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Research Article

Application of Laser Vibrometer to the Measurement and Control of Cable Tensile Forces in Cable-Stayed Bridges

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The tensile forces acting on the cable of long-span bridges are one of the most important factors since they reflect not only the structural stability of cables but also the overall quality of construction. Currently, indirect measurement using accelerometers attached to the surface of the cable is widely used to measure the natural frequency of cable. The frequency obtained from the accelerometer is converted to the tensile force of the cable. However, it sometimes requires many hazardous labors such as attaching the device on the surface of cable and wiring it with data logger, which could hinder the safety of workers during the erection of cables. In this study, a method using laser vibrometer is introduced to measure the tensile forces on cables at a distance. In addition, this study developed a unique postanalysis computer program that can calculate the tensile forces in real time. Compared with the values obtained from the accelerometers, the laser vibrometer system provided accurate and reliable matching.

1. Introduction

Long-span bridges have become more constructed since the market rapidly grew up from the late 1990s. During the construction of long-span bridges, various measurements such as acceleration, displacement, and tilt angle are performed to certify the safety of the constructions in stages. Among them, the tensile force on the cable of bridge is of the most importance since it reflects the overall structural stability of bridge under construction. Therefore, the measurement for tensile force on cable is required to be precisely measured and calculated for structural integrity when the construction is complete [1]. However, it is difficult to predict the structural displacements and the cable forces by erection simulation analysis because cable-stayed bridge has the characteristics of a slender, flexible, and nonlinear behavior. The cable forces have to be adjusted for the reduction of estimation errors in section modulus, dead load, fabrication, and installation during the construction and also for structural integrity when the construction is complete [2, 3].

Currently, for the calculation of tension force on cables, accelerometers attached to the surface of the cable are mainly used to measure the natural frequency of cable [4]. However, they sometimes require many hazardous works such as attaching the device on the surface of cable and wiring it with data logger, which could hinder the safety of workers in the middle of cable. It is sometimes even more dangerous when the bridge deck work is not yet finished. In recent studies, many wireless measuring instruments including GPS are used for health monitoring of high-rise buildings [5, 6] and bridges [7]. In particular, Yi et al. [8] measured the spectral displacements and the mode frequencies of a suspension bridge using the real-time kinematic (RTK) GPS, which showed consistent results compared to the ones from accelerometer and FEM analysis.

In this study, a measurement method using laser vibrometer and analysis software is developed to eliminate both the unsafe works and to expedite the construction. With the developed method, on-site engineers are able to figure out the tensile force of cable in no time while standing on the ground. In addition, compared with the previous method using accelerometers, the developed system is assumed to be accurate and reliable.

2. Development of the Noncontact Tension Measurement System

2.1. Theory. There are several ways to measure the tension of cables from the natural frequencies of the cable vibration using string vibration method, vibration method, and vibration equation [9]. As for the string vibration method, it is easy to apply using a simple equation but known to have a discrepancy because the cables are actually subjected to flexural rigidity and friction. The vibration method takes into consideration the flexural rigidity, sagging, and inclination angle of cables and thus provides more reliability than the string theory method [10]. However, this method contains conditional variables, which make the calculation complicated. Thus, we have applied the vibration equation method, which is more reliable and easy to apply, in this study.

The differential equation of motion considering the flexural rigidity of the y-direction is shown in (1) [11] and the equation for hinge boundary conditions at both ends is as follows as (2)

$$\frac{w}{g}\frac{\partial^2 y}{\partial t^2} - EI\frac{\partial^4 y}{\partial x^4} - T\frac{\partial^2 y}{\partial x^2} = 0 \tag{1}$$

$$T = \frac{4wf_n^2L_e^2}{n^2 g} - \frac{(n\pi)^2 EI}{L_e^2} \quad (n = 1, 2, \ldots), \tag{2}$$

where y = coordinate of vertical direction due to vibration, x = coordinate of longitudinal direction, t = time (sec), T = cable tension (kN), w = cable unit weight (kN/m), f_n = natural frequency of vibration at nth mode(Hz), L_e = effective length of cable (m), n = number of vibration mode, g = gravitational acceleration (= 9.8 m/sec^2), and EI = bending stiffness of cable(kN·m). The second item denotes the effect of the length of cable on the flexural rigidity. As shown in the equation, the shorter the cable is, the bigger the effect of flexural rigidity becomes. Generally, the measured values show the trend as shown in Figure 1 and can be expressed as primary regression equation. In the primary mode, once the values of slope "a" and "b" are defined, the tension T and the bending stiffness EI can be obtained as follows:

$$\left(\frac{f_n}{n}\right)^2 = \frac{Tg}{4wL_e^2} + \frac{EI\pi^2 g}{4wL_e^4}n^2 = b + an^2 \tag{3}$$

$$T = \frac{4wL_e^2}{g} \times b \tag{4}$$

$$EI = \frac{4wL_e^2}{\pi^2 g} \times a. \tag{5}$$

Then, the variables for "a" and "b" can be determined from the linear regression analyses between $(f_n/n)^2$ and n^2 as shown in Figure 1. When we take into account the sagging effect of the cable, we can obtain the tension of the cable using the following formula:

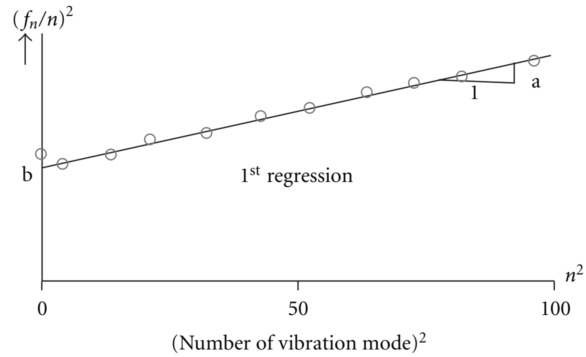


Figure 1: Regression analyses of the measured data.

$$\left[\frac{f_n}{n(1-\xi_n^2)}\right]^2 = \frac{g}{4wL_e^2}\left[1 + \frac{2\lambda^2}{\pi^4} - \frac{[1-(-1)^n]^2}{n^4}\right]T + g\frac{EI\pi^2}{4wL_e^4}n^2 = a + bn^2 \tag{6}$$

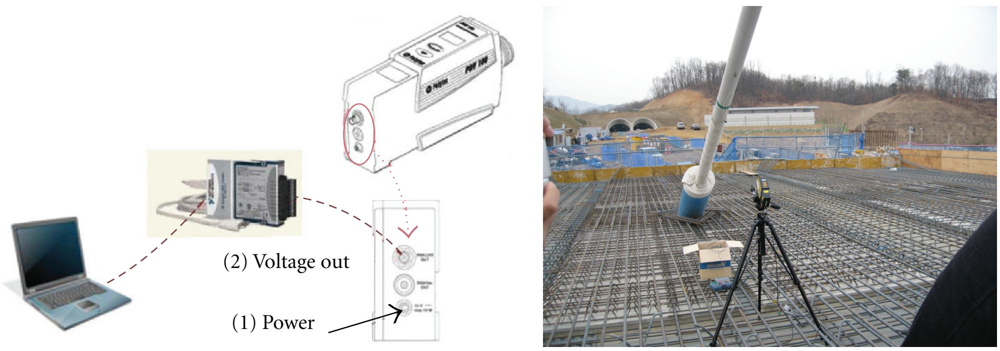
$$T = a\frac{4wL_e^2}{g\left[1 + (2\lambda^2/\pi^4) - \left([1-(-1)^n]^2/n^4\right)\right]}. \tag{7}$$

Please note that ξ_n is the damping ratio of cable and λ^2 the coefficient for the amount of sag. As the damping ratio of the cable is insignificant, we can ignore the term of the damping ration in (7). In addition, when we use only the even modes to take into account the sagging effect, the equation above can be expressed as follows:

$$T = a\frac{4wl^2}{g[1 + (2\lambda^2/\pi^4)]}. \tag{8}$$

2.2. System Configuration. In this study, we used a laser vibrometer PDV-100, manufactured by Polytec GmbH of Germany, to evaluate the tension of cables. This device is characterized by the followings. (1) It consists of a more precise laser and optic equipment and has the interferometer inside of the tool, so that it does not require additional setup time. (2) It does not have a homodyne interferometer, which does not show the directional information, but instead has the heterodyne interferometer, which shows the directional information. As it has its own decoder, it can check the speed up to the precision of 0.02 μm/s and provides not only the analogue information but also the digital information. (3) With a significantly lower noise floor, it helps us to observe the signal, which would be undetected if the analog analyzer is used. In addition, this device measures the minute vibration of the structures on site using a noncontact method.

The proposed system consists of laser vibrometer (PDV-100), USB DAQ, and notebook computer. The vibrometer basically measures the amplitude of vibration in the object from a distance since it uses laser beam projection. The measurement is basically the velocities and the maximum



(a) (b)

Figure 2: Configuration of the proposed measurement system and field setup.

range can be selected as one of 10 mm/s, 100 mm/s, and 500 mm/s with the frequencies from 0 up to 22 kHz. When the laser is projected onto the surface of the object, the laser reflection returns to the receiving sensor of the laser vibrometer. Therefore, the surface should be clean enough to reflect the laser beam. As shown in Figure 2, the device can be set away from the target cable. At this time, the vibrometer should be firmly fastened to tripod or order to minimize unnecessary noise. The working distance or sensing range can be up to 30 meters from the target to the vibrometer. The USB DAQ is used to convert the analog signals from the laser vibrometer into digital signal. The notebook computer is required to process the postdata to numerical analyses in the field. The configuration and field setup of system are shown in the Figure 2.

2.3. Algorithm of the System. We have reviewed how to convert the values measured from the portable vibrometer, PDV-100, into the tension for cables. In the United States, FHWA and CTL (Construction Technologies Laboratories, Inc.) jointly developed the laser-based portable cable tension meter in 1999 and have adopted it into the cable bridges for maintenance. It has been known that it measures 20 to 50 cables a day for their vibration as of 1999 (FHWA, 1999).

The values obtained from the device are velocity values, which can be converted into acceleration or sagging using the differential and integral calculus. In addition, either the acceleration or velocity data is used to obtain the number of vibration modes and relevant natural frequencies to get the tensional force. The basic processes for obtaining the tension are specified in Figure 3.

As for the application of the portable vibrometer in the field, it is recommended that the vibrometer is placed at the right angle to the cable for more accurate measuring. However, it is difficult to set the tool at the right angle with the cables. So, it is effective in terms of accurateness of measured values that the device is located within 15 degree from the right angle with the cable.

2.4. Software. In this study, we have developed a program based on the suggested algorithm. The developed software takes the velocity of the cable using the embedded DAQ

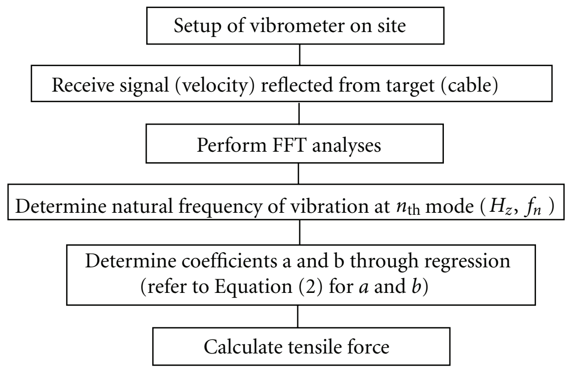


Figure 3: Basic process of measuring tension.

computer and a portable laser vibrometer. In Figure 4, from (1) to (9), we define the basic information of DAQ device channel, sampling rate, and scale factor. Then, the velocity data are collected and saved at the same time. The windows 1 and 2 in Figure 4 show the real-time data obtained from the laser vibrometer and the periods per each vibration mode obtained from the FFT analyses, respectively. Window 3 shows the result of regression analyses and window 4 the variations in the cable tensions in real time. Once the laser vibrometer is set in a distance from the cable to be measured, the focus of the laser has to be manually set in order to obtain the maximum reflective rate. In general, the cable is subjected to ambient vibration. Therefore, intentional vibration or impact on the cable is not required.

3. Verification of the Proposed Measurement System

The tension measuring system is applied for a cable-stayed bridge which was constructed in Yeongduk, Korea. The structural type is a cable-stayed bridge with a steel-composite girder and single steel pylon. The span length is 205.0 m (90 m + 115.0 m) with the bridge width of 23.40 m. Figure 5(a) shows the elevation view and the overview of the Yeongduk cable-stayed bridge.

Using the developed tension-measuring system, the tensional forces acting on cables are measured at the final

Table 1: Comparisons of tension forces for the Yeongduk cable-stayed bridge.

Cable number		SC1	SC2	SC3	SC4	SC5	SC6	EC6	EC5	EC4	EC3	EC2	EC1
Cable length (m)		91.24	83.15	75.14	64.7	54.6	45.1	44.34	53.69	63.61	73.9	84.44	95.22
Weight (kN/m)		1.128	1.128	1.128	1.128	1.128	1.128	1.128	1.128	1.128	1.128	1.128	1.128
Design tension (kN)		6,387	7,074	7,663	7,664	7,564	7,564	6,384	6,582	7,268	7,368	7,370	7,273
Measured tension (kN)	Accelerometer	6,296	7,021	7,636	7,654	7,545	7,549	6,182	6,439	7,199	7,355	7,388	7,295
	Laser vibrometer	6,341	6,762	7,263	7,403	7,371	7,413	6,254	6,429	7,259	7,208	7,121	6,931
Difference (%)		0.7	−4.4	−5.2	−3.4	−2.6	−2	−2	−2.3	0.1	−2.2	−3.4	−4.7

Note: SC means starting side of cable and EC means ending side of cable, see Figure 5.

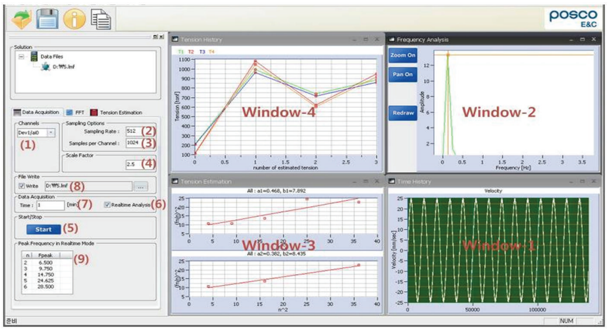


Figure 4: Measurement and postprocessing.

Table 2: Main erection process for the Incheon new port cable-stayed bridge.

Construction stages	Description
Step 1	Erection steel girder
Step 2	Cable 1st pulling
Step 3	Remove bent
Step 4	Slab casting
Step 5	Slab activation
Step 6	Cable 2nd pulling
Step 7	Superimposed load
Step 8	10000 day

stage of construction. For comparison and reliability analyses, the resultant tension forces measured from laser vibrometer and conventional accelerometers are given in the Table 1. As shown in the table, the differences between the tensional forces measured from both methods are less than 5% for most of the cases. Therefore, the method using laser vibrometer proved to be reliable. Furthermore, the developed method takes less than couple of minutes to measure tension on a cable, which is even more efficient than conventional method. In this study, we also measured the cable tensions at the stage of installment of steel girders. Measuring tension at the stage could have been a dangerous job for technicians because the space between girders is wide open without concrete deck slab. Thus, this method contributed to improve the safety of construction as well.

4. Application of the Proposed Measurement System to the Construction of a Cable-Stayed Bridge

Objectives of construction control are to adjust deck elevations and cable forces within management limitations using simulation analysis, field measurements, and verifications of structural system throughout the construction of cable-supported bridges. Construction control can be divided into two tasks: the collection (measurement) and the analysis of data. Since these two tasks are separately operated, data sharing is very important. While one of the inspection teams performs the verification of the measurements through a laser vibrometer, another team analyzes the data for adjustments of deck elevations and cable forces.

4.1. Description of the Bridge. A new port access road connecting an LNG terminal with a coastal road in Incheon, South Korea is planed to be opened in November 2012. The roadway consists of a twin-deck cable-stayed bridge with two spans of 105 meter. The decks are composed of concrete slabs on steel box girders carrying three lanes of traffic. A typical section of cable-stayed bridge is shown in Figure 5(b). The decks are supported by the total of 16 Parallel Wire Strand (PWS) cables and connected at 10 m intervals. Each cable has a bundle of 367 to 421–7 mm diameter parallel wires and is inserted to the dead anchorage of the single concrete tower. The cable force is developed at the live anchorage of the girder next to a center-hole jack. The single tower and the layout of the cables can be seen in Figure 5(b).

4.2. Simulation Analysis of Construction Process. Simulation analysis is one of the ways to calculate the structural displacements and cable forces of cable-stayed bridges having the characteristics of a slender, flexible, and nonlinear behavior. The erection process of the Incheon new port bridge is summarized in Table 2.

4.3. Measurements of Cable Tension Forces. During the erection of the cable-stayed bridge, we measured the tension of the stay cables, deck profile, and pylon deformation. There are some discrepancies between the simulation values and the actual responses of the bridge. Generally, structural engineers identify these discrepancies from stochastic sensitive analyses. In this study, we identified these discrepancies from the measurements of cable tensions because we could measure sixteen cable forces using a laser vibrometer within an hour. The global matrix of the cable-stayed bridge does

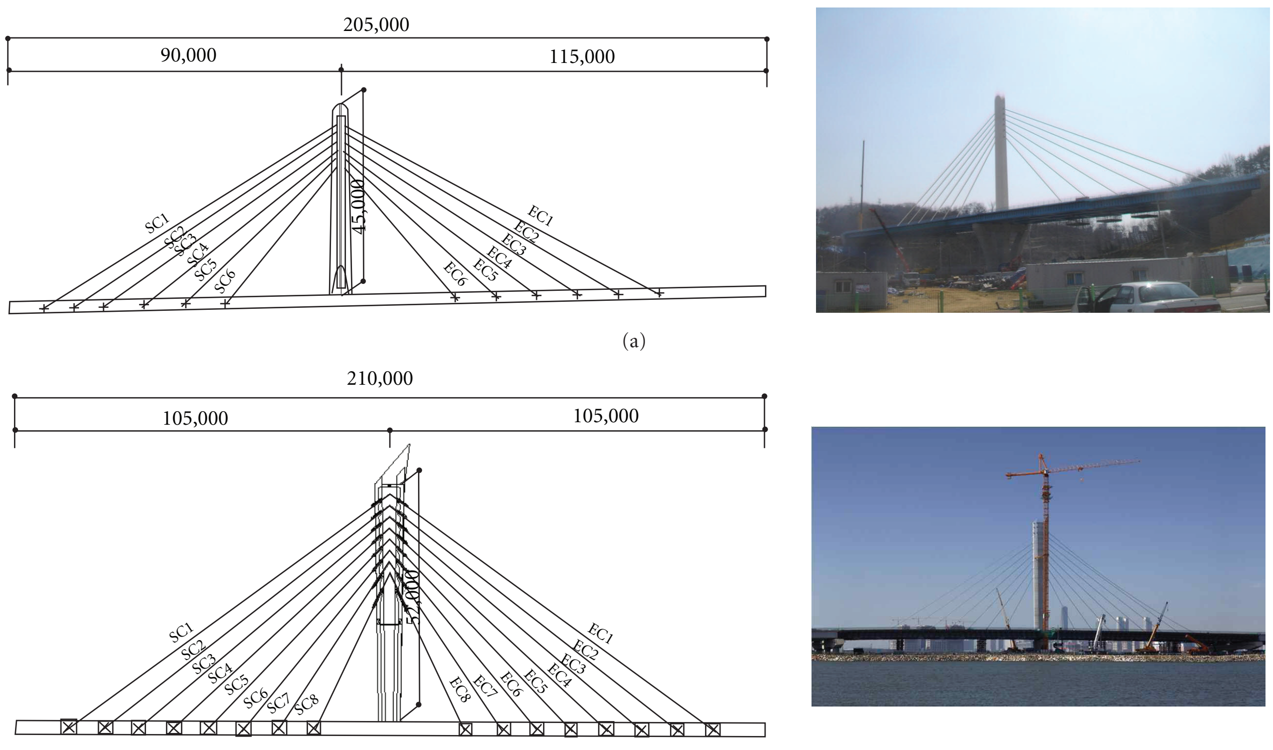


Figure 5: Dimensions and overviews of the bridges. (a) Yeongduk cable-stayed bridge. (b) Incheon new port cable-stayed bridge.

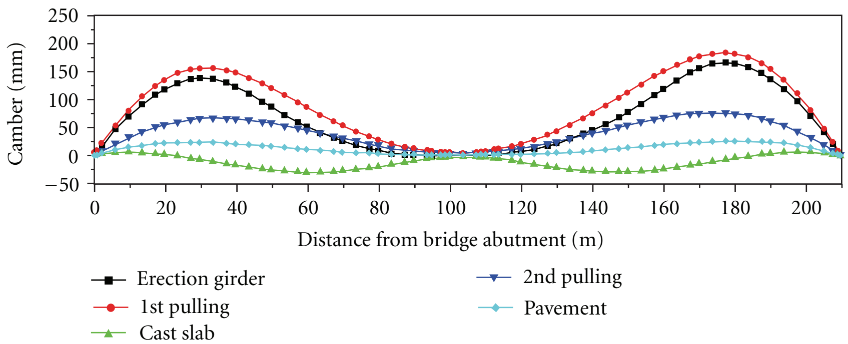


Figure 6: Camber diagram of the girder during erection.

not change after the composition of the bridge. Therefore, the influence matrix of cable forces obtained from the measurements during the 2nd pulling of cables can be used for the adjustments of the tension forces. Table 3 shows the measurements of the cable forces using the laser vibrometer system during the construction of Incheon new port bridge.

4.4. Control of the Bridge. During the construction of Incheon new port cable-stayed bridge, the first pulling of the stay cables started on March 17, 2012 and ended on April 9. For the second pulling of the cables, we measured and controlled the cable tension of the bridge. The results of deck elevations and camber diagram are illustrated in Figures 6 and 7.

5. Conclusions

In this study we have conducted research on how to obtain and control the tension of cables by using the portable laser vibrometer. This study has been the first trial to find out a tension measuring method using the portable vibrometer in Korea. We measured the cable tension of cable-stayed bridges using the portable vibrometer and compared the results with those obtained from accelerometers. As a result, the proposed noncontact tension measurement system using a laser vibrometer provided reliable values. The main findings are as follows.

(1) The tension of cables can be effectively obtained using the portable vibrometer and the program developed based on a suggested algorithm.

Table 3: Field measurement of the first tensioning for the incheon new port bridge's cables.

Cable ID		SC1	SC2	SC3	SC4	SC5	SC6	SC7	SC8	EC8	EC7	EC6	EC5	EC4	EC3	EC2	EC1
Unit weight (kN/m)		1.17	1.25	1.25	1.33	1.33	1.33	1.33	1.17	1.17	1.33	1.33	1.33	1.33	1.25	1.25	1.17
Effective length (m)		100.51	90.23	80.41	70.54	61.00	51.74	42.79	34.75	34.74	42.79	51.74	61.00	70.52	80.42	90.23	100.51
Allowable force (kN)		10614	11481	11481	11481	12176	12176	12176	11481	11481	12176	12176	12176	11481	11481	11481	10614
SC8 EC8	Simulation								**5,034**	**4,949**							
	Accelerometer								**4,909**	**4,950**							
	LVTMS								**4,926**	**4,969**							
SC7 EC7	Simulation							**4,645**	4,589	4,580	**4,598**						
	Accelerometer							4,541	4,716	4,603	**4,645**						
	LVTMS							4,353	4,636	4,507	**4,564**						
SC6 EC6	Simulation						**3,586**	3,679	3,943	3,950	3,657	**3,534**					
	Accelerometer						**3,476**	3,796	4,488	4,240	4,033	**3,513**					
	LVTMS						**3,316**	3,781	4,471	4,188	3,986	**3,488**					
SC5 EC5	Simulation					**3,605**	2,988	3,186	3,648	3,656	3,175	2,956	**3,561**				
	Accelerometer					**3,594**	2,864	3,456	4,282	3,992	3,715	3,066	**3,551**				
	LVTMS					**3,501**	2,835	3,488	4,265	3,996	3,639	2,991	**3,495**				
SC4 EC4	Simulation				**3,581**	3,339	2,743	3,003	3,546	3,549	2,989	2,714	3,307	**3,561**			
	Accelerometer				**3,566**	3,205	2,662	3,167	4,024	3,780	3,356	2,689	3,204	**3,533**			
	LVTMS				**3,388**	3,176	2,580	3,263	4,109	3,837	3,345	2,728	3,185	**3,387**			
SC3 EC3	Simulation			**3,507**	3,429	3,204	2,646	2,944	3,520	3,531	2,945	2,634	3,184	3,410	**3,501**		
	Accelerometer			**3,508**	3,420	3,221	2,562	3,086	4,054	3,924	3,356	2,684	3,132	3,252	**3,484**		
	LVTMS			n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a		
SC2 EC2	Simulation		**3,735**	3,024	3,007	2,869	2,439	2,853	3,507	3,514	2,861	2,447	2,874	3,005	3,014	**3,731**	
	Accelerometer		**3,531**	3,044	2,945	2,925	2,404	3,191	4,091	3,815	3,244	2,535	2,826	3,008	2,985	**3,434**	
	LVTMS		**3,518**	2,942	2,892	2,865	2,346	3,123	4,032	3,806	3,261	2,527	2,865	2,945	2,939	**3,421**	
SC1 EC1	Simulation	**3,729**	3,356	2,666	2,713	2,651	2,312	2,803	3,506	3,505	2,802	2,311	2,647	2,708	2,658	3,364	**3,729**
	Accelerometer	**3,720**	3,180	2,682	2,681	2,741	2,299	2,992	3,713	3,711	2,827	2,509	2,740	2,757	2,656	3,082	**3,662**
	LVTMS	**3,763**	3,150	2,715	2,685	2,738	2,296	2,988	3,731	3,697	2,822	2,525	2,736	2,727	2,638	3,138	**3,658**

Note: LVTMS designates laser vibrometer test meter system.

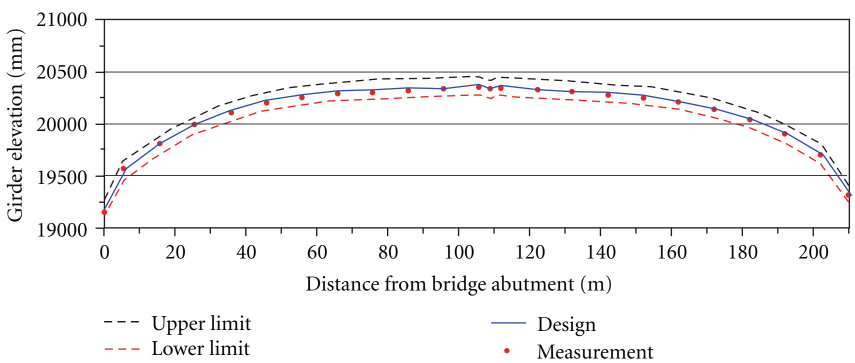


Figure 7: Deck elevation of the girders after the first pulling of the cables.

(2) The portable vibrometer has been found to be an effective way to check the tension of the cable and the maintenance of the bridge in cable-stayed bridges.

(3) The resultant tensional forces on cables show little difference from the conventional way using accelerometers. In other words, the maximum discrepancy in tensile forces between the ones from accelerometer and laser vibrometer is within 5%.

In the application of this proposed system to the construction of real cable-stayed bridges, we successfully measured and controlled the tensile forces of cables in cable-stayed bridges before the second pulling through the error correction work. The error correction work includes the jacking force calibration, geometric control of cables, and cable tensile forces. It proved that the error correction can be performed by comparing the data of structural analyses to the measurements using the laser vibrometer system. In addition, the influence matrix of cable forces obtained from the laser vibrometer system can be used for the adjustments of the tension forces for the second pulling of cables based on simulation analysis.

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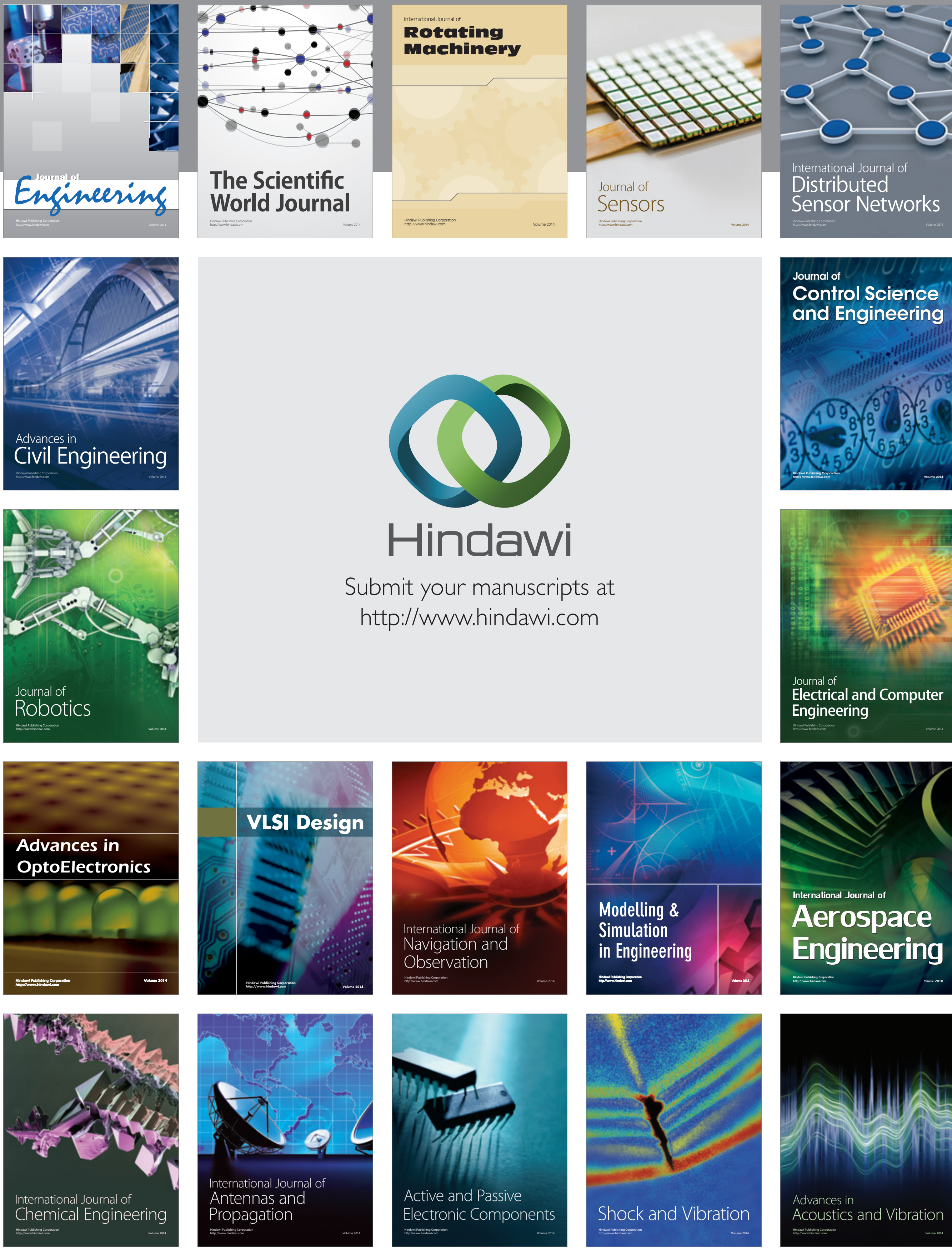
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