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Numerical Simulation of Electro-Mechanical Impedance Response in Cable-Anchor Connection Interface

Khac-Duy Nguyen* and Jeong-Tae Kim*†

Abstract In this study, a finite element(FE) analysis on electro-mechanical impedance response of cable-anchor connection interface under various anchor force is presented. In order to achieve the objective, the following approaches are implemented. Firstly, an interface washer coupled with piezoelectric(PZT) material is designed for monitoring cable-force loss. The interface washer is a small aluminum plate on which a PZT patch is surface-bonded. Cable-force loss could be monitored by installing the interface washer between the anchor plate and the anchorage of cable-anchor connection and examining the changes of impedance of the interface washer. Secondly, a FE model for cable-anchor connection is established to examine the effect of cable-force on impedance response of interface washer. Also, the effects of geometrical and material properties of the interface washer on impedance responses under various cable-forces are investigated. Finally, validation of the FE analysis is experimentally evaluated by a lab-scale cable-anchor connection.

Keywords: Electro-Mechanical Impedance, Piezoelectric, Cable Structures, Interface Washer, Finite Element Analysis

1. Introduction

Nowadays, due to high strength and light weight of steel cable, a large number of cable structures such as prestressed concrete bridge, suspension bridge and cable-stayed bridge have been widely constructed all over the world. Those kinds of structures usually cost a huge amount of expense and contribute an important role to living, transportation as well as economics. Therefore, the safety of these structures has to be ensured as well as possible. Among potential damages in cable structures, the damage of cable-anchor connection such as relaxation of cable stress, failure of connection components usually occurs. Structural health monitoring(SHM) on cable-anchor connection becomes an important issue to study since failure at that kind of connection could lead to failure of cables, reduction of load carrying capacity and severe disasters.

Related to SHM, there are two large branches as global SHM and local SHM. Up to date, many studies have been focused on SHM of structural connections by using global and local dynamic characteristics [1-8]. The global SHM which usually deals with acceleration-based methods can monitor structural integrity but not sensitive to local incipient damage. On the other hand, impedance-based local SHM is found to be very promising to capture small incipient damage at limited region like cable-anchor connection. The impedance-based method was first proposed by Liang et al. [9]. Since then, many researchers have improved the method and applied the method to various

[Received: October 21, 2010, Revised: December 2, 2010, Accepted: December 10, 2010] *Department of Ocean Engineering, Pukyong National University, Nam-gu, Busan 608-737, Korea, †Corresponding Author: idis@pknu.ac.kr

damage detection problems. The method utilizes electro-mechanical impedance in high frequency responses, which are typically higher than 30 kHz through surface-bonded PZT patches to monitor changes in structural mechanical impedance. In this method, PZT patches can act as both sensors and actuators based on their electro-mechanical coupling.

Beside the advantages of the impedance-based method, behavior of the electro-mechanical impedance due to the change in structural characteristics is still not clearly identified. Numerical study, therefore, has been becoming an interesting topic. Giugiutiu and Zagrai [10] established a numerical simulation of electro-mechanical impedance for a free-free aluminum beam with consideration of different thicknesses and widths of the beam. Park et al. [11] examined effects of multiple cracks in concrete beam on electro-mechanical impedance signatures by using finite element(FE) analysis. It is found necessary to establish a FE model for cable-anchor connection to examine the effect of cable-force on electro-mechanical impedance.

In this study, a FE analysis on electro-mechanical impedance response of cable-anchor connection interface under various anchor forces is presented. In order to achieve the objective, the following approaches are implemented. Firstly, an interface washer coupled with piezoelectric(PZT) material is designed for monitoring cable-force loss. The interface washer is a small aluminum plate on which a PZT patch is surface-bonded. The cable-force loss could be monitored by installing the interface washer between the anchor plate and the anchorage of cable-anchor connection and examining changes of impedance of the interface washer. Secondly, a FE model for cable-anchor connection is established to examine the effect of cable-force on impedance response of interface washer. Also, the effects of geometrical and material properties of the interface washer on impedance responses under various cable-forces are investigated. Finally, validation of the FE analysis is experimentally evaluated by a lab-scale cable-anchor connection.

2. Background of Impedance-Based Method

Impedance-based method is based on the coupling of mechanical and electrical features [9]. In this method, a piezoelectric patch is usually surface-bonded to host structure. The electrical effects of piezoelectric are partly controlled by the mechanical effects of host structure. As shown in Fig. 1, the interaction between piezoelectric patch and host structure is conceptually explained as an idealized 1-D electro-mechanical relation. The host structure is described as the effects of mass, stiffness, damping, and boundary condition. Meanwhile, the PZT patch is modeled as a short circuit powered by a harmonic voltage or current. The electro-mechanical admittance Y(ω) (the inverse of electro-mechanical impedance Z(ω)) which is generated from the PZT patch is the combined function of mechanical impedance of the host structure, Zs(ω), and that of the piezoelectric patch, Za(ω), as follows:

$$Y(\omega) = i\omega \frac{wl}{t_c}\left[\left(\varepsilon_{33}^T - d_{3x}^2 Y_{xx}^E\right) + \frac{Z_s(\omega)}{Z_a(\omega)+Z_s(\omega)} d_{3x}^2 Y_{xx}^E \left(\frac{\tan kl}{kl}\right)\right] \tag{1}$$

In eqn. (1), Y_{xx}^E is the Young's modulus of the PZT patch at zero electric field, ε_{xx}^T is the dielectric constant at zero stress, d_{3x} is the piezoelectric coupling constant in the x-direction at zero stress, k is the wave number; w, l, and t_c are the width, length, and thickness of the piezoelectric transducer, respectively. In that equation, the mechanical impedance of the host structure $Z_s(\omega)$ is a function of mass [M], stiffness [K] and damping [C] as follows:

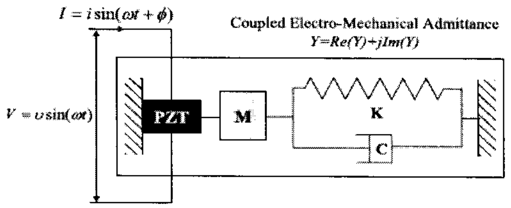


Fig. 1 1-D model electro-mechanical interaction between piezoelectric patch and host structure (Liang, 1996)

$$Z_s(\omega) = \frac{1}{j\omega}\left([K] + j\omega[C] - \omega^2[M]\right) \quad (2)$$

Assume that electrical and mechanical properties of the PZT patch remain unchanged when damage occurs, the change in electro-mechanical impedance would be controlled by the mechanical impedance of structure. Note that, the PZT patch has ability to vibrate the host structure only in a limited area. Therefore, this method is efficient for local SHM. Since damage occurs in the structure, the change in electro-mechanical impedance is then quantified by a statistical method using root mean square deviation (RMSD) index as follow:

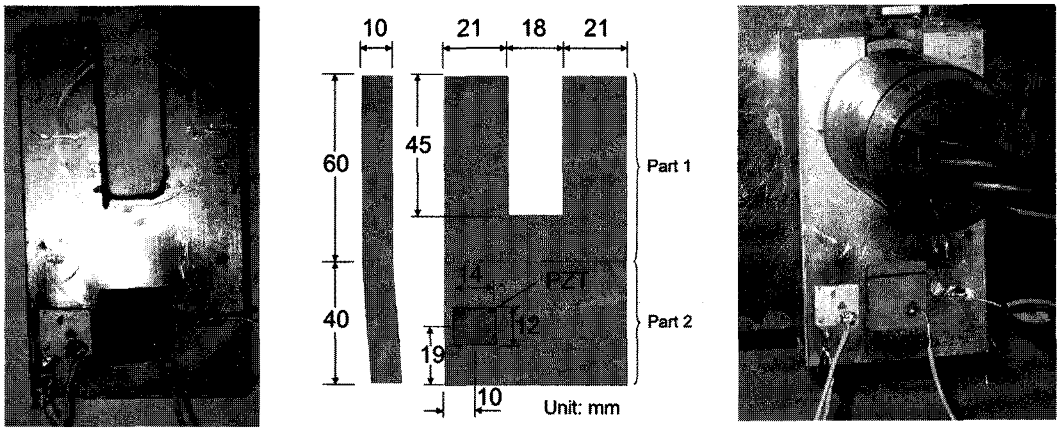
$$RMSD = \sqrt{\sum_{i=1}^{n}\left[\mathrm{Re}(Z^*(\omega_i)) - \mathrm{Re}(Z(\omega_i))\right]^2 \Big/ \sum_{i=1}^{n}\left[\mathrm{Re}(Z(\omega_i))\right]^2} \quad (3)$$

where, $Re(Z(\omega_i))$ and $Re(Z^*(\omega_i))$ are the real parts of impedance signatures at the ith frequency measured before and after damage occurrence, n is the number of frequency points in the sweep.

3. Interface Washer for Cable-Force Loss Monitoring

In the previous study by Kim et al. [8], an MFC patch was directly bonded to an anchor plate of a cable-anchor connection to monitor cable force loss of a prestress concrete girder. Signatures of electro-mechanical impedance which were measured by a commercial impedance analyzer (HIOKI3532-50) were found to be sensitive to prestress loss at the frequency range of 880-980 kHz. This commercial impedance analyzer costs a large expense of about $15,000 and is not convenient for field test application. The solution for these issues is to adopt wireless impedance sensor devices [6,12]. Dealing with wireless sensors, the high costs associated with the conventional SHM system can be greatly reduced [13-18]. Another advantage for using wireless sensors is that autonomous operations for the SHM can be implemented by embedding advanced system technologies [12,19]. In order to apply the new approach, however, the measurable frequency range of 10 kHz - 100 kHz of the wireless sensors should be dealt appropriately for impedance measurement as well as feature extraction. Another problem is that, the effective impedance frequency range is various depending on target structures and usually obtained by trial and error. That causes difficulty when applying impedance-based method to real structure since the effective frequency range is almost unknown and may take much effort to obtain it by trial and error.

To overcome the above-mentioned drawbacks, an interface washer equipped with a PZT patch is designed as shown in Fig. 2(a). The interface washer is made of aluminum, and its entire dimension is 100×60×10 mm. The PZT patch is PZT-5A type and its size is selected as 14×12×0.2 mm. It is bonded on the surface of the interface washer at 10 mm from the left edge and 19 mm from the bottom edge of the interface washer. The dimensions of interface washer and PZT patch are described in detail in Fig. 2(b). Basically, the interface washer can be separated to two parts. Part 1 is installed to a cable-anchor connection and controlled by cable force, and part 2 is the flexible plate which is



(a) Interface washer (b) Dimension of interface washer and PZT patch (Unit: mm) (c) Installed interface washer

Fig. 2 Interface washer for cable-force loss monitoring

vibrated by the PZT patch. Fig. 2(c) shows how the interface washer can be used for monitoring a cable-anchor connection. As shown in Fig. 2(c), the interface washer is attached between an anchorage and a steel plate. By this way, any change in cable force will be represented by the changes in boundary condition and stress field of the interface washer, which in turn affect the electro-mechanical impedance from the PZT patch. The advantage of using interface washer is that the effective frequency range of impedance is known and can be controlled by design the specifications of interface washer as well as PZT patch. Therefore, it can be installed to many kinds of structural connection. Another benefit of using the interface washer is that the effective frequency range of impedance is relatively low, that is suitable for using wireless impedance devices.

4. Impedance Simulation for Cable-Anchor Connection Monitoring

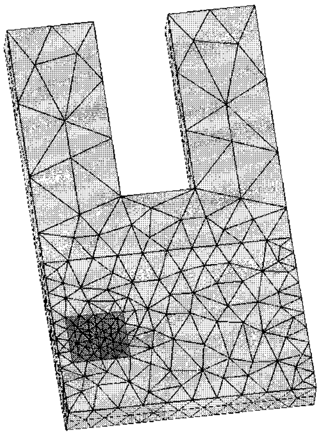
4.1. Performance Evaluation of FE Model of Interface Washer

In this study, a commercial FE software, COMSOL 3.4 [20], is used to simulate the impedance response of interface washer. This software has the capability to couple two different physical quantities, structural mechanics and electrical module, and furthermore enables to simulate the electro-mechanical impedance of a structure-piezoelectric system. In order to evaluate the performance of FE analysis, the interface washer with free boundary condition is modeled as shown in Fig. 3(a). The PZT patch is fine-meshed densely enough to capture the high order mode shapes of interface washer. The mesh is relatively loosened by two to four times for the interface washer. In the FE analysis, viscous damping is assumed for all elements. Material properties of interface washer and PZT patch assumed in this model are outlined in Table 1.

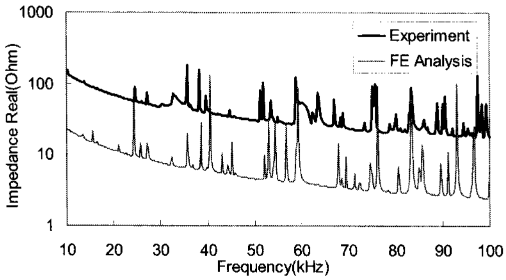
To vibrate the interface washer, a harmonic voltage of 2V is applied to the upper surface of PZT patch while the lower surface is ground. The excitation frequency is swept from 10 kHz to 100 kHz with an interval of 225 Hz. The interval frequency should be selected small enough to capture all resonance frequency in the examined frequency range. The resonance response of structure occurs when the excitation

Table 1 Material properties of interface washer and PZT patch

Quantity	Interface washer	PZT patch
Young's modulus (E)	70 GPa	-
Young's modulus (Y_{11})	-	120 GPa
Poisson's ratio (υ)	0.33	-
Mass density (ρ)	2700 kg/m^3	7750 kg/m^3
Damping loss factor (η)	0.01	0.005
Coupling piezoelectric constant (d_{31})	-	-1.71×10^{-10} m/V
Permittivity (ε_{33})	-	1.505×10^{-8} F/m
Dielectric loss factor (δ)	-	0.015



(a) FE model of interface washer



(b) Impedance signatures by FE analysis and experiment

Fig. 3 Finite element analysis of interface washer in free boundary condition Interface washer for cable-force loss monitoring

frequency is close to the natural frequency of structure. By using the interval frequency of 225 kHz, the maximum error of resonance frequency is 2.25% (i.e., 225/10,000 = 2.25%). This error could be acceptable for overall assessment of wide frequency range of 10 kHz - 100 kHz. As shown in Fig. 3(b), the electro-mechanical impedance signatures from the numerical analysis are computed and compared with the experimental results to verify the feasibility of the FE model.

As shown in Fig 3(b), the numerical impedance signatures are well matched with the experimental ones both in trends and in impedance peaks. Compared with other studies on electro-mechanical impedance simulation [10,21], the matching of resonance frequency between numerical and experimental results could be acceptable. The impedance level could be corrected by system identification(SID) for the parameters of piezoelectric material, such as PZT dimension, dielectric loss factor and bonding condition. However, SID was not considered in this study. Note that the changes in resonance frequency and in resonance magnitude are the preferred focus in impedance-based method since they are sensitive to the change in mechanical impedance of structure. The good agreement provides a confidence to utilize FE analysis of electro-mechanical impedance for more complex cable-anchor connection modeling.

4.2. Finite Element Model of Cable-Anchor Connection

To evaluate the performance of interface washer on cable force loss monitoring, an FE model of a cable-anchor connection is established. The purposes of this simulation are to examine patterns of impedance signatures due to loss of cable force and so far to establish a baseline model for real-scale cable-anchor connection.

Fig. 4 gives the schematic of cable-anchor connection for experimental setup. As shown in Fig. 4, the interface washer is installed between an anchor plate and an anchorage, and held by cable force. The force for healthy connection was set as 79.5 kN. The interface washer in this situation works like a cantilever plate. The impedance signature from the PZT patch was measured by an impedance sensor node [12] with excitation voltage of 2V. The experimental impedance signature in frequency range of 10 kHz - 100 kHz under 79.5 kN of cable force is given in Fig. 5. Compared with the impedance signatures in Fig. 3 (i.e., for the interface washer in free condition), many peaks are disappeared or damped out. Based on the impedance signature in Fig. 5, a narrower frequency range of 30 kHz - 40 kHz is selected for monitoring.

According to the experimental setup, a FE model of cable anchor connection is established as shown in Fig. 6. The FE model includes an anchor plate, an interface washer and an anchorage. Fig. 6(b) shows the side view of the FE model to give a clearer look on boundary condition. The anchor plate is fixed to the remaining part (i.e., concrete girder) which has the infinite mechanical impedance. The anchor plate and the anchorage are both made of steel with material properties as follows: Young's modulus, E = 200 GPa; mass density, ρ = 7850 kg/m^3; Poisson's ratio, υ = 0.33. Viscous damping is also assumed for the anchor plate and the anchorage with damping loss factor (η)

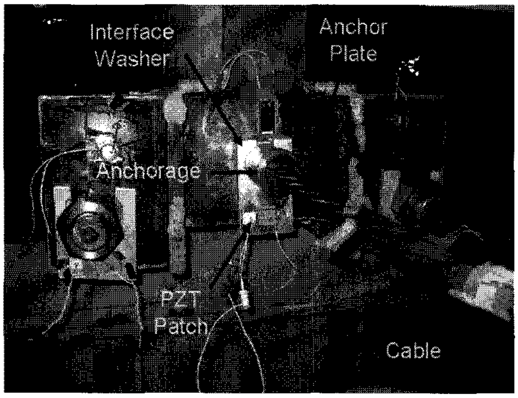


Fig. 4 Experimental setup of cable-anchor connection

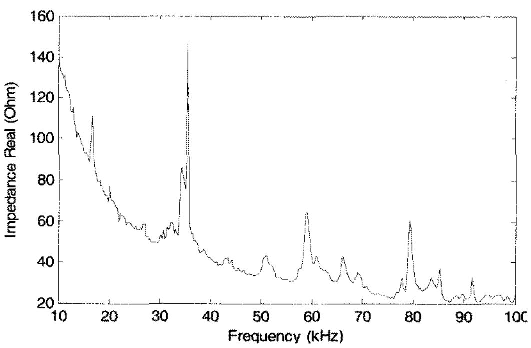
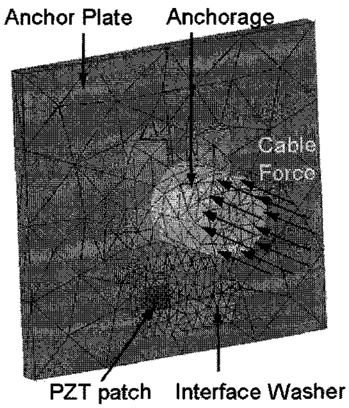
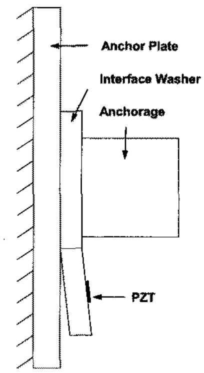


Fig. 5 Experimental impedance signature for 79.5 kN of cable force



(a) 3-D view of FE model



(b) Side view of FE model

Fig. 6 Finite element model of cable-anchor connection

Table 2 Cable force levels

Case	Cable force (kN)	Relative loss (%)
P1	79.5	0
P2	72.6	8.68
P3	66.7	16.1
P4	60.8	23.52
P5	29.4	63.02

as 0.01. The other material properties are kept as same as those in the model of interface washer with free boundary condition.

To include the effect of cable force on impedance signatures, a static force is simulated on the flat surface of anchorage as shown in Fig. 6(a). The change in cable force would lead to the changes in structure's dynamic responses, which are expected to be represented by the changes in electro-mechanical impedance. To examine the effect of cable force on electro-mechanical impedance, five cases of cable force which are ranged from 29.4 kN to 79.5 kN are applied to the FE model. Among them, the model with cable force of 79.5 kN is considered as the healthy connection, the others are in damaged condition. By considering 79.5 kN as the reference force, the relative losses of other cable forces are calculated by ratio of the relative change to the reference force. The detail cable forces and their relative losses are outlined in Table 2.

For each level of cable force, the model is first run with only static cable force (without harmonic voltage) to obtain initial values of stresses, strains, and displacements caused by cable force. After that, the model with the initial values as mentioned above is run with harmonic excitation by input voltage. The voltage of 2V is used to excite the PZT patch in the frequency range of 30 kHz - 40 kHz. Thus, the effects of both cable force and harmonic voltage are included in the model. For the higher sensitivity of the change in impedance signatures due to

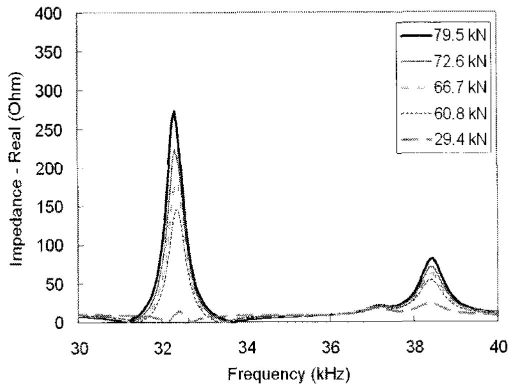


Fig. 7 Numerical impedance signatures for various cable forces

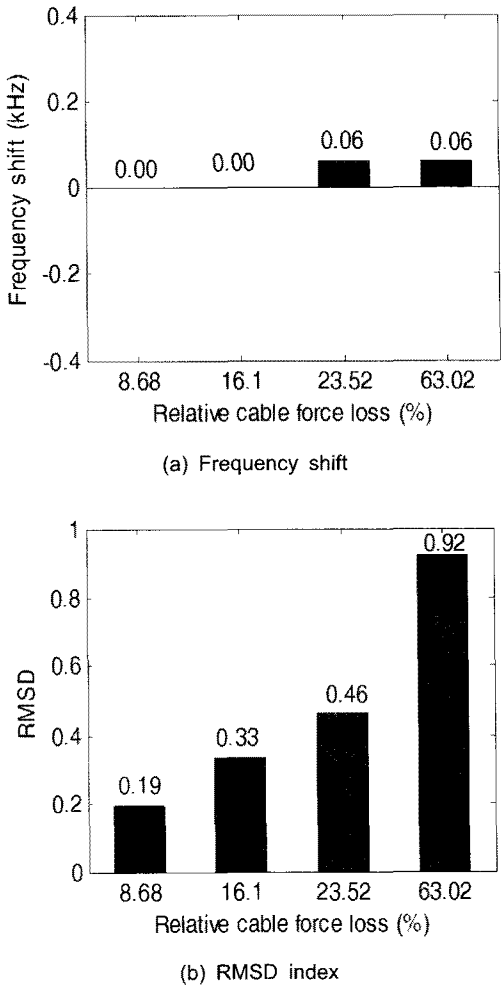


Fig. 8 Analysis results for numerical impedance signatures

the change in structural condition, the smaller interval frequency as 62.5 Hz is selected for calculating electro-mechanical impedance in frequency range of 30 kHz - 40 kHz. The minimum frequency change of 62.5 Hz in impedance signature is monitored.

Since most of mechanical impedance of structure is presented in real part of electro-mechanical impedance signatures, only changes in real parts of electro-mechanical impedance signatures are monitored. Fig. 7 shows the real part of electro-mechanical impedance signatures in frequency range from 30 kHz to 40 kHz for various cable forces. As shown in the figure, the impedance signatures obtained by FE analysis are resonant around 32 kHz and 38 kHz. By examining the impedance peaks, the magnitudes of resonances are decreased due to the loss of cable force. The frequency shift of the stronger impedance peak (around 32 kHz in frequency) is also investigated as shown in Fig. 8(a). It shows that, by FE analysis, the peak frequency is slightly increased or shifted right when cable force is reduced.

In order to examine the effect of cable force loss on electro-mechanical impedance in whole frequency range, root mean square deviation (RMSD) index which was described in eqn. (3) is employed. The values of RMSD due to the loss of cable force are shown in Fig. 8(b). As illustrated in the figure, by FE analysis, the RMSD indices of impedance increase since cable force decreases. Therefore, by using RMSD as a damage index, all cases of cable force loss can be indicated.

4.3. Effects of Material and Geometrical Properties of Interface Washer on Impedance Response

For optimal design of interface washer, the effects of material and geometric parameters of interface washers, type of PZT sensor, and its location on impedance signatures should be investigated. In this study, the effects of material and geometrical properties of interface washer are considered.

4.3.1. Cable-Anchor Connection Model Using Steel Interface Washer

In the FE model above, the aluminum interface washer was used to monitor the cable-anchor connection. An FE analysis for cable-anchor connection monitoring using a steel interface washer is now established. Simplicity, material properties of the interface washer are changed as follows: Young's modulus, E = 200 GPa; Poisson's ratio, υ = 0.33; mass density, ρ = 7850 kg/m^3. The damping loss factor of steel interface washer is kept as same as that of aluminum interface washer.

Electro-mechanical impedance signatures by using the steel interface washer under five cases of cable force are then calculated as shown in Fig. 9. As observed in Fig. 9, the peak frequencies of impedance signatures by using the steel interface washer are shifted left (or decreased) compared with those by using the aluminum interface washer. That shifting could be explained by considering the ratios of Young's modulus to mass density of two kinds of material. This ratio for steel is 0.0255 which is smaller than that for aluminum, 0.0259. As a result, the resonance frequencies of impedance signatures by using the steel interface washer are smaller. By analyzing the change of impedance peak magnitudes due to cable force loss, the same pattern as using the aluminum interface washer is obtained. The peak magnitudes are reduced due to the decrease of cable force. The change in RMSD indices according to the loss of cable force are also analyzed for the steel interface washer. Fig. 10 shows a comparison of these indices when using the aluminum and steel interface washers. As shown in Fig. 10, the RMSD indices when using the steel interface washer are increased when cable force reduces. These values of RMSD are almost as same as those when using the aluminum interface washer. Hence, the sensitivity of RMSD to cable force loss almost remains unchanged by using the steel interface washer. Note that, damping loss factor of the steel interface washer was assumed as same as that of the aluminum interface washer since it is difficult to know the exact value of damping. This parameter may affect the sensitivity of impedance signatures to cable force loss and should be examined in future study.

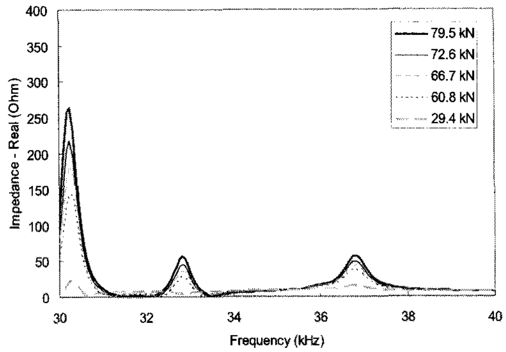


Fig. 9 Numerical impedance signatures using steel interface washer

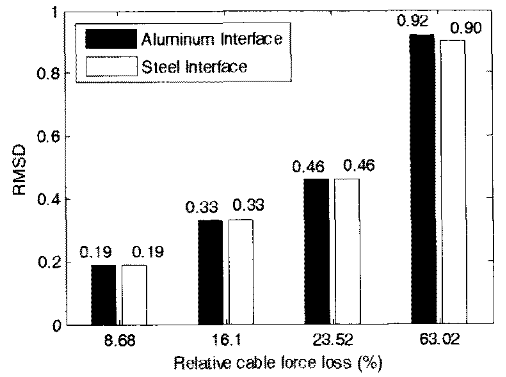


Fig. 10 Comparison of RMSD indices by using aluminum and steel interface washer

4.3.2. Cable-Anchor Connection Model Using Interface Washer with Various Thickness

To analyze the effect of geometrical properties of interface washer on electro-mechanical impedance response, five interface washers with different thicknesses as 0.6 cm, 0.8 cm, 1 cm, 1.2 cm and 1.4 cm are modeled. The material of the interface washer used in the FE model is aluminum. For each kind of the interface washer, cable-anchor connection is modeled with two levels of cable force, which are 79.5 kN and 72.6 kN. The FE model with 79.5 kN of cable force is considered as the healthy connection, the latter is in damaged condition with 8.68% loss of cable force. Because the peak frequency can shift when the thickness of interface washer changes, the wider frequency range of 25 kHz - 50 kHz is used for impedance simulation. The electro-mechanical impedance signatures for various interface washer thicknesses under 79.5 kN of cable force are shown in Fig. 11. It is found that the impedance peak is damped to lower magnitude and shifted to higher frequency when the thickness of interface washer is increased. The reduction of peak magnitude may result the decrease of sensitivity of impedance signatures to cable force change. To analyze the effect of interface washer thickness on sensitivity of impedance response, RMSD index is computed when cable force is lost. Fig. 12 shows the RMSD indices for cable-anchor connection models with different interface washers at 8.68% loss of cable force. It is observed that the RMSD indices decrease due to the increment of thickness of interface washer. This implies that the sensitivity of impedance signatures to cable force loss is reduced when the interface washer becomes thicker. This decrement can be explained by that the interface washer becomes harder to be vibrated by the PZT patch when its thickness increases. It is worth noting that, by using low sensitive interface washer in real-scale structure, changes

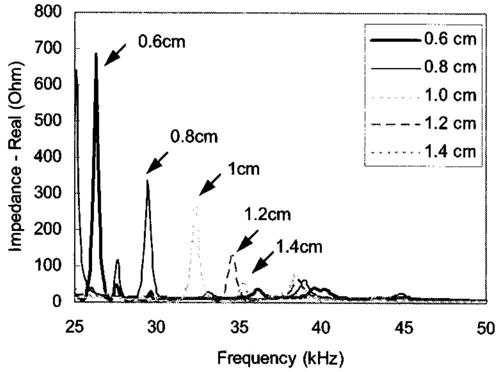


Fig. 11 Numerical impedance signatures for various thicknesses of interface washer under cable force 79.5 kN

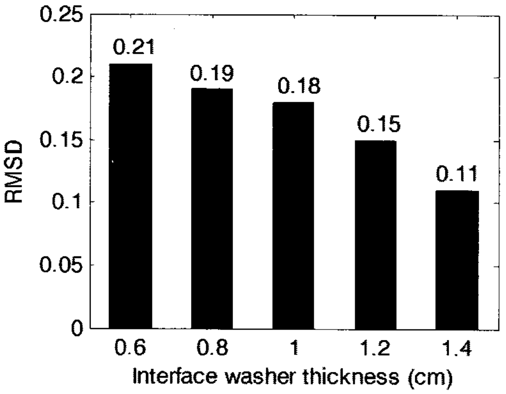


Fig. 12 RMSD indices for 8.64% loss of cable force by using interface washers with various thicknesses

in impedance signatures due to cable force loss and due to noise could not be separated. Therefore, using interface washer with thickness as small as 0.6 cm can give better results for cable-anchor connection monitoring.

5. Experimental Evaluation

To verify the feasibility of the FE analysis, an experiment on lab-scale cable-anchor connection was carried out. An aluminum interface washer with thickness of 1 cm was used to monitor the loss of cable force. The experimental setup of cable-anchor connection is shown in Fig. 4(a). In this experiment, the cable was first prestressed to 79.5 kN as the healthy condition. The cable force was then reduced to four lower levels as 72.6 kN, 66.7 kN, 60.8 kN and 29.4 kN. A wireless impedance sensor node (Park et al., 2010) was used to excite the PZT patch and measure electro-mechanical impedance. The PZT patch was excited with a harmonic voltage of 2V in frequency range of 30 kHz - 40 kHz. Fig. 13 shows the electro-mechanical impedance signatures of the cable-anchor connection for five levels of cable force. The resonance frequency is found around 35.5 kHz. This value is quite larger than the strong peak's frequency by numerical analysis (around 32 kHz). Therefore, under the cable force, the FE model needs to be updated in structural parameters such as stiffness, mass, damping. This work will be done in future study. Nevertheless, as the same pattern obtained by the numerical study, the peak magnitude of experimental impedance is reduced since cable force is decreased.

The shift of peak frequency due to the loss of cable force is also investigated as shown in Fig. 14(a). It is found that, since cable force decreases the peak of impedance signature tends to shift to lower frequency. The peak frequency is slightly decreased within the small loss of cable force, up to 23.52%, and become very large for a huge quantity of cable force loss. On the contrary, the frequency is lightly increased by the FE analysis. This could be explained by that the interaction between the interface washer and the anchor plate as well as between the interface washer and the anchorage becomes weaker when cable force decreases. Meanwhile, in the FE model, this interaction is assumed unchanged since the strength reduction in this kind of interaction could not be simulated by FE analysis. However, those shifts could be neglected for monitoring small changes of cable force by FE analysis. For examination of impedance signatures in whole frequency range,

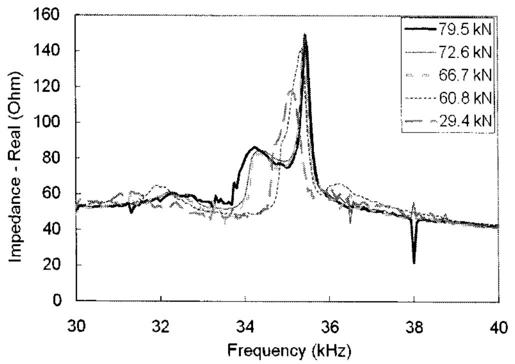
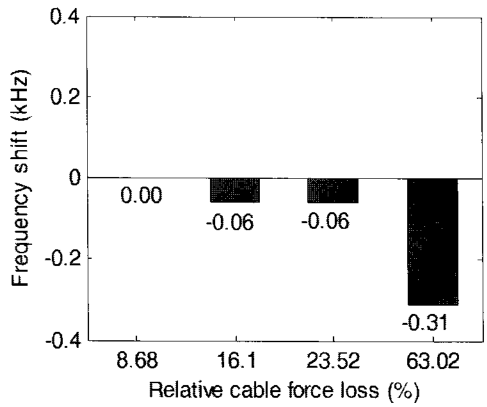
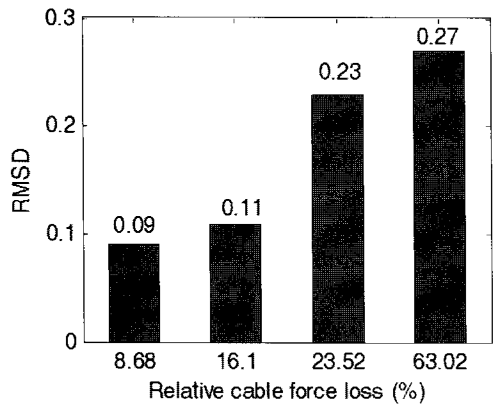


Fig. 13 Experimental impedance signatures for various cable forces



(a) Frequency shift



(b) RMSD index

Fig. 14 Analysis results for experimental impedance signatures

RMSD index is once more employed. Fig. 14(b) illustrates the RMSD indices of impedance signatures due to the loss of cable force. As shown in the figure, the RMSD indices increase since cable force is reduced. Such pattern is successfully reflected by the FE analysis.

6. Summary and Conclusion

In this study, a FE analysis of electro-mechanical impedance response in cable-anchor connection under various cable forces was presented. The following approaches were implemented to achieve the objective. Firstly, an interface washer coupled with piezoelectric material was designed for monitoring cable-force loss. Secondly, a FE model for cable-anchor connection was established to examine the effect of cable-force on impedance response of interface washer. Also, the effects of geometrical and material properties of the interface washer on impedance signatures under various cable forces were investigated. Finally, the validation of the FE analysis was experimentally evaluated by a lab-scale cable-anchor connection.

From the experiment and FE analysis, the following conclusions have been obtained. Firstly, the FE analysis of electro-mechanical impedance for the interface washer in free boundary condition was successfully established. The impedance signatures by FE analysis were well matched with experimental ones both in trend and in resonance frequencies. Secondly, the numerical impedance responses of cable-anchor connection model presented successfully the patterns of changes in impedance magnitudes and RMSD indices when cable force reduced. However, the FE analysis failed to reflect the tendency of peak frequency change since the loss of cable force increased. Thirdly, by FE analysis, the sensitivities of impedance signatures to cable force loss are similar when using steel and aluminum interface washers. However, it needs further study to determine damping loss factor of the two materials. It was also found that the sensitivity of impedance signatures to cable force loss increased since thickness of interface washer was reduced.

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