Unsteady Galloping Force and Response Prediction of a Slender Prism Using a Novel Wind Tunnel Test Technique

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ABSTRACT

This paper examines a new measure of the unsteady galloping force of a slender prism using a hybrid pressure-aeroelastic test (HPAT) technique. The HPAT was performed to simultaneously observe the unsteady crosswind force and response of a test model. The observed crosswind force contains amplitude-dependent non-wind-induced aerodynamic force that was caused by the interaction between the oscillating test model and the surrounding air. The unsteady galloping force of the test model was therefore evaluated by removing the non-wind-induced aerodynamic force identified by using a forced vibration technique from the observed unsteady crosswind force. The amplitude-dependent mechanical nonlinearities (damping and stiffness) of the HPAT system were identified by using a wavelet method from a free decay response of the test model. By substituting the obtained unsteady galloping force and the mechanical nonlinearities into the governing equation of motion of the test model, the galloping responses of the test model were predicted. The results show that the galloping responses of the test model predicted by the identified unsteady galloping force are identical to the experimentally measured response, and

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the unsteady galloping force can give a better galloping prediction than a classical quasi-steady theory, indicating that both the HPAT technique and the identified unsteady galloping force were accurate and reliable. This study provides a way to address the problem that the classical quasi-steady theory is, in some cases, not applicable in galloping predictions of three-dimensional prisms.

INTRODUCTION

Galloping is characterized by a divergent-type of self-controlled aerodynamic instability, which often occurs on slender structures, such as transmission lines \cite{1, 2}, bridge pythons \cite{3}, bridge deck sections \cite{4}. Due to its destructiveness, galloping of structures has attracted much attention by engineers and researchers. The classical theory on galloping instability was proposed by Den Hatog in 1932 \cite{5} and later known as the quasi-steady analysis. In 1964, Parkinson and Smith \cite{6} refined the quasi-steady theory through a comprehensive experimental and theoretical investigation of galloping of a square prism. It was found that the galloping response of the prism predicted by the quasi-steady theory was in close agreement with that observed from an aeroelastic wind tunnel test, indicating that the quasi-steady theory was valid to predict galloping responses of structures. Since then, the quasi-steady theory has been widely utilized for galloping predictions of structures.

Despite the quasi-steady theory can well predict galloping oscillations of structures, it is not applicable in some cases. Blevins \cite{7} reported that, to use the quasi-steady theory, the galloping frequency of a structure should be at least twice smaller than the vortex shedding frequency of the structure, which suggests that in the case of combined VIV-galloping oscillations, the quasi-steady theory is no longer applicable. This particularly interesting combination of VIV and galloping is the so called ‘quenching’ effect that arises when the quasi-steady onset wind speed is lower than the VIV onset wind speed \cite{8-10}. Moreover, as illustrated in a previous study \cite{11}, the quasi-steady theory cannot predict the oscillations of structures at the second galloping region, which means the quasi-steady theory is not applicable for the region after galloping occurs. In addition, Hu et al. \cite{3, 12} pointed out that the quasi-steady theory is not applicable for backward and forward inclined prisms, which may be attribute to the effect of the axial flow and vortex shedding of the prisms. This study aims to (1) propose a HPAT technique, (2) measure the unsteady galloping force, and (3) improve the galloping prediction of the slender prism.

EXPERIMENTAL SETUPS

Test model and test rig

A slender test model with pressure tubes installed was elastically mounted on a test rig (Figure 1). The design process of the rest rig can be found in a previous
The dimensions of the test model were 50.8 mm (in depth) × 50.8 mm (in width) × 915 mm (in height) and the corresponding aspect ratio (height/width) was around 18:1.

Figure 1. The test model and test rig of the HPAT: (a) plan view of the test rig; (b) stereogram of the test rig; (c) test rig in a wind tunnel; (d) details of rotating plate and pivot.

Wind profile

The HPAT was carried out in the high wind speed section of the wind tunnel at the CLP Power Wind/Wave Tunnel Facility of the Kong University of Science and Technology. The dimensions of the high wind speed section are 3 m (in width) × 2 m (in height). Correspondingly, the blockage of the test model calculated by the dimensions of the test model and the high wind speed section was around 0.78% that was much smaller than the critical value of 5% suggesting no adverse pressure gradient occurred during wind tunnel test \[14\]. The incoming wind flow was simulated according to the terrain category II defined in the Standards Australia / Standards New Zealand \[15\] by adjusting roughness elements. The mean wind speed $U$ during the test ranged from 2.38 m/s to 16.68 m/s, and the corresponding Reynolds number $Re$ ranged from $1.2 \times 10^4$ to $8.5 \times 10^4$ taking the characteristics length of 50.8 mm into account.

Pressure and aeroelastic hybrid measurement

The test model vibrated in the crosswind direction under the action of wind. The response of the test model was observed by the laser displacement sensor (LDS) installed on the underneath side of the test rig (Figure 1). The tip response of the test model was determined by the response observed from the LDS through a proper calibration (obtain the relationship between the tip response and the LDS observed response). The sampling frequency was 500 Hz and the duration was 110 s. The
oscillating frequency \( f_s \) and mechanical damping ratio \( \xi \), of the HPAT were 7.82 Hz and 0.7\%, respectively, which were determined by a signal of free decay response using a linear identification method. In the following section, the nonlinearities of the frequency and mechanical damping ratio will be considered. The stiffness \( k_s \) was 441.7 N/m that was determined by a static calibration as reported in a previous study [16]. The sectional density \( \rho_s \) of the test model was therefore estimated as 277.65 kg/m\(^3\) by \( f_s = \frac{1}{2\pi} \sqrt{\frac{3k_s}{\rho_s D^2 H}} \), where \( D \) and \( H \) are the width and height of the test model, respectively. The Scruton number \( Sc \) that is often utilized for evaluation of galloping or VIV-galloping [17] was determined as 62.5 by \( Sc = \frac{2m_c \xi}{\rho D} \), where \( m_c \) is the sectional mass of the test model and \( m_c = \rho_s D^2 \); \( \rho \) is the density of air and \( \rho = 1.225 \) kg/m\(^3\).

The pressure measurement was synchronous with the response measurement, and the synchronization was realized by inputting a reference signal as mentioned in a previous study [18]. The pressure was sampled by using a synchronous multi-pressure sensing system (SMPSS). The sampling frequency was 500 Hz and the duration was 110 s. The reference of static pressure was selected on the upstream side of the prism at a height of 1.1 m. It should be emphasized that, in order to reduce the mass of the test model so that to get large oscillation (galloping), only the two side faces of the test model in the crosswind direction were installed with pressure tubes. There were 72 pressure taps in total distributed in 9 levels of the test model (Figure 2) and the pressure tubes connected with 6 electronic pressure scanners and 1 high-speed pressure scanning equipment. It should be noted that the effect of tube diameter (2 mm) and tube length (1.2 m) was deducted from the collected pressure data by using a validated correction program.

![Figure 2. The distribution of pressure taps of the test model (units in millimeter).](image)
ANALYTICAL SCHEMES ON UNSTEADY GALLOPING FORCE

For the test rig system (Figure 1), it has been verified in a previous study\cite{13} that the mechanical nonlinearities (nonlinear mechanical stiffness and damping) of the HPAT system should be well considered especially under large oscillations such as galloping. The governing equation of motion during galloping is expressed as Eq. (1) in terms of the mechanical nonlinearities.

\[ m\ddot{y} + [c_s(y, \dot{y}) + c_0(y, \dot{y})]\dot{y} + [k_s(y, \dot{y}) + k_0(y, \dot{y})]y = P_{se}(t) \tag{1} \]

where, \( m \) is the generalized mass of the test model, and \( m = \int_0^H \rho D^2 \phi(z) dz \). In the present study, the test model is pivoted to oscillation in crosswind and linear mode shape is considered. Therefore, \( \phi(z) = z/H \); \( c_s(y, \dot{y}) \) and \( k_s(y, \dot{y}) \) are the oscillating amplitude-dependent mechanical damping and stiffness coefficients. \( k_0(y, \dot{y}) \) and \( c_0(y, \dot{y}) \) are the non-wind induced amplitude-dependent aerodynamic stiffness and damping coefficients, which are caused by the interaction between the still air and the oscillation of the test model. \( P_{se}(t) \) is the generalized unsteady galloping force that is also known as the self-excited force.

The unsteady crosswind force is determined by integrating the observed unsteady pressure from the HPAT along the height of the test model. It is obvious that the unsteady crosswind force from the HPAT includes two main components: (1) a wind-induced aeroelastic force component, and (2) a non-wind-induced aeroelastic force component that is caused by the interaction between the oscillating test model and the surrounding air. Even though the latter component is relatively small, it has been verified to have significant effect on unsteady galloping force and cannot be neglected\cite{19}. A forced vibration technique detailed in a previous study\cite{18} is used to accurately identify the displacement-dependent parameters, \( k_0(y, \dot{y}) \) and \( c_0(y, \dot{y}) \).

The mechanical nonlinearities can be identified by using a modified Morlet wavelet transform (MMWT) method or a time domain equivalent linearization approximation method from a free decay response of the test model\cite{13, 20}.

After the unsteady galloping force, non-wind-induced aerodynamic nonlinearities, and mechanical nonlinearities are determined, Eq. (1) can be solved by using the Newmark-beta method or a step iterative method\cite{21} to predict the galloping response of the test model. The analytical scheme on the identification of unsteady galloping force and the prediction of galloping response of the test model based on the HPAT is summarized in Figure.
EXPERIMENTAL RESULTS

The non-wind-induced aerodynamic damping and aerodynamic stiffness ratios, and the mechanical nonlinearities of the test model are determined by the analytical scheme in Figure 3. The non-wind-induced nonlinearities and mechanical nonlinearities are presented in Figure 4 and Figure 5, respectively.

Figure 4. Non-wind-induced nonlinearities: (a) non-wind-induced aerodynamic damping ratio; (b) zero-wind induced aerodynamic stiffness ratio.
Figure 5. The mechanical nonlinearity of the HPAT system: (a) nonlinear mechanical frequency; (b) nonlinear mechanical damping ratio.

After the non-wind-induced forces are obtained, the unsteady galloping force of the test model can be evaluated. Taking one case (the reduced wind velocity $V_R = U / f_D = 42$) as an example, the unsteady galloping force in Figure is extracted by subtracting the non-wind-induced damping force and the non-wind-induced stiffness force from the experimentally measured crosswind force, as depicted in Figure (a) and Figure (b).

Figure 6. Unsteady force components ($V_R = 42$): (a) time-history unsteady force; (b) a short section of the time-history unsteady force.
VALIDATION OF THE IDENTIFIED UNSTEADY GALLOPING FORCE

Galloping prediction

The galloping response of the test model can be predicted by the identified unsteady galloping force following the analytical scheme depicted in Figure 7. Taking the case (the reduced wind velocity $V_R = 42$) for an example, the comparisons of the time-history galloping response predicted by the identified unsteady galloping force and that directly measured from the HPAT are presented in Figure 8. In Figure 8, both the amplitude and the phase of the time-history response predicted by the above identified unsteady galloping force are in close agreement with that directly measured from the HPAT, indicating that the HPAT technique is reliable and the identifications of the mechanical and non-wind-induced nonlinearities are accurate. Also, the identified unsteady galloping force can be utilized for galloping response predictions of the test model.
Comparison with quasi-steady theory

Comparisons of the galloping responses experimentally measured from the HPAT, the responses predicted by identified unsteady galloping force and the responses predicted by a classical quasi-steady theory are presented in Figure . In Figure 9, $U^r$ and $y^r$ are normalized wind speed and normalized response, respectively. Details about galloping prediction of the test model can be found in a previous study [3]. Figure 11 shows that the onset galloping wind speed evaluated by the quasi-steady theory is $U^r = 0.71$ that corresponds the reduced wind speed of $V_R = 28.3$. The predicted onset galloping is close to that directly measured from the HPAT. However, it is noteworthy that the galloping responses predicted by the quasi-steady theory are substantially much larger than those directly measured from the HPAT, and the trend of the predicted galloping response is much different from the experimentally measured. Figure 9 also shows that both the onset galloping wind speed and the trend of the galloping responses predicted by the identified unsteady galloping force are identical to the experimentally measured, indicating that the identified unsteady galloping force can give better galloping prediction of the test model than the classical quasi-steady theory.

![Figure 9. Comparisons of galloping responses predicted by identified unsteady galloping force and the quasi-steady force with those directly measured from the HPAT.](image)

CONCLUDING REMARKS

(1) The proposed HPAT technique that is used to measure the unsteady pressure and response of a slender was validated by comparing the galloping responses calculated by unsteady galloping force with those experimentally measured from the HPAT. It has been verified that the HPAT technique is reliable.
(2) The galloping responses of the test model calculated by the identified unsteady galloping force are identical to the experimentally measured, indicating the identified unsteady galloping force is accurate and reliable.
(3) The identified unsteady galloping force can give better galloping prediction of the test model than the classical quasi-steady theory.

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