),

$\mu = 0$ for n > 1 (in – plane),

$\mu = 0$ for all n (out – of – plane),

n = mode number,

$\alpha = 1 + 0.039\mu$,

$L_e = L(1 + (mgL\cos\theta/H)^2/8)$,

I = equivalent moment of inertia,

g = acceleration of gravity,

θ = inclination angle of cable chord,

L = chord length,

m = mass per unit length of cable,

H = tension force,

E = equivalent modulus of elasticity of cable cross-section,

A = equivalent cable cross-sectional area.

4.2. Damping Measurement. Normally, for measuring damping, cables are excited manually and let free to allow recording of the time history. Figure 4 shows manual excitation of cables using a rope for stay cables and impacting with hammer for hanger ropes. With the vibration time history, various methods can be used to calculate the damping including decay method and half-power bandwidth method [13]. If the measurement is performed in windy condition, wind speed and direction is also measured for calculating the aerodynamic damping that is used in calculation of effective damping for cables [5].

5. Health Monitoring and Damage Detection Using Laser-Based Vibration Technique

The laser-based noncontact vibration technique described above has the ability to detect damage in individual cables and elsewhere in the structure that would affect the cable response. It can also be employed to determine the vulnerability of the cables against wind-induced excessive vibration that has the potential for damaging the cable and the structure by overstress, fatigue, and collision.

5.1. Vulnerability to Wind-Induced Vibration. One of the primary parameters which affect the susceptibility of cables to aerodynamic vibration problems is the cable damping. Cables normally have minimal intrinsic damping that is not normally adequate to suppress wind-induced vibration. Cables can potentially be driven to large amplitude oscillations by a variety of wind-related mechanisms. Of the various wind-related mechanisms, the structural cables and stays are generally susceptible to three main phenomena, namely, rain-wind-induced vibrations, galloping (dry and wake galloping), and vortex excitation. Of these three, the rain-wind phenomenon is a widespread problem resulting in large amplitude vibration of the cables under moderate wind and light rain and has been reported on several bridges around the world. Formation of water rivulets during light rainfall with moderate winds is associated with this phenomenon [1]. Dry and wake galloping normally occur at higher wind speeds and require certain angles of attack with respect to the cable axis and position of adjacent cables with respect to each other. The amplitude of vibration for ordinary structural cables (e.g., stay cables and hanger ropes) subject to vortex excitation is normally small and structurally insignificant.

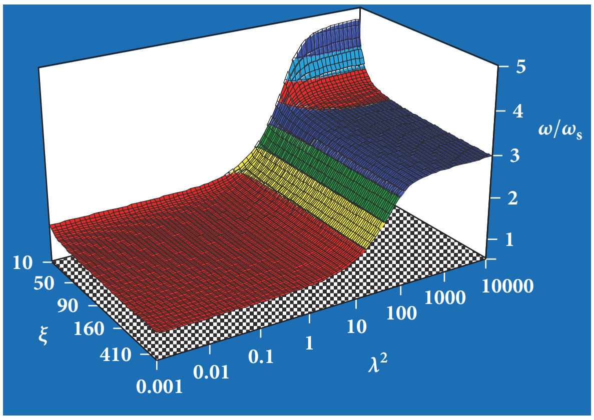

Figure 3: Parametric study for first-mode inplane vibration frequency of cables with respect to sag and bending stiffness.

In addition to the external sources such as wind, live load, and ground motion, the interaction between the structure and supporting cables can generate excitation in one caused by vibration of the other. Cables may experience noticeable oscillation by "motion-induced" and/or "parametric excitation" [14, 15]. This phenomenon is characterized by motion of the cables induced by motion of the structure, e.g., deck and towers of a bridge, during operational response of the structure (i.e., wind, traffic, pedestrian, excitation, etc.).

To investigate the vulnerability of cables to wind-induced and other types of excitations, various measures and criteria have been introduced. Comparison of dynamic characteristics of cables measured with the laser-based method with the respective criteria determines the adequacy of existing measures or the need for additional means for preventing excessive and damaging oscillations. For example, in the case of stay cables of cable-stayed bridges, Scruton Number, Sc (shown in (2)) is a nondimensional parameter calculated based on the measured damping ratio, air density, and cable diameter, and mass and is used as a measure of susceptibility of cables to rain-wind-induced vibrations.

$$Sc = \frac{m\xi}{\rho D^2} \quad (2)$$

In this equation, Sc is the Scruton Number, ξ is the damping ratio, ρ is the air density, and D is the cable outer diameter. Lower Scruton Numbers correspond to higher susceptibility to wind-induced oscillations. Normally, a minimum Scruton Number of 10 is recommended for stay cables to avoid large-amplitude rain-wind-induced vibration [5]. If this number cannot be achieved for a stay cable, each external measure or a combination external measures such as cable surface modification, viscous and other type of dampers, and cross-ties will need to be implemented to suppress the vibration. Figure 5 shows Scruton Numbers calculated for a cable array and comparison with the criteria discussed above.

5.2. Damage to Individual Cables. In general, it is expected that if dead load force (or a constant loading state) in a cable shows a noticeable drop due to a potential loss of cross-section, slippage, or similar anomalies, the cables adjacent to it should take the majority of the dropped load and therefore would show an increase in their forces. This (local) pattern of force changes would be indicative of a permanent force variation and a potential damage in the cable showing force drop. Accordingly, inspection of pattern for force variation can lead to detection of potential damage to an individual cable. Figure 6 shows a sample force comparison with a pattern indicating potential damage in a cable. This, at a minimum, will warrant a special inspection of suspect cable with the use of various available NDT methods [2].

5.3. Global Damage Detection. Structures when exposed to varying environmental conditions can undergo changes in stiffness, material properties, and boundary conditions over time. Damage can initiate from various sources. With a systematic and rational method, in general, measured changes in structural parameters reflected by individual sensor outputs can be related to damage sources and locations. These parameters may include member forces, geometry profiles (deflections), support reaction forces, structural strains, and support settlements. This forms a general framework for most global damage detection techniques.

Several investigations have been performed on damage detection of structures including vibration-based modal analysis [16], dissipated energy density method [17], and parameter estimation methods [18, 19]. These methods usually require a relatively large computational effort and a knowledge of exact loading configuration. An analytical procedure, Precursor Transformation Method (PTM), was proposed by Mehrabi et al. [20] identifying the location(s) and relative significance of possible damage sources based on measured changes in structural response parameters over time. This method offers advantages in sensitivity and cost efficiency when compared to other available methods. Developed originally for cable-supported structures, this method takes advantage of the fact that cables and tension members are very suitable for reliable structural health monitoring adaptation as surrogate sensors for detecting damage and deterioration.

Variation of forces and other dynamic characteristics of cables not only are indicative of their own condition but also can be indication of damage at any other location in the structure. Damage and changes at any location on the cable-supported structure do induce a change in the force distribution of all members, including the cables. Therefore, in this method, changes in the state of the structure are experimentally assessed through measurement of structural response parameters such as displacement, strain, or internal cable forces for the case of cable-supported structures at discrete points on the structure at a reference time and later at any desired time. For application of this method, the external loading state at different measurement times should be constant. This loading could be the dead load of the structure alone or augmented with additional live load. To uncouple the effects of different sources of damage and to determine their locations and relative significance

Figure 4: Manual excitation for damping measurement; using rope (left) and making impact with rubber mallet (right).

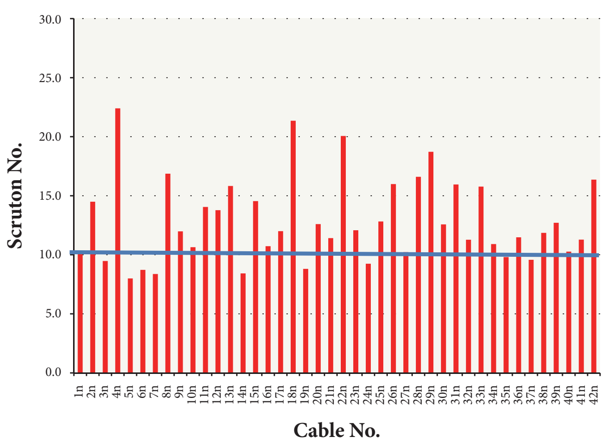

Figure 5: Sample Scruton Number calculated for cables using data recorded with the laser technique.

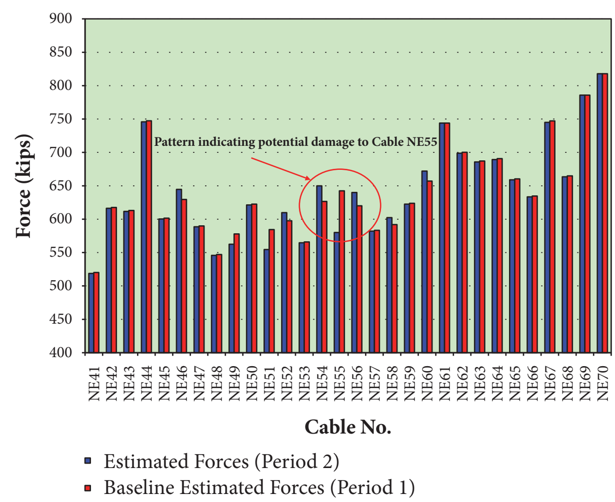

Figure 6: A sample of force comparison with a pattern indicating potential damage in cable.

based on the experimental data, an analytically determined transformation matrix is utilized.

From an analytical standpoint, the sources of damage can be characterized as precursor events (or damage precursors) that precipitate changes in the state of the structure. Precursors are externally imposed and are therefore independent of the structure and the subsequent changes in the state of the structure. Examples of damage sources that can be modeled as precursor events include loss of material or stiffness, joint slippage, support settlements, and loosening of bolts. For the case of cable-supported structures, the precursor transformation matrix contains patterns of force changes in cable array each generated analytically for a specific precursor [20]. Figure 7 shows force variation calculated for cables of a cable-stayed bridge (Figure 7(b)) and calculated precursors as damage identified for three of its cables (Figure 7(c)).

Laser-based vibration measurement technique has been used also for investigation of cause of damage or estimation of remaining service life in cable-supported bridges. Examples are force measurement of hanger ropes in the Hoan Arch Bridge (Figure 8) and the Bosporus Suspension Bridge (Figure 9).

6. Success in Implementation

The laser-based noncontact vibration technique for structural health monitoring was initially developed for condition assessment of cable-stayed bridges. Its application was limited to stay cables of certain configuration. However, the method has been evolving in time to include various stay cable conditions, and its application was extended into evaluation of cables and ropes in suspension and arch bridges. It can, in general, be utilized for any structure with slender structural

Table 1: List of bridges for which the laser-based vibration technique has been employed.

Cable-Stayed Bridges	Location	Scope	Date(s)
Second Vivekananda Bridge	Kolkata, India	Stay Cable Force Measurement	2016
Leonard Zakim Bridge	Boston, MA	Stay Cable Force Measurement	2015
Sunshine Skyway Bridge	St. Petersburg, FL	Stay Cable Force and Damping Measurement	1999, 2009,2015
Dames Point Bridge	Jacksonville, FL	Testing and Evaluation	2008,'10,'12,'16
Luling Bridge	Luling, LA	Stay Cable Force and Damping Measurement	2002-2006
Queen Elizabeth II	Dartford, UK	Stay Cable Force Measurement	2008
Maumee River Crossing	Toledo, OH	Stay Cable Force Measurement	2006
Varina-Enon Bridge	Henrico, VA	Stay Cable Force Measurement	1999 & 2007
C&D Canal Bridge	Middletown, DE	Stay Cable Force Measurement	2005
Fitchburg Bridge	Fitchburg, MA	Stay Cable Force Measurement/ Construction Phase	2003
Talmadge Memorial	Talmadge, GA	Stay Cable Force Measurement	2000
Cochrane Bridge	Mobile, AL	Stay Cable Force and Damping Measurement	1998
Weirton-Steubenville	Weirton, WV	Stay Cable Force Measurement	1997
Suspension Bridges			
Bosporus Bridge	Istanbul, Turkey	Hanger Force Measurement, Failure and Fatigue Analysis	2004
Tazlina Pipeline Bridge	Glennallen, AK	Hanger Ropes Force Measurement	1999 & 2004
Tanana Bridge, AK	Delta Junction, AK	Hanger Force Measurement	2001
Carquinez Bridge	Vallejo, CA	Hanger Force Measurement/ Construction Phase	2003
Paseo Bridge	Kansas City, MO	Hanger Force Measurement	2002
Arch Bridges			
Hart Bridge	Jacksonville, FL	Hanger Force Measurement/ Construction Phase	2016
Sherman-Minton	Louisville, KY	NDE Testing	2011
Troup Howell	Rochester, NY	Hanger Force Measurement/ Construction Phase	2006 & 2007
Telegraph Road	Taylor, MI	Hanger Force Measurement/ Construction Phase	2007
Cass Street Bridge	La Crosse, WI	Hanger Force Measurement/ Construction Phase	2004 & 2005
Belle-Vernon Bridge	Belle-Vernon, PA	Hanger Force Measurement/ Following Accident	2003
Hoan Bridge	Milwaukee, WI	Hanger Force Measurement /Failure Analysis	2001

elements. A list of twenty-five major bridges for which this method has been utilized is shown in Table 1.

6.1. New Developments. Following describes some of the later applications for this technique.

6.2. Pipeline Bridges. In 1999, 2001, and 2005, engineers were able to stand on the spectacular Tanana and Tazlina River banks in Alaska and measure remotely the forces of suspender and other cables of two suspension bridges carrying Trans Alaskan Pipeline System with great efficiency, accuracy, and speed. This was a part of scheduled evaluation project to determine the safety and soundness of this major pipeline to continue carrying crude oil in Alaska [21]. Figure 10 shows laser being used for force measurement of hangers in one of these bridges.

6.3. Construction-Phase Force Verification. The exceptional value of the laser-based vibration technique for construction-phase cable force verification was quickly recognized. The technique offered a rapid and economic yet accurate method as alternative to logistically cumbersome methods such as lift-offs. Additionally, the remote noncontact nature of the technique made it the only reasonable choice for unfinished structures where access to the cables is extremely limited. Table 1 identifies the bridges for which the technique has been used during construction to verify the forces and apply adjustments if necessary.

6.4. Extradosed Bridges. In 2016, the laser-based vibration technique was used to measure forces in stay cables of the Second Vivekananda Bridge in Kolkata, India, as a part of routine maintenance and inspection program. This bridge, shown in Figure 11, is the first extradosed bridge for which this technique has been utilized. One of the unique features of stay cables in an extradosed bridge is their relatively short length and higher bending stiffness.

6.5. Ungrouted Stay Cables. Most of the newer generation of stay cables in the US and elsewhere do not use grout filling as corrosion protection method. Having unbonded and normally detached cover pipe was thought to introduce complications in vibration measurement of the stay system, therefore resulting in difficulties for estimating the force from uncoupled vibration characteristics. The laser-based technique adapted for taking into account the noncomposite action of the cable cross-section was used successfully for the first time in 2015 for force measurement of ungrouted

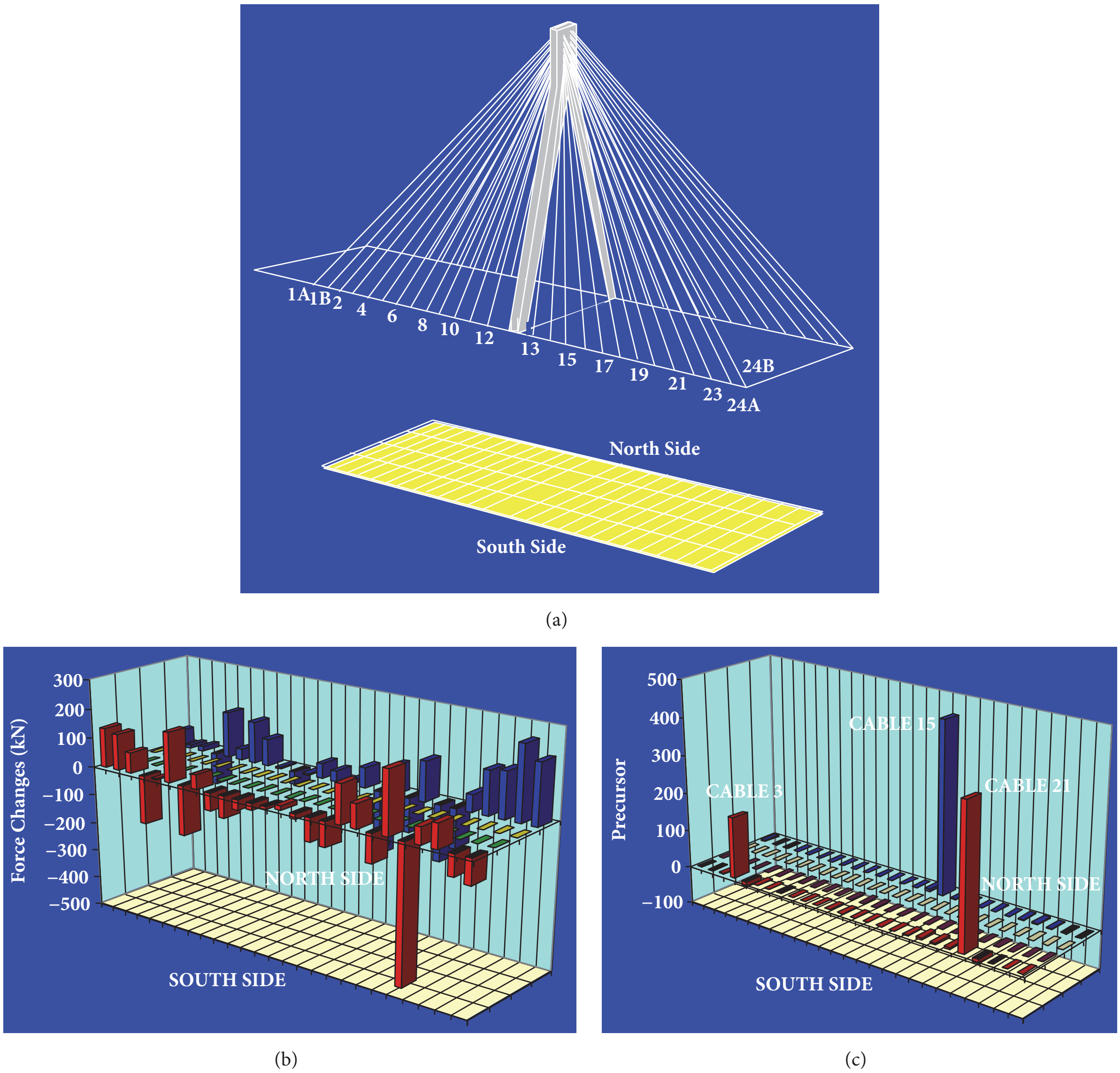

FIGURE 7: Damage detection using precursor transformation method. (a) schematic of a cable-stayed bridge superstructure, (b) force variation in cables, and (c) damage detected in three cables.

stay cables of the Leonard Zakim Bridge in Boston, MA (Figure 12).

6.6. Tied Stay Cables. Cross-ties, designed as a measure for vibration suppression of structural cables, alter dynamic characteristics of the cables, making it difficult to identify their individual vibration frequencies for force calculation using the available algorithms. Dames Point Bridge in Jacksonville, FL, is a cable-stayed bridge whose stay cables are tied to each other using cross-ties (Figure 13). After a series of verification experiments and research in 2008 to 2010, a new procedure for field application was developed and numerical formulation was complemented for taking into account the connectivity of cables. The laser technique has since been used for two successful periodic cable force measurements as part of its routine maintenance, inspection, and health monitoring program. The technique was also used in 2015 for force measurement of tied stay cables of the Leonard Zakim Bridge in Boston, MA (Figure 12).

6.7. Structural Health Monitoring Using Periodic Force Measurement. The laser-based vibration technique is being used by some bridge owners for periodic force measurement as part of bridge health monitoring and maintenance programs. The Sunshine Skyway Bridge in Florida shown in Figure 14 is one of these bridges. For this bridge, in addition to force measurement, the laser technique is also used for damping measurement of the cables with and without contribution of the external damping devices. This ensures proper functioning of the dampers and adequacy of the overall damping for suppression of wind-induced vibration.

Figure 8: Hoan Bridge in Milwaukee, WI.

Figure 9: Bosporus Bridge in Istanbul Turkey.

6.8. External Posttensioning Tendons. Currently, the laser-based method is being considered for a new application to external posttensioning tendons of a segmental concrete box girder bridge. Most external posttensioning tendons utilize a system very similar to grouted stay cables; therefore, their force estimation can be performed using the same field and analysis procedure described earlier. Tendons however are normally stressed to much higher stress levels than stay cables and hence possess dynamic characteristics that are different from those of stay cables. Tendons are expected to have higher frequencies owing to their shorter lengths and higher forces in comparison with stay cables.

6.9. Future Applications. Technological advances in the application of automated unmanned vehicles and robotics have created new opportunities for application of nondestructive methods for structural health monitoring. Undoubtedly, the laser vibration technique discussed in this paper has a great potential as a tried and verified method to be implemented with an automated delivery, let it be aerial or ground vehicle.

7. Summary and Conclusion

A laser-based vibration technique for health monitoring of cable-supported structures was discussed in this paper. The technique includes field implementation of noncontact remote sensing laser vibrometer to record the vibration and calculate the dynamic properties and a formulation developed specifically for structural cables for calculation of their tension forces. The comparison between estimated cable forces using this technique and previously measured or expected forces can be used to establish a pattern of

Figure 10: The use of laser-based vibration technique for pipeline bridges.

Figure 11: Extradosed cable-stayed bridge for which the laser-based technique was used.

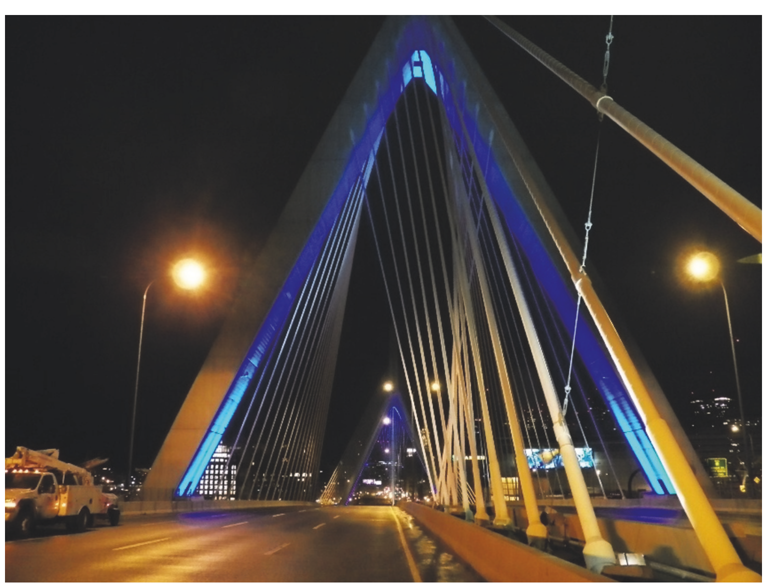

Figure 12: Laser technique was used for evaluation of ungrouted stay cables of the Leonard Zakim Bridge.

Figure 13: The forces of tied stay cables of the Dames Point Bridge are periodically evaluated using the laser technique.

Figure 14: The Sunshine Skyway Bridge in Florida.

changes indicative of location, type, and intensity of the potential damage to the cable and the structure elsewhere. The damping measured for cables with this technique is used for comparison against predefined thresholds and to determine their vulnerability to various types of wind-induced and other oscillations. Though developed originally for condition assessment of cable-stayed bridges, the laser-based vibration method was adapted for use in other types of bridges. The technique has been used successfully for evaluation of twenty-five major bridges in the US and abroad that include cable-stayed, extradosed, suspension, pipeline, and arch supported bridges. In recent years, this vibration method has been complemented with operational and formulation features to apply to differing conditions of cable systems including ungrouted stay cables and cables connected to each other with cross-ties. It has also found a valuable place in construction-phase activities for verification of forces in tension elements with minimal efforts. The technique has proven to provide a rapid, cost-effective, and accurate method for evaluation and health monitoring of cable-supported bridges. Its application is also extending into segmental bridge construction and force estimation of external posttensioning tendons. Future endeavors for automation and aerial delivery are being considered for this technique.

Data Availability

Data underlying the findings of the research work described here is available through the references cited in this paper. Availability of data generated during bridge evaluation projects referenced in this paper is with discretion of the funding authorities and bridge owners.

Disclosure

Opinions expressed in this paper are those of the authors and do not necessarily represent those of the sponsors.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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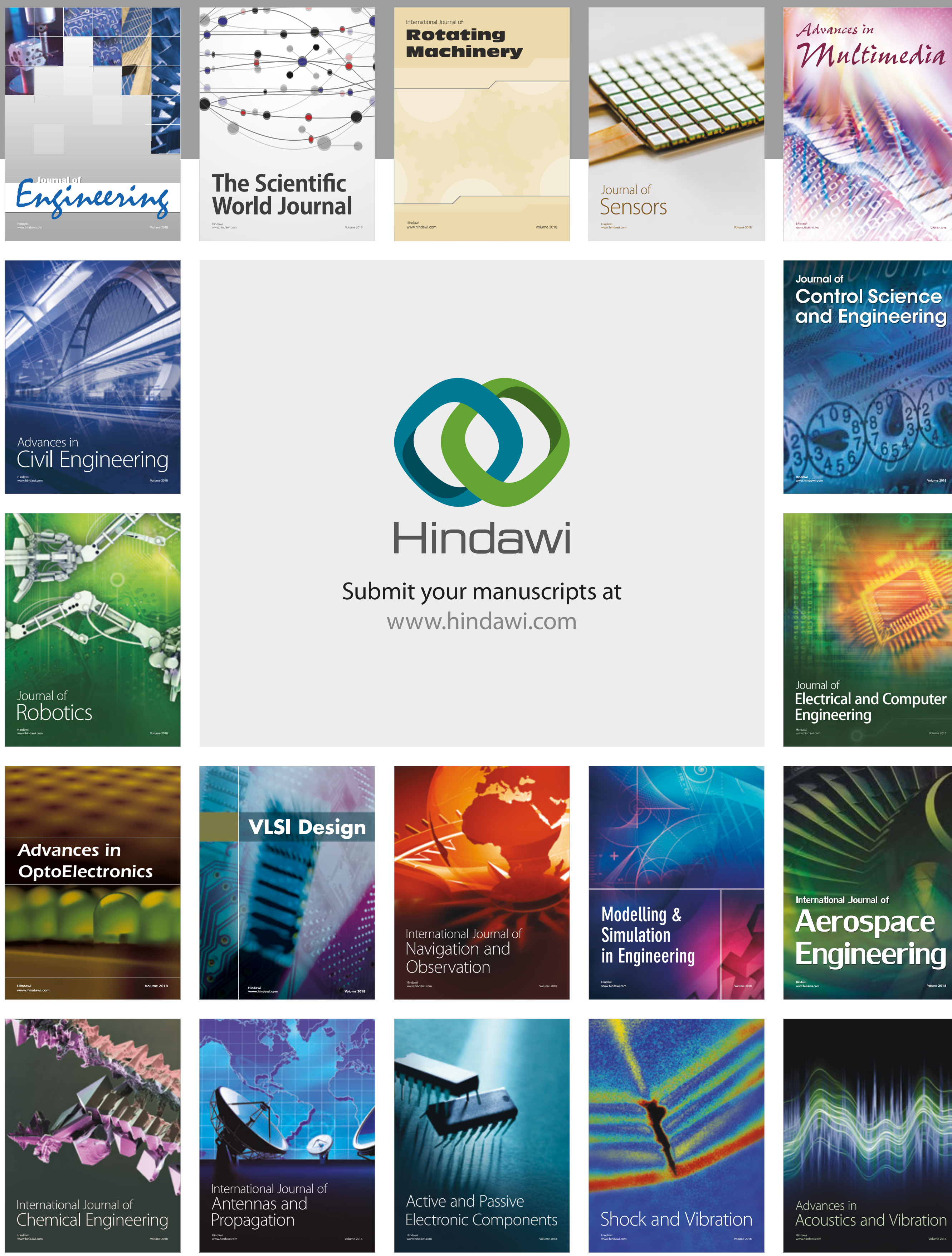
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