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Measurement of rivulet movement on inclined cables during rain–wind induced vibration

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ABSTRACT

The large amplitude vibration of stay cables has been observed in several cable-stayed bridges under the simultaneous occurrence of rain and wind, which is called rain–wind induced vibration (RWIV). During RWIV, the upper rivulet oscillating circumferentially on the inclined cable surface is widely considered to have an important role in this phenomenon. However, the small size of rivulets and high sensitivity to wind flow make the measurement of the rivulet movement challenging. This study proposes a digital image processing method to measure the rivulet movement in wind tunnel tests. RWIV of a cable model was excited during the test and a digital video camera was used to record the video clips of the rivulets, from which the time history of the rivulet movement along the entire cable is identified through image processing. The oscillation amplitude, equilibrium position, and dominant frequency of the upper rivulet are investigated. Results demonstrated that the proposed non-contact, non-intrusive measurement method is cost-effective and has good resolution in measuring the rivulet vibration. Finally the rivulet vibration characteristics were also studied when the cable was fixed. Comparison demonstrates the relation between the upper rivulet and cable vibration.

1. Introduction

Stay cables may experience large vibration under support movements [1,2] or rain and wind loadings [3]. Vibration of stay cables in some cable-stayed bridges have been observed under the simultaneous occurrence of rain and wind, which is referred to as rain–wind induced vibration (RWIV). Such a large amplitude vibration may cause severe damage, such as the reduction of the cable's life, destruction of the connections, breakdown of the protection [3], and damage of the dampers [4]. Extensive research have been conducted to reveal the excitation mechanisms of RWIV through field measurements [5–8], wind tunnel tests [3,9–15], and numerical analysis [16–21]. Most of researchers believe that the upper rivulet located on inclined cable surface plays the most important role in this kind of phenomenon. However, the excitation mechanisms of RWIV are still not fully understood given the limited information of the rivulet. The rivulet has become a crucial factor in understanding the RWIV of cables.

Several researchers have investigated the rivulet on cables theoretically and numerically during past decades. For the first time, Lemaitre et al. [22,23] proposed a lubrication theory-based numerical model to simulate the evolution of a water film around a cylinder under the action of wind. Taylor and Robertson [24,25] developed a computational approach combining the discrete vortex method and lubrication theory to calculate the evolution and growth of rivulets on the cable surface when the cable with water film on surface is blown by wind. Bi et al. [26] derived 2D coupled equations of water film evolution, for the first time, by combining the lubrication theory and single-mode system vibration theory. The water film evolution, lift force and cable vibration were numerically investigated by solving the coupled equations.

However, directly measuring the rivulet in field or laboratory is very difficult and challenging because the rivulet is small, thin, and sensitive to wind flow. To date, no measurement of rivulet has been conducted on-site and only few have been reported in wind tunnel tests. For example, Cosentino et al. [12,13] measured the thickness of the upper rivulet ranging from 0.2 to 0.5 mm by using eight pairs of wires. Li et al. [14] employed an ultrasonic technique to investigate the shape, thickness, position, and movement of rivulets on an inclined cable model in a wind tunnel test. The thickness and mean width of the water rivulet were measured as approximately

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0.5 mm and 7.96 mm, respectively. The lower rivulet was more or less fixed, whereas the upper rivulet oscillated around the circumferential direction of the cable at the same frequency of the cable model.

In the study of Cosentino et al. [12], however, the wires on the surface could affect the formation and movement of the upper rivulet. As such, non-intrusive measurement technique could provide more reliable information. In the study of Li et al. [14], the material of the surface of the cable model differed from that of the real stay cable. Therefore the measured rivulets might differ from that formed on real cables as rivulets are very sensitive to the cable surface. In addition, the above two experiments measured the rivulet at a fixed section of the cable only. Distribution of the rivulet along the entire cable was not available.

Under the circumstance, the non-contact digital image processing technique has potential to avoid the aforementioned disadvantages. The technique has advantages of the non-intrusion, non-destruction, multi-point measurement, high resolution, and cost-effectiveness. For these reasons, it has been applied to displacement measurement of civil structures. For example, Lee and Shinozuka [27] developed the method to measure the dynamic displacement of a flexible bridge. Pankanin et al. [28] applied it to quantitatively determine the geometric parameters of the Karman vortex street. Zhou et al. [29] used it to measure the cable vibration of a real cable-stayed bridge. Choi et al. [30] demonstrated the precision and cost-effectiveness of the digital image processing method in measuring structural dynamic displacement.

In this paper, the digital image processing method is developed and applied to measure the position of the rivulet on real cable models. The large RWIV of the model was reproduced in a wind tunnel. Water rivulets were simulated by colored water. The movement of the upper rivulet on the cable model was recorded using a digital video camera. Through digital image processing, the time history of the upper rivulet vibration along the entire cable was obtained. During this test, the movement of the rivulet was not disturbed. Finally, the characteristics of the rivulet movement during RWIV were investigated. The results will help elucidate the excitation mechanism of RWIV of cables.

2. Methodologies

In this study, RWIVs are simulated in a wind tunnel. The water rivulets were simulated by real water, colored either in red or blue. Black marks were drawn on the cable surface as reference. These enable the rivulet more distinguishable from the cable. During the test, a digital video camera was installed at one end of the cable model and moved together with the cable (see Fig. 8b). When the RWIV of the cable occurred, the rivulet moved in the circumferential direction relative to the cable, which was recorded by the camera. The video clips will then be processed via three steps, namely, image pre-processing, rivulet identification, and rivulet locating, to obtain the rivulet movement on the cable.

2.1. Image pre-processing

The recorded video clip is first converted into a series of images. The video camera used in this test captures 25 frames per second and each frame has 720 (height) × 1280 (width) pixels. The frames of the video clip are converted into a series of RGB images. RGB refers to the three hues of light (red, green, and blue) of each pixel, which arrange from 0 to 255 and can form any color by mixing together. For example, three intensities of 255 create the white color and three zeros present the black. The kth image can be represented as a three-dimensional matrix I^k with the size of

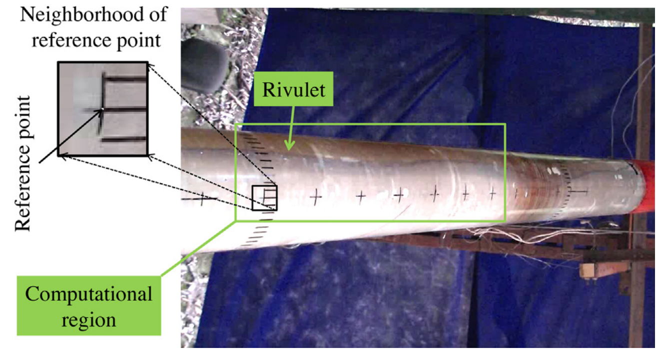

Fig. 1. An original image from the video clip.

720 × 1280 × 3, which corresponds to the three RGB intensities of each pixel. These images are named as raw images.

The raw images contain a big region irrelevant to the cable (see Fig. 1). They are then cropped such that only the key area including the cable with rivulet remains. Consequently, the computational region in each image is reduced. To make sure the cable model located at the same position in all cropped images, one particular crossing point on the cable surface is chosen as the reference point in all images (see Fig. 1). Its position in image k (or I^k) is set as (r_k, c_k), where r_k and c_k denote row and column numbers of the reference point, respectively. The reference point is identified by examining the neighborhood of the point, which is a 51 × 51 pixels square in this study (see Fig. 1). In the first original image, the position of the reference point (r_1, c_1) is defined by the user. The neighborhood is determined such that its center is located at (r_1, c_1). The RGB of the neighborhood, denoted as R^1, is a three-dimensional matrix of 51 × 51 × 3. In the subsequent image, for example I^k, a 51 × 51 pixels square marching R^1 best is found and its center (r_k, c_k) is the reference point of I^k. That is,

$$(r_k, c_k) = \{(r, c)|\min(|R^k - R^1|)\} \quad (1)$$

where

$$R^1 = I^1(r_1, c_1)_{51\times51\times3} \quad (2)$$

$$R^k = I^k(r, c)_{51\times51\times3} \quad (3)$$

R^1 is the RGB matrix of the neighborhood of the reference point in I^1 with the central point at (r_1, c_1), and R^k is the RGB matrix of a 51 × 51 pixels square in I^k with the central point at (r, c). When $|R^k - R^1|$ reaches the minimum, the central point of R^k (r_k, c_k) will be identified as the reference point of I^k.

After the reference point is identified, the identical computational region is determined in all images. In this study, the computational region is a 170 (height) × 650 (width) pixels rectangle. The reference points in all cropped images are located at (150, 50). The origin (1, 1) is located at the upper-left corner of the image.

Subsequently, the contrast of the cropped images is enhanced with the histogram equalization method to make the rivulet more distinguishable. Finally, the cropped and enhanced RGB images are converted into a grayscale image, as shown in Fig. 2. The three intensities (R, G, and B) of each pixel in the RGB image are translated to one gray intensity in the grayscale image (gray intensity = 0.2989 × R + 0.5870 × G + 0.1140 × B). The grayscale image, hereinafter, is referred to as the objective image, which is denoted by a two-dimensional matrix with the size of 170 (row) × 650 (column). Each item in the matrix represents the gray intensity of the pixel.