Accounting for Environmental Effects during Monitoring of the Dowling Hall Footbridge

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ABSTRACT: This document provides an overview of three different studies to investigate the effects of ambient temperature on dynamic properties of the Dowling Hall Footbridge and how to account for these effects in structural identification. In the first study, different static (polynomial) and dynamic (autoregressive) models were proposed to represent the relationship between the identified natural frequencies and measured temperatures [1]. In the second study, effects of changing ambient temperatures on finite element model updating of the footbridge were investigated using the proposed models from the first study [2]. Finally, a Hierarchical Bayesian model updating framework was proposed in the third study to account for the effects of ambient temperature and excitation amplitude [3].

Test Structure and Measured Data

Dowling Hall footbridge is located at Tufts University, Medford campus. Figure 1 shows the south view of the footbridge, which is 3.9 m wide and consists of two 22 m spans. In the fall 2009, eight accelerometers and ten thermocouples were installed on the footbridge. The monitoring system records five minutes of the bridge acceleration response every hour. More information about the footbridge and its monitoring system can be found in [4].

Fig. 1 South view of Dowling Hall Footbridge

The Stochastic Subspace Identification method was used to extract the modal parameters from acceleration time histories. Overall, 8721 sets of modal parameters were identified during the period of January 2010 to March 2012 with 1824 sets corresponding to temperature below the freezing point. The effects of changing ambient temperature on natural frequencies of the footbridge were studied in [1]. It was observed that the frequencies increase drastically at temperatures below the freezing point. Figure 2 shows the identified frequencies of the first bending and the first torsional modes versus the recorded air temperatures. The observed trend can be attributed to the freeze of the moist inside concrete. The identified natural frequencies are also sensitive to the level of excitations. Figure 2 also shows the identified frequencies (recorded at temperature above 5^{oC}) versus the root-mean-square (RMS) of the signal recorded at a reference channel. The trend can be due to the reduction of effective concrete stiffness at higher excitation amplitudes.

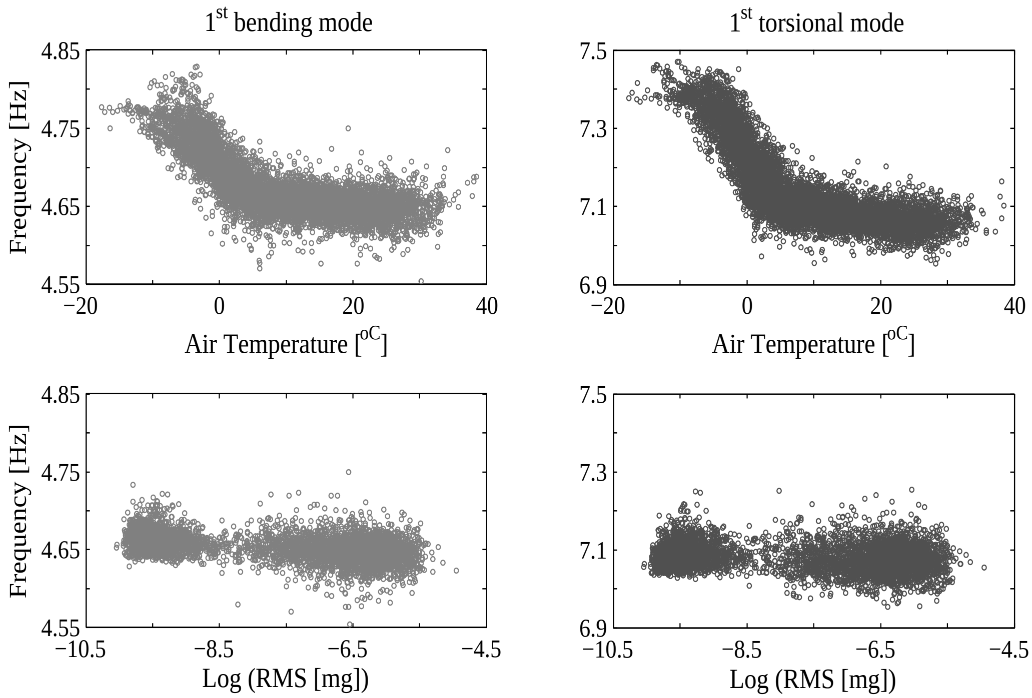

Fig. 2 Effects of ambient temperature and excitation amplitude on the identified natural frequencies

SHM Methodology and Results

The effective Young's modulus of concrete deck was updated using the available 8721 sets of data collected at the undamaged state of the footbridge. The observed variability of the identified modal parameters and therefore structural stiffness and/or mass can be due to the effects of (1) ambient temperature, (2) excitation amplitude (wind speed, traffic load), (3) pedestrians weight on the structure, (4) cable noise, and (5) estimation errors in the identification of modal parameters. The study in [3] presented a model within the Hierarchical updating framework to account for the effects of the first two items (ambient temperature and excitation amplitude). The updating structural parameter θ was defined as a modification factor for the effective Young's modulus of concrete deck, i.e., $E = \theta E_0$, where E_0 is the initial value considered as 23,763 [N/mm^2] and E is the updated value.

Three cases of model updating were performed to update the initial FE model of the footbridge using different levels of information. In the first case, only the identified modal parameters were used for model updating while in the second case, the temperature measurements were also considered. In this case, a model is proposed to represent the effects of temperature on the updating structural parameter. Finally in the third case, the identified modal parameters, temperature measurements and the excitation amplitudes (RMS of a reference channel) were used in the model updating process. The model between stiffness and temperature used in case 2 was extended to account for the excitation amplitude as well.

Figure 3 presents the estimated mean μ_θ and coefficient-of-variation $\sigma = \sigma_\theta / \mu_\theta$ of the updating parameter θ at the three information levels. The mean μ_θ is shown at different temperatures and three excitation levels, namely the minimum, average, and maximum values of RMS at the reference channel. From this figure, it can be observed that the estimated variability of concrete Young's modulus is significantly reduced when accounting for temperature effects. This variability is further reduced by another 5% (from 0.0418 to 0.0396) after accounting for the effects of the excitation amplitude.

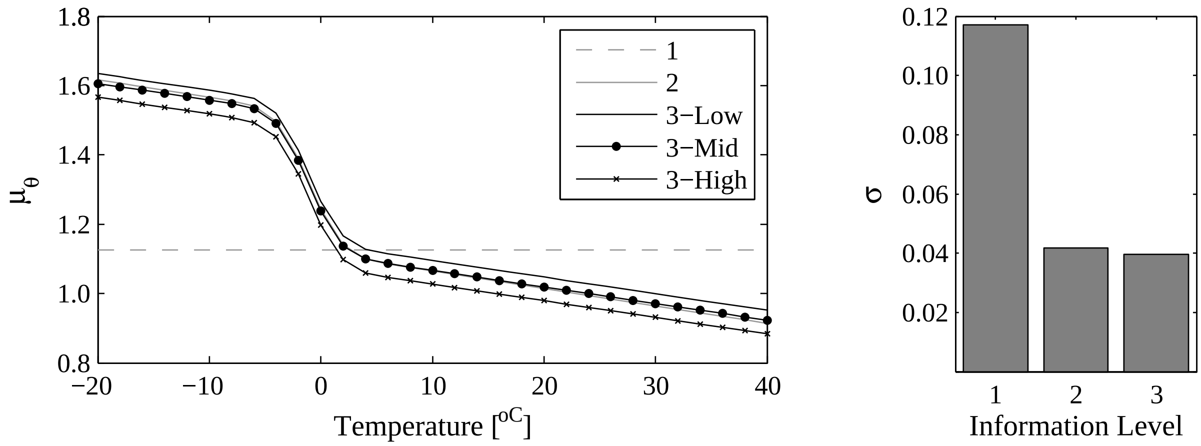

Fig. 3 Mean and coefficient-of-variation of θ estimated at different information levels

Lessons Learned

Three major sources of uncertainties in structural identification applications were discussed, namely (1) parameter estimation uncertainties, (2) inherent variability of structural parameters due to changing ambient/environmental conditions, and (3) modeling error uncertainties. In the reviewed studies, it was shown that the parameter estimation uncertainties are negligible if a sufficient number of data is available, and therefore, it can be considered as the least problematic source of uncertainty among the three mentioned sources. On the other hand, the variability of structural parameters due to changing environmental/ambient conditions can be significant. It was shown that by adding the temperature measurements and excitation amplitudes in an underlying model to explicitly consider their effects, the estimated inherent variability of the structural parameters are significantly reduced. The effects of modeling error uncertainties were highlighted for structural identification and response predictions. It was also shown that the variability of structural parameters alone cannot provide a realistic confidence interval for the predicted natural frequencies of the footbridge. However, by including the modeling error uncertainties, accurate confidence intervals were estimated for model-calculated response predictions.

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