

REAL-TIME AEROELASTIC HYBRID SIMULATION FOR SECTION MODEL TESTING

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Abstract. *Section-model testing of long-span bridges typically consists of three types of experiments: force-balance tests, spring-supported tests, and prescribed-motion tests. The spring-supported test is fundamental for identifying vortex-induced vibration (VIV) and flutter instability; however, it captures only the resulting aeroelastic motion without providing information on the underlying wind-induced forces. Conversely, the force-balance test can measure wind-induced forces with or without structural motion, but it cannot represent aeroelastic interaction between the wind and the structural response. In this study, we develop a Real-Time Aeroelastic Hybrid Simulation (RTAHS) system and its application concept using linear motors and real-time controllers. The dynamic modal properties of the bridge deck are modeled numerically, whereas the aerodynamic and aeroelastic forces are physically realized through a scaled section model in the wind tunnel. Real-time wind loads are measured using load cells installed at both ends of the model. The time-delay of the system should be overcome by introducing compensation algorithm. The removal of inertia force is also critical challenge in a low-damping modal system. The proposed RTAHS framework offers several advantages for long-span bridge aerodynamics. First, because the structural parameters are implemented in the numerical model, the experimental setup time in the wind tunnel is significantly reduced. Second, as the section model vibrates, the wind-induced forces are automatically measured in real time, providing deeper insight into aeroelastic phenomena by simultaneously capturing the deck's dynamic response and the corresponding aerodynamic forces.*

1 INTRODUCTION

Vortex-induced vibration (VIV) is a well-recognized aeroelastic phenomenon that occurs in bridge deck structures as a result of the mutual interaction between periodic vortex shedding and structural oscillation. Conventional spring-supported sectional model experiments have formed the backbone of VIV research, providing reliable estimates of lock-in onset velocities and peak vibration amplitudes [1, 2].

In most established frameworks, VIV is treated as an excitation whose frequency synchronizes with the structural natural frequency during lock-in. Prevailing aerodynamic force models often represent the vortex-induced force (VIF) as a motion-dependent contribution to system damping, expressing the force explicitly as a function of structural velocity or displacement. These formulations have proven effective in reproducing experimentally observed response envelopes.

A fundamental limitation of traditional experimental approaches is that they do not permit direct measurement of the aerodynamic force during coupled vibration. Consequently, the excitation characteristics must be inferred indirectly from recorded structural responses, which inherently restricts the ability to trace how the forcing evolves through the lock-in process. Critical attributes of the vortex-induced force—such as its instantaneous frequency content and phase relationship with structural motion—have therefore remained largely unverified through direct experimental observation under true aeroelastic conditions.

In particular, two specific aspects of VIV have not been rigorously examined: (i) whether the aerodynamic force frequency remains strictly constant and equal to the structural natural frequency throughout lock-in, and (ii) how the phase difference between aerodynamic force and structural displacement evolves as vibration amplitude develops.

To overcome these shortcomings, the present study adopts a real-time aeroelastic hybrid simulation (RTAHS) strategy. Within this framework, the aerodynamic force on the section is measured directly in a wind tunnel while the corresponding structural response is computed in real time using a numerical model and physically imposed on the test specimen via an actuator system. This closed-loop configuration maintains fluid–structure interaction while simultaneously providing access to both the aerodynamic force and structural motion records.

A rectangular cross-section with $B/D = 5$ is selected as the test geometry. This bluff-body configuration has been widely adopted as a canonical benchmark in bridge aerodynamics and permits systematic study of fundamental VIV characteristics without the geometric complexities inherent in realistic bridge sections.

The principal objective of this investigation is to trace the evolution of aerodynamic force characteristics as VIV enters and develops through the lock-in regime. Specific attention is directed to three quantities: the variation of the dominant force frequency with wind speed, the change in phase lag between force and displacement. Prescribed-motion experiments are conducted in parallel to isolate the effect of vibration amplitude on the measured force and to provide a complementary perspective on the aeroelastic behavior.

By furnishing direct experimental evidence of the evolving vortex-induced force, this study seeks to advance the physical understanding of lock-in VIV and to provide a basis for a more dynamically consistent interpretation of the phenomenon.

2 EXPERIMENTAL FRAMEWORK

2.1 Real-Time Aeroelastic Hybrid Simulation

The RTAHS framework employed in this study enables direct measurement of aerodynamic forces on a moving cross-section while preserving the coupled interaction

between the fluid and structure. The system integrates physical force acquisition in a wind tunnel with real-time numerical computation of the structural response.

The dynamic behavior of the structural subsystem is governed by the single-degree-of-freedom equation of motion:

$$m\ddot{x}(t) + c\dot{x}(t) + kx(t) = f_w(t) \quad (1)$$

where $x(t)$ is the vertical displacement of the section model and $f_w(t)$ is the instantaneous aerodynamic force measured during the simulation.

In the RTAHS setup, load cells mounted within the wind tunnel record the aerodynamic force acting on the model at each time step. The measured force is transmitted to a numerical integration routine that evaluates the structural response based on predefined inertia, damping, and stiffness parameters. The resulting displacement is then actuated on the physical model, thereby closing the feedback loop.

This arrangement allows both the aerodynamic force and structural displacement to co-evolve consistently with the governing equation of motion. Compared with conventional spring-supported test methods, in which the excitation force cannot be directly isolated during oscillation, the present configuration provides unambiguous access to the aerodynamic force under fully coupled aeroelastic conditions. A fixed integration time step of 2 ms was adopted to ensure numerical stability and accurate capture of both transient and steady-state aeroelastic behavior.

2.2 Experimental Setup

All experiments were carried out using a rigid rectangular sectional model with a cross-sectional breadth of 0.30 m and a depth of 0.06 m, yielding the target B/D ratio of 5. To facilitate vertical-mode vortex-induced vibration, the model was positioned at a small positive angle of attack of 5° relative to the oncoming flow direction, as illustrated in Figure 1. The incident flow was uniform with low turbulence intensity, ensuring well-defined vortex shedding conditions.

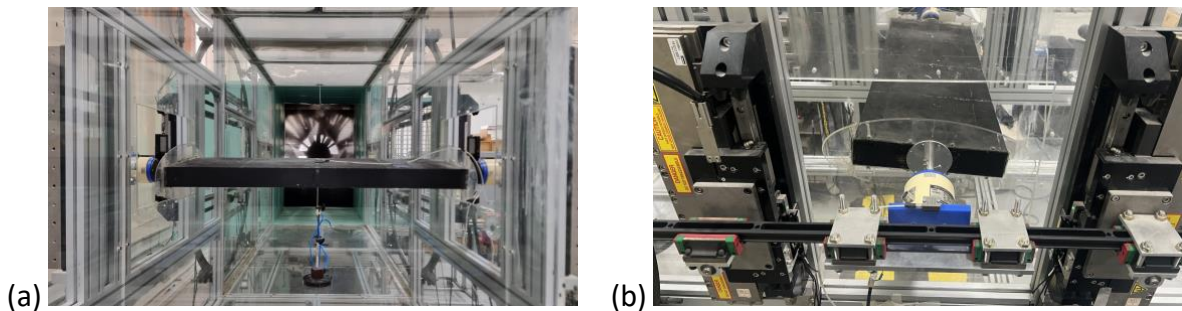


Figure 1 RTAHS experimental configuration for the B/D = 5 rectangular section
(a) front view, (b) side view

Structural parameters for the numerical model, including the natural frequency and damping ratio, were chosen to reproduce representative VIV conditions. Several damping levels were examined to assess their influence on lock-in response characteristics.

Wind velocity was varied systematically across a range spanning both pre-lock-in and lock-in conditions, enabling observation of the transition into VIV as well as the progressive development of aerodynamic force characteristics within the lock-in band.

2.3 Test Conditions

Aeroelastic tests were conducted using the RTAHS methodology, in which structural vertical motion was allowed to develop freely under the coupled simulation. The aerodynamic force and structural displacement were recorded concurrently and subsequently analyzed in both the time and frequency domains. A summary of the test parameters is provided in Table 1. The dominant frequency of the aerodynamic force at each wind speed was extracted via FFT, and the phase lag between the force and displacement signals was evaluated.

Test ID	Test method	Target mass, m (kg)	Target natural frequency, f (Hz)	Target damping ratio, ζ (%)
S1	Spring support	15	5	0.19
R1	RTAHS			0.19

Table 1 Summary of test parameters for aeroelastic and spring-supported tests

3 AERODYNAMIC FORCE CHARACTERISTICS OF THE B/D = 5 RECTANGULAR SECTION

3.1 Validation of VIV Response

Prior to examining the aerodynamic force characteristics, the fidelity of the RTAHS framework is assessed by comparing the aeroelastic response it produces with that obtained from a conventional spring-supported experiment conducted under nominally identical dynamic conditions.

Figure 2 presents the variation of vibration amplitude with wind speed for target damping ratio. The vibration amplitudes predicted by the RTAHS framework are in close agreement with those measured in the spring-supported tests, both in terms of the lock-in wind speed range and the magnitude of the peak response. The onset and termination velocities of lock-in are consistently captured by both approaches, and the maximum amplitudes are of comparable magnitude.

A well-defined lock-in regime is identified across a limited band of wind speeds, within which the amplitude rises steeply to a peak value before declining as the wind speed is further increased. The correspondence between the two methods confirms that the RTAHS framework faithfully reproduces the fundamental response characteristics of vortex-induced vibration for the present section geometry. This agreement substantiates the physical validity of the measured aerodynamic forces and justifies their use in the subsequent analyses of force frequency, phase evolution.

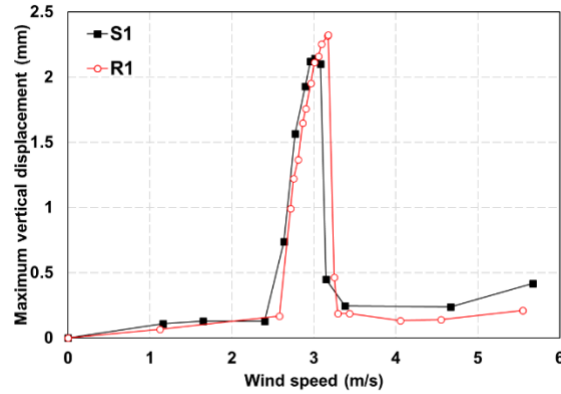


Figure 2 Comparison of vibration amplitude as a function of wind speed between RTAHS and spring-supported test results

3.2 Frequency Characteristics of Aerodynamic Force

The frequency content of the fluctuating lift force was tracked across the full range of tested wind speeds to characterize its behavior as VIV develops. The dominant aerodynamic force frequency was determined by applying an FFT to the measured lift-force signal and identifying the frequency corresponding to the maximum spectral amplitude. Figure 3 shows the variation of the dominant aerodynamic force frequency with wind speed together with the corresponding vertical displacement response. Figure 3 (b) is an enlarged view of the lock-in region shown in Figure 3 (a).

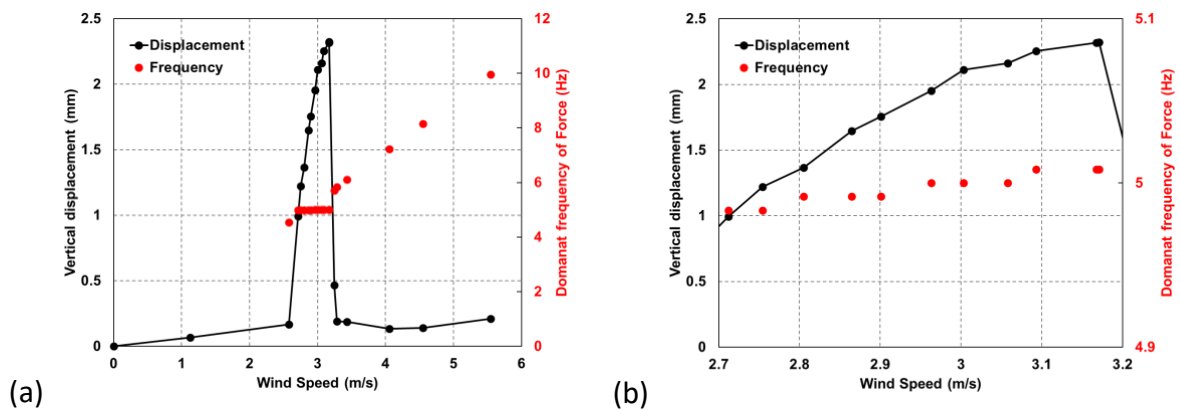


Figure 3 Variation of the dominant aerodynamic force frequency and the corresponding vertical displacement with wind speed: (a) overall wind-speed range; (b) enlarged view of the lock-in region.

Within the lock-in regime, the dominant frequency of the measured aerodynamic force maintained proximity to the structural natural frequency; however, the frequency was not strictly fixed. A continuous, gradual drift with increasing wind speed was observed throughout the lock-in band. This behavior stands in contrast to the commonly adopted simplification that the excitation frequency is held constant at the structural natural frequency during lock-in.

As wind speed increased within the lock-in range, the force frequency underwent a slight but systematic shift while remaining in the vicinity of the structural resonance. This indicates

that the aerodynamic force frequency is not locked to a single fixed value even within the lock-in regime, but instead shifts gradually with wind speed while remaining near the structural natural frequency.

3.3 Phase Characteristics of Aerodynamic Force

The evolution of the phase lag between the aerodynamic force and the structural displacement with wind speed is presented in Figure 4, together with the corresponding vibration amplitude.

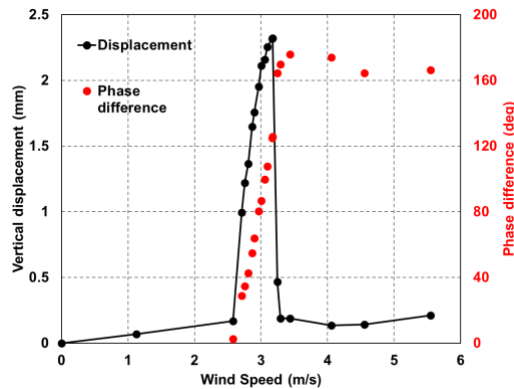


Figure 4 Phase difference between aerodynamic force and structural displacement as a function of wind speed, overlaid with vibration amplitude

As wind speed increases into the lock-in regime, the phase difference between the aerodynamic force and the structural displacement increases progressively from near-zero values and eventually exceeds 90° at peak response levels. This pattern of phase evolution closely resembles the phase characteristic observed in a classically forced single-degree-of-freedom system, where the phase lag transitions continuously from 0° to 180° as the excitation frequency passes through the natural frequency.

As shown in Section 3.2, the dominant aerodynamic force frequency does not remain fixed during lock-in but shifts gradually with wind speed while staying near the structural natural frequency. Under such a slowly varying excitation frequency, the phase difference between the forcing and the structural response is expected to evolve continuously in a manner consistent with the frequency-response function of a forced vibration system. The observed phase behavior in Figure 4 is consistent with this expectation.

On this basis, the lock-in response of the rectangular section can be interpreted as a resonance phenomenon driven by an external aerodynamic excitation whose frequency evolves continuously with wind speed, rather than representing a fundamentally distinct aeroelastic mechanism. This interpretation provides a physically consistent framework for understanding VIV within the classical theory of forced structural vibration.

4 CONCLUSION

This study investigated the aerodynamic force characteristics of a $B/D = 5$ rectangular section during vortex-induced vibration using a real-time aeroelastic hybrid simulation

framework. By directly measuring the aerodynamic force under coupled aeroelastic conditions, it was possible to examine how the force evolves throughout the lock-in regime without relying on indirect inference from structural response alone.

The results demonstrated that the dominant frequency of the aerodynamic force remains in the vicinity of the structural natural frequency during lock-in, but is not strictly fixed. A gradual and continuous shift in frequency with increasing wind speed was observed throughout the lock-in band, indicating that the synchronization between vortex shedding and structural vibration is maintained within a narrow evolving band rather than at a single invariant frequency.

The phase difference between the aerodynamic force and the structural displacement was found to increase progressively with wind speed, eventually exceeding 90° within the lock-in regime. This phase evolution closely mirrors the behavior of a classically forced single-degree-of-freedom system as the excitation frequency passes through the natural frequency. Given that the aerodynamic force frequency shifts gradually within the lock-in range, this phase behavior can be naturally explained within the framework of forced vibration theory.

Taken together, these findings suggest that lock-in VIV of the rectangular section can be interpreted as a resonance response driven by an external aerodynamic excitation with a continuously evolving frequency. This interpretation offers a physically consistent basis for understanding VIV within the classical theory of forced structural vibration, and may contribute to the development of more refined aerodynamic force models for bridge deck sections.

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