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Calibration of initial cable forces in cable-stayed bridge based on Kriging approach

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ABSTRACT

Although optimization methods are useful in the preliminary design of cable-stayed bridges for sizing of components and getting optimal bridge configurations, further fine-tuning is invariably conducted in the detailed design thus affecting various sensitive properties such as the deck profile and cable forces. The zero-displacement method that adjusts the initial cable lengths repeatedly to achieve the design deck profile is both computationally intensive and prone to convergence difficulty. Therefore a calibration method is proposed based on a Kriging surrogate model built using the uniform design approach. Apart from establishing the relationship between the bridge deck geometry and the initial cable forces by statistical method, the Kriging model also obviates the need for a large number of repeated finite element analyses. A simple cable-stayed bridge is used to verify the feasibility and accuracy of the proposed method. In real-life cable-stayed bridges with many cables, a staged calibration is implemented so that the Kriging model is used to identify reasonable initial forces in the critical stay cables so that the zero-displacement method or similar can be used for further adjustments. Verification shows that this staged calibration can address not only the deck level tolerance but also the control of cable forces.

1. Introduction

Cable-stayed bridges have become more and more popular over the past 50 years because of their desirable structural and aesthetic characteristics. With the continual development in design methodology and construction technology, cable-stayed bridges have opened up a new era of long-span structures with spans over 1000 m, in which suspension bridges have been predominant until recently. Since the 1990s, a few notable long-span cable-stayed bridges have also been built in Hong Kong, including the Kap Shui Mun Bridge, Ting Kau Bridge and Stonecutters Bridge, to meet various transportation needs.

The finite element method is extensively employed to analyse the behaviour of sophisticated structures under dynamic excitations such as earthquake, wind and vehicular loading [1,2]. However, in the development of finite element models, various simplifying assumptions are normally made because of the complexity of the actual structures. In the determination of the dynamic and static responses, it is inevitable to have discrepancies between the predictions by the structural model and their corresponding measured values. Therefore the initial finite element model needs to be properly calibrated so that the discrepancies between theoretical predictions and field measurements are brought within certain acceptable tolerances for monitoring and condition assessment purposes. A cable-stayed bridge typically comprises the deck, the towers and the cables. As the cables are effectively the only structural components that allow site control, it is essential to study the distribution of cable forces and their effects on the subsequent bridge behaviour. In view of this, the development of a finite element model by suitably adjusting the initial cable forces is an important milestone to provide a reference for more accurate analyses afterwards. Although adjustments of cable forces affect the geometry of not only the deck but also the towers, the vertical profile of the deck in particular is often accorded more importance in the calibration process while the geometry of the towers is often controlled by the horizontal displacements at the top. In the calibration process, the number of control points is meticulously chosen to avoid having an over-constrained optimization problem that brings along not only tedious computations but also lack of solution in many cases.

Deck profile calibration can be carried out iteratively by systematically updating a set of initial cable forces in each cycle until certain criteria are satisfied by the final set of cable forces. Based on the criteria or approach employed, the method of deck profile calibration can be categorized into several groups. In the extensively used zero-displacement method [3], satisfactory deck profile under permanent loading is obtained by adjusting the

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initial cable forces to give zero-displacements especially at the cable anchorages. In the optimization method [4,5], the initial cable forces are adjusted based on certain objective functions from the perspective of efficiency or economy such as optimizing shapes of post-tensioning functions using the B-spline curves [6], maximum stresses in constraints and minimum stresses in stays [7], and optimizing the cable sections based on the load combinations [8]. The force equilibrium method [9] can easily account for the effect of prestressing and the additional bending moments due to the vertical profile of bridge deck, and therefore it can also address concerns of the long-term time-dependent behaviour. The unit force method [10] takes into account all relevant effects in the design of cable-stayed bridges, including construction sequence, second-order behaviour, large displacements, sag effect as well as time-dependent factors.

Although various optimization methods are most useful in the preliminary design stage for sizing of components and getting an optimal bridge configuration, further fine-tuning is invariably carried out during the detailed design stage to make it practical for actual erection. For example, steel plates are manufactured to have certain standard thicknesses, stay cables consist of a number of strands of standard sizes, reinforcing bars have certain standard sizes, and the variations of deck section is often in steps rather than being continuous. The stiffness and mass will be slightly varied. While the final design after adjustments is still reasonably close to the optimum, various sensitive properties such as the deck profile and cable forces are often affected, thus requiring further calibration. Therefore, whether or not the design of a cable-stayed bridge has gone through the optimization process, subsequent calibration is indispensable for accurate structural analysis of service behaviour and long-term monitoring.

In view of the complexity of real-life cable-stayed bridges, cable force calibration is often achieved by iteration using various commercial finite element packages with programming facilities [11] that allow optimization to be carried out under various constraints considered appropriate. After specifying a set of initial cable forces by approximate equilibrium conditions or certain assumed initial cable strains or stresses, structural analysis is conducted. The redistributed cable forces under permanent loading are extracted and the criteria for iteration are checked. If the deviations are considered unacceptable, the cable strains are modified, and then the optimization process is repeated until the specified tolerance is satisfied. Continuing in this manner, it is theoretically possible to arrive at a set of admissible cable forces eventually. However modern cable-stayed bridges tend to have many closely spaced small-size cables to facilitate erection rather than just a few large-size cables. As these cable-stayed bridges are invariably structures with high degrees of statical indeterminacy and the interaction among cables is not easily predictable, the determination of suitable initial values of cable forces is often a critical step for the subsequent optimization. Actually, an algorithm may fail to converge if there are too many specified objective functions or if the tolerances are made too stringent. Moreover, finite element analysis is carried out repeatedly in the iterative process, thereby substantially increasing the amount of computation required and reducing its efficiency. It is therefore desirable to develop an efficient and practical method for the calibration process.

2. Use of surrogate models in sophisticated engineering problems

In many fields of engineering, the surrogate model or meta-model has been promoted as a promising method for finite element model updating [12–16] and damage identification [17]. In essence, the surrogate model examines various design variables and their responses in order to identify the design variables that give the best response. Using this, the original sophisticated finite element model can be replaced by a simplified surrogate model constructed by statistical approximation [16]. The surrogate model, which can be constructed after determining the relationship between the variables and the responses using design points [13], has the advantages of high efficiency, easy implementation and adequate accuracy. In the simplest surrogate model, the unknown function of interest is approximated by a polynomial with the random errors assumed to be normally distributed with zero mean, independent and identically distributed. Many alternative surrogate models are available, including the response surface method, Gaussian process meta-model, Kriging model, etc.

To address the drawbacks of various available methods for deck profile calibration, an efficient Kriging surrogate model is proposed to calibrate the initial cable forces. Compared with the conventional response surface method that requires an understanding of the qualitative tendency of the entire design space, the Kriging model [18] provides better flexibility of modelling response data with multiple local extreme values. Having originated from geographical space statistics, the Kriging algorithm is a data interpolation scheme to predict unknown values from data at known locations and it is a virtually unbiased minimum variance estimation model [19]. The local estimation characteristics of the model can predict the function value distribution satisfactorily by means of a correlation function. With the development of the Kriging toolbox based on Matlab-DACE [20], the Kriging model has been extensively applied in several computer response models based on approximate simulation [21–24]. This is particularly useful in the application to "computer experiments" such that the sets of input and response are highly dimensional. For example, in the practical application to the design of an aerospike nozzle, only the constant "global" Kriging model has been shown to be more accurate than the conventional response surface models [25]. As the Kriging model is much better at prediction capability than many other fitting methods and it can greatly reduce the computation time, it is extensively applied in the reliability analysis [26].

The complicated relationship between the geometry of the bridge deck and the initial cable forces of a cable-stayed bridge can be obtained by establishing a Kriging model using statistical methodology. Updating can be carried out with the established Kriging model by minimizing the residuals between the displacements of the deck at the control points and the objective values. For those bridges with a large number of cables, the surrogate model can be used efficiently together with the traditional method. In the present study, a cable-stayed bridge with a moderate number of cables is studied first. A reasonable number of design points are identified using uniform design to ensure adequate accuracy of the relationship between the cable forces and deck displacements. The outputs at these design points calculated by the finite element model are taken as the real responses of the bridge for this numerical study. In practice, bridge loading tests can be carried out to measure the displacements and other responses of interest. The quality of the Kriging model constructed is mainly assessed based on the accuracy of predictions. The uncertainties of the identified initial cable forces due to modelling errors and measurement noise can be quantified separately by the analysis of variance [27,28] so that a full factorial design of experiments can be applied to the corresponding factors. In addition, the method is also applied to a long-span cable-stayed bridge in Hong Kong for verification of its applicability to real cases.

3. Calibration of initial cable forces by Kriging surrogate model

The construction of the Kriging model for calibration of initial cable forces consists of several steps as elaborated below.