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Effects of thermal environment on structural frequencies: Part I – A simulation study

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ABSTRACT

Vibration based structural health monitoring methods often use the changes in the modal parameters to identify damage. However, the modal parameters are not only influenced by damage but also by environmental factors including thermal and humidity conditions. The environmental effects can be large enough to mask the changes caused by damage, especially in the bridge structures that are always exposed to environmental elements. In this paper, a simulation study is conducted to examine the variations in the modal frequencies of concrete box girder and T-beam bridge structures caused by the ambient temperature, solar irradiance and wind speed, utilizing the environmental data recorded at a site in North Carolina, USA. The study includes the effects of temperature dependent material modulus, thermal gradients and prestressing effects on the modal frequencies. Like the environmental temperature variations, the bridge temperatures and model frequencies variations have strong yearly (seasonal) and diurnal trends. The study provides temperature–frequency data at hourly intervals for each bridge structure for future studies and the companion paper where, recognizing the observed seasonal and diurnal trends, the models are proposed to estimate frequencies across seasons from the measured temperature values of a bridge structure.

1. Introduction

It has been of much interest to use the changes in modal parameters such as modal frequencies, modal modeshapes and damping characteristics of a structure, for the purposes of damage detection and health monitoring. It is, however, realized that these parameters are affected not only by damage but also by environmental conditions such as changes in temperature, radiation, wind speed, and humidity surrounding the structure. The boundary conditions of the bridge structure can also be affected by environmental changes, and they are also known to strongly affect the modal parameters. Field observations [1–3] have confirmed that changes in the modal frequencies caused by the environmental factors can be significant to mask the changes in modal frequencies due to actual damage. Similar observations have been reported in the strain distributions for static loading [4,5]. The focus of this and the companion paper [6] is to study the impact of the environmental thermal variations on the structural frequencies of two typical bridge super-structures and then utilize the generated data to develop validated models for estimating the structural frequencies under different thermal environmental conditions.

The field observations such as those cited above are made for limited durations. In such observations, it is difficult to collect data for all possible thermal conditions or more importantly, collect data for different damage scenarios. Due to lack of availability of adequate data, researchers have thus utilized numerical simulations to examine the effect of different temperature and damage conditions on the vibration characteristics of structures of interest [7]. To study the problem more comprehensively, and to develop/test models for estimating frequency changes under different environmental conditions in different seasons, it is quite necessary to generate comprehensive data through a simulation study utilizing recorded field measurements and numerical approaches such as finite element analysis. In this paper, therefore, we conduct such a simulation study to investigate the effect of thermal conditions of the environment on the modal frequencies of concrete box girder and T-beam bridges. First, we briefly describe the basic steps of the thermal analysis needed to provide the temperature distribution inside the bridge body, followed by the steps to include the effects of temperature gradient and geometric stiffness on the modal frequencies. The numerical results generated with these steps are then examined to assess the impact of environmental thermal variations on the trends in frequency variations. This study

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Nomenclature

ρ	mass density
C	specific heat capacity
T	nodal temperature
T_∞	ambient temperature
r	heat generated per unit volume
k	thermal conductivity
$[M]_T$	global thermal mass matrix
$[K]_T$	global thermal conductivity matrix
$[M]$	global mass matrix
$[K]$	global stiffness matrix
$[K_\sigma]$	geometric stiffness matrix
ω	modal frequency
ϕ	modal shape
$\{Q\}$	global thermal influx at boundaries
$\{F_{tr}\}$	traction forces
$\{F_{body}\}$	body forces
σ	stress tensor, with $_{ij}$ as it components
$\epsilon,\ \epsilon_T$	mechanical and thermal strain tensor, with $_{ij}$ as it components
$\hat{U}_i$	specified boundary displacement on essential boundaries (Γ_E)
$\hat{t}_i$	specified forces on natural boundaries (Γ_E)
β	coefficient of convection
v	wind velocity
E	modulus of elasticity

provides the data needed in the companion paper [6] to develop models for estimating the system frequencies from the measured body temperature values and to evaluate their performance across different seasonal thermal regimes.

2. Environmental effects and structural frequencies: Finite element analysis

The environmental thermal variations affect the vibrations characteristics of a bridge structure due to the following reasons. First, the modulus of elasticity of concrete and asphalt used in the bridge structure are temperature-dependent [8,9]. Second, the modal characteristics are also affected by thermal pre-stress that can occur due to physical constraints or due to thermal gradients that occur in the body. This effect can be included through the consideration of the geometric-stiffness matrix [10,11]. Third, the thermal environment can also change the boundary conditions due to freezing and thawing of the supports. In this study, we primarily focus on the study of the effects of temperature dependent material properties and pre-stress effects caused by the thermal gradients within the structure, except for a brief consideration of boundary constraints.

The calculation of temperature and time dependent modal frequencies involves the following three sequential steps of (a) calculating time-dependent temperature distribution within the body and hence temperature dependent stiffness values, (b) calculating thermally induced stresses and related geometric stiffness matrix, and (c) the solution of the eigenvalue problem to obtain the modal characteristics using the stiffness matrix which includes temperature dependent modulus of elasticity property and geometric stiffness matrix. Thermal and stress analysis can be considered uncoupled as the thermal condition change at a much slower rate than the response of a vibrating bridge structure.

The temperature field within a structure exposed to outside thermal environment is governed by the following heat conduction equation:

$$\rho C \frac{\partial T}{\partial t} = \nabla \cdot (k \nabla T) + \rho r \tag{1}$$

wherein, C is the specific heat, ρ is the mass density, k is the thermal conductivity, ∇ is the gradient operator and r is the heat generated per unit volume. To solve the above equation for structures with irregular shapes and boundaries such as bridge structures, it is necessary to use a numerical approach like the finite element method. Using the standard weak form formulation with Galerkin approach, Eq. (1) can be represented in the finite element framework by the following equation:

$$[M]_T \left\{ \frac{\partial T}{\partial t} \right\} + [K]_T \{T\} = \{Q\} \tag{2}$$

where $[M]_T$ is global thermal mass matrix, $[K]_T$ global thermal conductivity matrix, $\{T\}$ the global nodal temperature vector, and $\{Q\}$ global thermal influx at the boundaries. The global matrices are assembled using the element matrices, briefly described in Appendix A.

Possible thermal boundary conditions for a bridge structure exposed to environment are: (a) essential boundary condition, which specifies the value of the ambient temperature $T_\infty(t)$ at the boundary node; (b) natural boundary conditions, which specifies the heat flux or the amount of radiation at a given surface and; (c) mixed boundary condition, which specifies the wind induced convection effects. The three boundary conditions are defined by the following equation where, β, is the coefficient of convection:

$$T_{boundary} = T_\infty(t) \quad Q_{boundary} = Q(t) \tag{3}$$
$$Q_{boundary} = \beta(T - T_\infty)$$

These boundary conditions are defined in terms of the temperature, solar irradiance and wind velocity which continuously change with time. In this study, their values measured at regular time intervals are used. Fig. 1 shows such measurements, made at 5-min intervals at a site in Elizabeth city, North Carolina, USA [12] for a period of about ten years. In the temperature and radiation records, the yearly cyclic trends are clearly visible and the Fourier analysis also showed the dominant diurnal cycles as well. The wind velocity, however, did not have any such trends. For such time-dependent

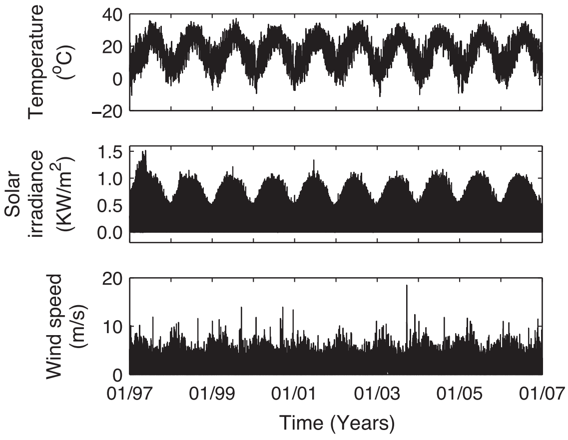

Fig. 1. Records of environmental thermal variables at Elizabeth city, NC, USA.

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