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Health monitoring of a cable-stayed bridge considering the temperature change

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ABSTRACT: Various types of structural responses including strains, displacements, and accelerations are measured from the sensors installed in a cable-stayed bridge. Abnormal health condition of the bridge is usually judged by the pre-defined control limits for each type of responses based on the design guidelines. Since the response of a cable-stayed bridge exposed to natural environments is influenced by the change in temperature, it is necessary to evaluate the abnormality or the control limits with the consideration on the change in the structural response corresponding to the change in temperature. However, such an influential action in a cable-stayed bridge may be relatively negligible compared to those in the other types of bridges so that it is also necessary to examine the relative significance of the temperature influence on the structural responses of a cable-stayed bridge. The research provides a systematic approach of considering the change in a monitored structural response corresponding to the change in temperature: including the recovery of missing data, the elimination of the influence due to temperature change, and the evaluation of health condition of the bridge using the managed data. ARX scheme has been applied to recover response data in the missing parts. The proposed approach is examined through an application to a cable-stayed bridge. The measured data from the cable-stayed bridge for more than six years are utilized for the research.

1 INTRODUCTION

As the development of technique has accelerated, modern structures are huge in size and complex in behaviors. Such structures are influenced loads with impact - earthquake and hurricane etc., environmental effects - temperature and humidity and extra loads. Because of unexpected factors, damage occurs at structure and then it is possible that structures collapse by deteriorated damage. To preventing such serious accidents, SHMS(Structural Health Monitoring System) is implemented for the structures. SHMS is a system for evaluating and managing comprehensive status of structures by monitoring consistently them in operation.

Researches for SHMS started since 1970’s and extended to BHMS(Bridge Health Monitoring System) in 1980’s. Especially researches considering environmental effects on bridges started from 2000’s. Shon *et al*.(1998) and Peeters(2000) studied temperature effects on bridges based on the change in the natural frequencies by applying regression methods. Also Serker *et al*.(2009) detected structural damage occurred by environmental and operational change, and Kullaa(2005, 2009) estimated missing data using correlation of measured data and eliminated environmental effects.

This study proposes a systematic approach to monitor structural health with 3-step analysis of dynamic characters' change occurred by damage. Existing SHMS has analyzed the data – acceleration, displacement, temperature etc. – collected from sensors installed at a bridge, and then determines damage of the bridge. However it needs more accurate data to determine damage more reliably because some parts of measured data are missing by malfunction of sensors and some parts are outlier by environmental effects. Therefore it is important to estimate the missing data and to eliminate the environmental effects. In recovering the missing data, the ARX method has been applied in the current context. In the final stage, damage is investigated through calculating the health index using the revised data. This approach is verified through the application to the field data.

2 DATA ANALYSIS CONSIDERING THE TEMPERATURE CHANGE

2.1 Recovery of missing data

Various data – acceleration, strain, displacement, temperature, etc. - was collected from sensors installed at bridge. This data is analyzed with various methods for monitoring the status of bridges but reliability of results is always not strong. Because missing data or outliers occur due to malfunction of sensors, measured data is usually incomplete. Therefore, it need recover missing data and calibrate outliers for a highly reliable result.

In this study it recovers missing data with linear relationship of measured data between natural frequencies and temperature using MISO ARX Model. It is defined by Eq.(1).

$$A(q)y(t) = B_i(q)x_i(t) + v_i(t) \quad i = 1,2,\cdots,m \tag{1}$$

where A(q) and B_i(q) are the operators defined by Eq. (2) and (3). Eq.(1) is composed of input data(x_i) of m and output data(y) where the input signal is expressed by combination of past output signals. And it is expressed using backward shift operator q^{-1} in Eqs. (2) and (3).

$$A(q) = 1 + \bar{A}(q) = 1 + a_1q^{-1} + a_2q^{-2} + \cdots + a_{n_a}q^{-n_a} \tag{2}$$

$$B_i(q) = b_{i1}q^{-n_k} + b_{i2}q^{-(n_k+1)} + \cdots + b_{in_b}q^{-(n_k+n_b-1)} \tag{3}$$

Components of data are expressed by inserting the upper Eqs. into Eq. (1) and then Eq. (4) can be obtained.

$$y(t) + \sum_{j=1}^{n_a} a_j y(t-j) = \sum_{j=1}^{n_b} b_{ij}x_i(t-n_k-j+1) + v_i(t) \tag{4}$$

The left side of Eq. (4) is composed of only Auto Regressive Output combination from past output ($y(t-n_a)$) to current output y(t). Another side is composed of combination from input ($u(t-n_k)$) with delay n_k to past input ($u(t-n_k-n_b+1)$) and white noise ($v_i(t)$) where n_a is order, n_b is B order, and n_k is system delay (Kim *et al*. 2005).

2.2 *Elimination of Environmental Effects*

Dynamic properties of bridge are more influenced by environmental and operational factors - temperature, humidity, vehicle load etc. - than local damage occurred at bridges. Especially temperature effect is the largest influential factor so that actually dynamic character isn't expressed in measured data because of temperature effect. To overcome this problem, it eliminates temperature effect on bridges using Factor Analysis (FA) method of a statistics technique. FA is a technique to reduce a dimension of data by extracting common factors and summarize information in the data. It is expressed by Eq.(5).

$$\mathrm{X} = \wedge\,\mathrm{F} + \epsilon \tag{5}$$

where $X(n\times N)$ is measured data, $F(m\times N)$ is common factor or environmental factor, $\wedge\,(n \times m)$ is factor loading matrix, $\epsilon(n\times 1)$ is unique factor or dynamic character. Eq. (5) is expressed by reducing a dimension from n to m (m<n). Eq. (5) is expressed using covariance matrix in Eq. (6).

$$\mathrm{X} = [\wedge\;\; \mathrm{I}]\begin{bmatrix}\mathrm{F}\\ \epsilon\end{bmatrix} \tag{6}$$

$\mathrm{Y} = \begin{bmatrix}\mathrm{F}\\ \epsilon\end{bmatrix}$ is defined, covariance matrix is Eq. (7). And Eq. (7) is substituted for Eq. (6), getting Eqs. (8) and (9).

$$\Sigma_{\mathrm{YY}} = \begin{bmatrix}\Sigma_{\mathrm{FF}} & \Sigma_{\mathrm{F}\epsilon}\\ \Sigma_{\epsilon\mathrm{F}} & \Sigma_{\epsilon\epsilon}\end{bmatrix} = \begin{bmatrix}\Phi & 0\\ 0 & \mathrm{D}_{\varphi}\end{bmatrix} \tag{7}$$

$$\mathrm{X} = [\wedge\;\; \mathrm{I}]\begin{bmatrix}\Phi & 0\\ 0 & \mathrm{D}_{\varphi}\end{bmatrix}\begin{bmatrix}\wedge^{\mathrm{T}}\\ \mathrm{I}\end{bmatrix} = \wedge\,\Phi\,\wedge^{\mathrm{T}} + \mathrm{D}_{\varphi} \tag{8}$$

$$\mathrm{D}_{\varphi} = \mathrm{X} - \wedge\,\Phi\,\wedge^{\mathrm{T}} \tag{9}$$

In Eq. (8) covariance matrix of measured data X is composed of only $\wedge\,\Phi\,\wedge^{\mathrm{T}}$, measured data X is composed of $\wedge\,\Phi\,\wedge^{\mathrm{T}}$ and D_{φ}. Where diagonal components of $\wedge\,\Phi\,\wedge^{\mathrm{T}}$ mean commonality of variable X, diagonal components of D_{φ} mean uniqueness. Therefore Eq. (9) means separating a dynamic properties of bridges by eliminating temperature effect.

2.3 *Estimation of Health Index*

Health Index is a numerical index of structural damage status. As many data is collected from sensors set up bridges, it is difficult to analyze this data on-line and to determine the structural status. Therefore, the health index is an useful indicator for determining the structural damage status. This study proposes Mahalanobis distance of a novelty detection technique as health index. Mahalanobis distance is a machine learning system and has a feature of fluctuating values if it has a huge different value comparison with learned contents. This index is distance from the center comprised of median values of various variables, and defined in Eq. (10).

$$\mathrm{MD} = \sqrt{(\mathrm{x}-\mathrm{m})^{\mathrm{T}}\mathrm{R}^{-1}(\mathrm{x}-\mathrm{m})} \tag{10}$$

where x is measured data that is residual data eliminating temperature effect, m is average value of x, and R is covariance matrix of x. Mahalanobis distance uses residual data and eliminates environmental effect from original measured data. Analyzing the residual data, it has to satisfy independence and homoscedasticity and adhere to normal distribution. If it dosen't satisfy them, probability of existing a outlier is more bigger. To overcome this problem, it proposes a new Mahalanobis distance with log such Eq. (11).

$$\mathrm{MD_k} = \log(\sqrt{(\mathrm{x}-\mathrm{m})^{\mathrm{T}}\mathrm{R}^{-1}(\mathrm{x}-\mathrm{m})}\,) \tag{11}$$

Calculating Mahalanobis distance, it suggests a criteria of upper and lower limit applying to control chart to determine region of criteria deciding structural health status in Eq. (12).

$$\begin{aligned} &\mathrm{CL(Center\ Line)} = \mathrm{m_{MD_k}} \\ &\mathrm{UCL(Upper\ Limit)} = \mathrm{m_{MD_k}} + \alpha\sigma_{\mathrm{MD_k}}, \quad \mathrm{LCL(Lower\ Limit)} = \mathrm{m_{MD_k}} - \alpha\sigma_{\mathrm{MD_k}} \end{aligned} \tag{12}$$

where $\mathrm{m_{MD_k}}$ is average value of Mahalanobis distance and α is usually 3. This value means 99.7% of confidence interval in standard normal distribution.

3 APPLICATION TO FIELD DATA

3.1 Measured Data Processing

The field data were measured from Seohea Grand bridge, cable-stayed bridge shown in Figure 1. The total length of the cable-stayed bridge part is 990 m (60+200+470200+60 m)(Kim *et al*. 2012). In this study, the temperature and frequency data measured for more than six years are used for verifying the proposed systematic approach considering the temperature change.

Figure 2 shows the change of frequencies data from 1st to 5th. It confirms the missing data parts. In the figure, when the value was considered outlier, the value was switched to zero and plotted.

The temperature change is drawn in Figure 3 showing that it changes from -10 ℃ to 30 ℃. And it confirms that the temperature data has missing parts and outliers, too. For analyzing these data, it regenerates missing data parts and outliers of them using the 1st order liner regression. And then it supposes that the 2-year of regenerated data is a set of reference data and the other 4-year data is considered as a set of validation data. Figure 4 presents correlation between 1st frequency data and temperature data. It confirms a linear relationship with correlation coefficient 0.71, because they have inverse proportional relationship. Actually a correlation coefficient of 0.71 means usually strong linearity.

Figure 1 View of the test bridge (Kim *et al*. 2012)

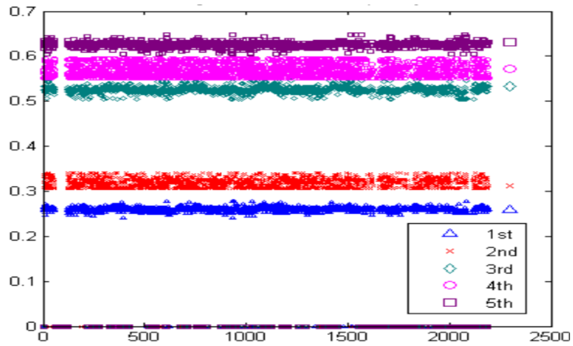

Figure 2 Variation of natural frequencies from a cable-stayed bridge for six years (Kim *et al*. 2012)

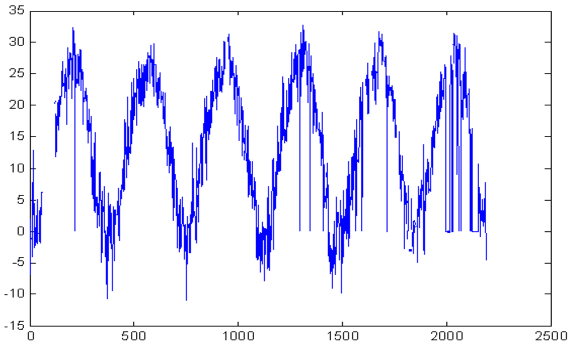

Figure 3 Temperature variation (Kim *et al*. 2012)

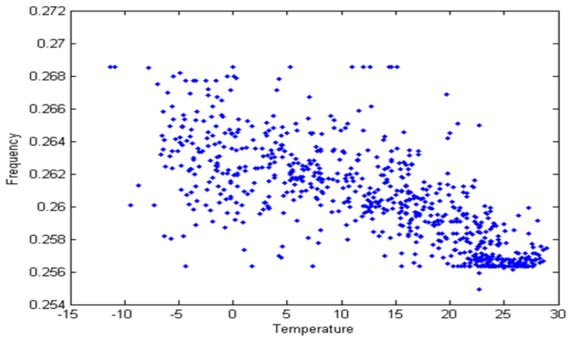

Figure 4 Correlation between natural frequency and temperature (coeff. = 0.71) (Kim *et al*. 2012)

3.2 *Recovery of Missing Data*

Using the correlated data, missing data was recovered using the ARX model. The ARX model is composed of temperature as input and frequencies as output of the reference data. And frequencies of validation data as output are estimated using temperature variables as input. Its results are shown in Figure 5. MSE of the estimation through the ARX model is 2.25E-05 between the estimated data and original measured data and the relative error is 0.9251%. In other word, numerical match rate is quite high in numerical values and the trend of data aspect. In the other modes of frequencies match rate is also quite high because MSEs are also small and the relative errors are smaller than 2%. Therefore the estimated data through the ARX model can be substituted for both of missing data and outlier data of the original measured data.

3.3 *Elimination of Environmental Effects*

The frequency data calibrated through the ARX model are applied. To extract the environmental effects, it need find out how many environmental factors exist. For this reason, eigenvalues of the correlation matrix calculated from the frequency data are shown in Figure 7, where the value larger than 1 is a single case. This factor is considered as temperature effect, eliminated through FA. The result is shown in Figure 8. The trend is almost the same as the data by extracting temperature effect from calibrated data. It can separate dynamic properties by eliminating the temperature effect from calibrated data. Then, the data is used to evaluate the health condition.

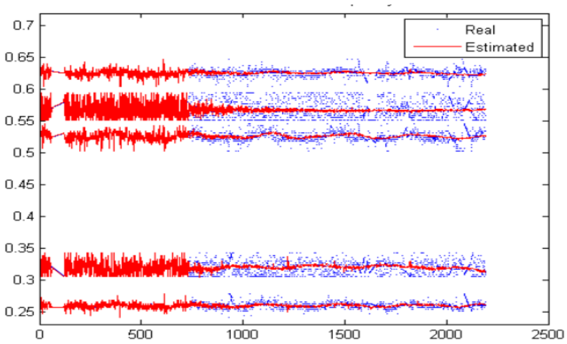

Figure 5 Estimation of natural frequency through ARX model

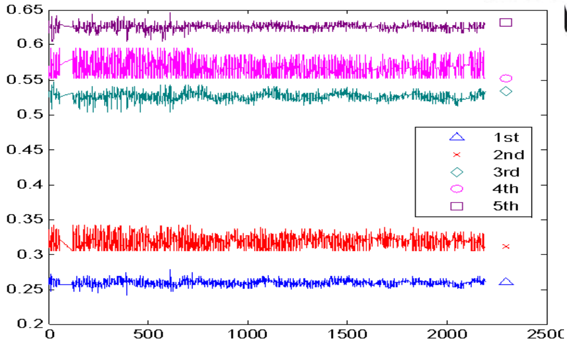

Figure 6 Data calibrated through ARX

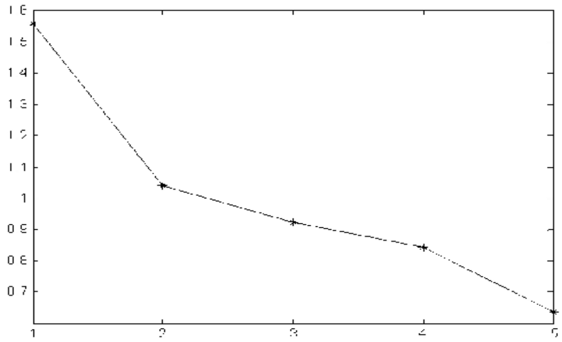

Figure 7 Eigenvalue of natural frequency correlation matrix

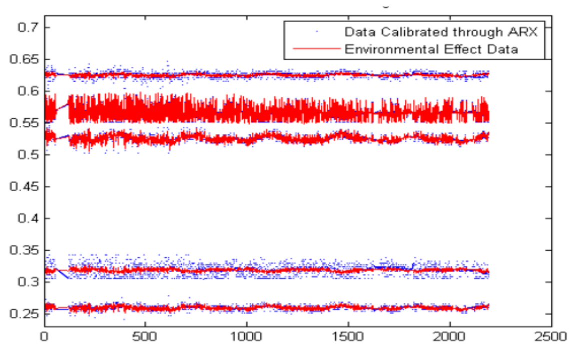

Figure 8 Comparison of environmental effect data and data calibrated through ARX

3.4 *Estimation of Health Index*

The data after eliminated temperature effect is used to estimate the health index. Mahalanobis distance is a guidance for evaluating the health of bridge. Figure 9 shows Mahalanobis distance calculated by Eq. (11). Outer lines are the upper and lower limits, solid line of the left side is the reference data and dotted line of the right side is validation data. The reference data is an intact case so that the indices for validation data demonstrate a healthy condition in overall. But some indices divagate from limits temporarily. They are outliers because an average value of health indices divagates from limit permanently if structural damage occurs (Shin *et al*. 2012).

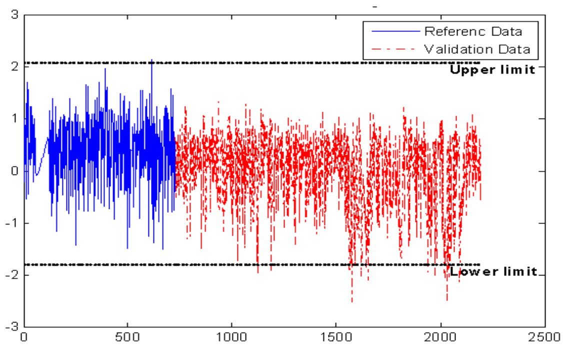

Figure 9 Mahalanobis distance

4 CONCLUSIONS

This study proposes a systematic approach of health monitoring considering temperature change with the steps of; (a) recovery of missing data, (b) elimination of temperature change in bridges, (c) evaluation of health condition using a health index. And this 3-step approach verifies its validity by applying the measured data of cable-stayed bridge for more than six years.

First of all, to recover the missing data, it applies an ARX model estimating the frequencies with the change in temperature. Its relative error is smaller than 2% compared with the original measured data. So the estimated data through the ARX model can be substituted not only for missing data but also for outlier in the original measured data.

To eliminate temperature effects on the bridge, it applied FA using the data calibrated through the ARX model. The data after extracting temperature effect is plotted in Figure 8 by comparing with the calibrated data. The trends are almost the same and thus the dynamic properties of the data could be separated by eliminating the temperature effect from calibrated data. By using this revised data, the health index was calculated as shown in Figure 9. In overall the test structure is healthy because health indices are within the limits. However, some indices can be considered as outliers divagated from the limits temporarily and need further investigation with more information.

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