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# *Vortex-Induced Vibrations and Fluid-Structure Interaction in Bridges and Tall Buildings*

**Siqi Ding**

*Santa Margarita Catholic High School, Rancho Santa Margarita, USA*
*ethanding0902@gmail.com*

***Abstract.*** Vortex-induced vibration (VIV) is an important wind-engineering problem for flexible structures such as long-span bridges and tall buildings. It originates from unsteady separated flow and vortex shedding, but significant VIV cannot be explained solely as a periodic aerodynamic force acting near a structural natural frequency. Once structural motion becomes large enough to modify the wake, the fluid and structure interact through a two-way feedback process that can produce synchronisation, or lock-in, over a range of reduced velocities. This paper reviews the fundamental fluid mechanics of VIV, including the roles of Reynolds number, Strouhal number, reduced velocity, mass-damping parameters, structural geometry, turbulence, and three-dimensional vortex coherence. VIV is also distinguished from flutter and buffeting. The behaviour of bridge decks and tall buildings is compared, emphasising their different geometries, modal properties, wind environments, and engineering performance criteria. Finally, aerodynamic modifications, structural control systems, wind-tunnel testing, computational fluid dynamics, and coupled fluid-structure interaction simulations are discussed. The review shows that reliable VIV prediction requires consideration of both local vortex dynamics and global structural response rather than frequency matching alone.

***Keywords:*** Vortex-induced Vibration, Fluid-structure Interaction, Bridge Aerodynamics, Tall Buildings, Lock-in

## 1. Introduction

Wind-induced vibration is an important engineering problem for long-span bridges and tall buildings because modern structures are becoming increasingly long, tall, slender, and flexible. Wind does not simply produce a constant horizontal force. Instead, interaction between atmospheric flow and a structure creates time-dependent pressure distributions and aerodynamic forces. These loads can cause noticeable structural motion, increase fatigue demands, reduce occupant or user comfort, interrupt normal operation, and, in more difficult aeroelastic situations, threaten structural stability.

One important form of wind-induced motion is vortex-induced vibration (VIV). When wind flows around a bluff body such as a bridge girder or tall building, the flow may separate from the structural surface and form an unsteady wake. Vortices can then develop and shed alternately from different sides of the structure. The associated pressure fluctuations create oscillating aerodynamic

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forces. VIV has therefore become an important problem in both fluid mechanics and structural engineering, particularly for lightly damped flexible structures [1, 2].

For a stationary or weakly moving bluff body, a characteristic natural vortex-shedding frequency can often be estimated using the Strouhal relationship. However, this fixed-body frequency should not be confused with the frequency observed after strong fluid-structure coupling develops. When the structure begins to oscillate, its motion alters the relative flow, separation process, wake formation, and timing of vortex shedding. Over a finite range of wind speeds, the shedding can synchronise with structural motion. This condition is known as lock-in or synchronisation. During lock-in, the shedding frequency is influenced by structural motion and therefore does not necessarily continue to follow the fixed-body Strouhal relation linearly with wind speed [1].

For this reason, VIV is not simply ordinary resonance caused by an external force whose frequency happens to equal a structural natural frequency. The aerodynamic forcing and structural motion affect each other. Wake-induced forces drive the structure, while the moving structure changes the wake that generates those forces. The resulting response depends on reduced velocity, mass-damping properties, geometry, turbulence, aerodynamic phase relationships, and the three-dimensional coherence of the flow, as well as frequency proximity.

VIV must also be distinguished from flutter and buffeting. Flutter is a self-excited aeroelastic instability associated with motion-dependent aerodynamic forces, while buffeting is primarily a random forced response to atmospheric turbulence. In real structures, these mechanisms are not always completely isolated, and several components of the wind response may coexist. This paper therefore focuses not simply on the presence of vortices, but on the coupled feedback process that develops between the wake and structural motion.

## 2. Fundamental fluid mechanics of vortex-induced vibration

### 2.1. Flow separation, wake formation, and vortex shedding

The aerodynamic process leading to VIV begins with flow separation. As air travels around a bluff body, the boundary layer may no longer be able to remain attached to the surface. Separated shear layers then form downstream and create a wake. Under appropriate conditions, these shear layers roll into vortical structures that are released alternately from different sides of the body.

For a simple bluff body, the repeating wake pattern is often associated with a von Kármán vortex street. As each vortex forms and leaves the surface, the pressure distribution around the structure changes. Alternating vortex formation therefore produces a fluctuating cross-wind aerodynamic force. For a fixed structure, this fluctuating force is the basic aerodynamic excitation from which VIV may develop.

However, periodic vortex shedding alone does not guarantee a large structural response. The aerodynamic force must interact with a structural mode strongly enough to produce noticeable motion, and that structural motion must then become large enough to influence the flow itself. Practical bridge girders can also generate more complicated vortex systems than an ideal cylinder, including leading-edge, trailing-edge, and motion-induced vortices. This makes actual bridge VIV more complex than a simple textbook vortex street [3, 4].

### 2.2. Strouhal number and fixed-body shedding frequency

For a stationary bluff body, the characteristic vortex-shedding frequency can be described using the Strouhal number,

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$$St = \frac{f_s D}{U} \tag{1}$$

where $St$ is the Strouhal number, $f_s$ is the natural vortex-shedding frequency of the fixed body, $D$ is a characteristic dimension, and $U$ is wind speed. Rearranging gives

$$f_s = \frac{StU}{D} \tag{2}$$

This relation is useful because it connects structural scale, wind velocity, and wake frequency. If the Strouhal number remains approximately constant, the fixed-body shedding frequency increases approximately linearly with wind speed.

The limitation of this relation is especially important in VIV analysis. The Strouhal relation represents the natural shedding behaviour of a stationary or only weakly coupled body. Once structural motion becomes strong enough to modify the wake, the aerodynamic system changes. In the lock-in region, vortex shedding can adjust toward the structural oscillation frequency and remain synchronised with it over a finite range of wind speeds. The relevant distinction is therefore between the natural vortex-shedding frequency of a fixed body and the synchronised frequency of a coupled fluid-structure system [1].

### 2.3. Reynolds number and scale effects

Another important nondimensional parameter is the Reynolds number,

$$Re = \frac{UD}{\nu} \tag{3}$$

where $\nu$ is the kinematic viscosity of air. Reynolds number compares inertial and viscous effects in the flow and influences boundary-layer behaviour, separation, wake structure, aerodynamic coefficients, and sometimes the Strouhal number.

Reynolds-number effects are especially important when wind-tunnel experiments are used to represent full-scale structures. A small bridge or building model may reproduce the geometry of the real structure accurately while operating at a Reynolds number that is orders of magnitude lower. Schewe and Larsen examined a bluff bridge-deck section under model- and prototype-level Reynolds numbers and found significant changes in aerodynamic behavior [3]. This demonstrates that geometric similarity alone does not guarantee full aerodynamic similarity.

The importance of Reynolds number nevertheless depends on structural geometry. In some sharp-edged sections, separation occurs at fixed geometric locations, which can reduce Reynolds-number sensitivity over a limited range. For this reason, scale effects must be evaluated for the specific structure rather than treated as a single universal rule.

## 3. Fluid-structure interaction and lock-in

### 3.1. Reduced velocity and the development of synchronisation

Every flexible bridge or tall building has a set of natural frequencies determined by its mass, stiffness, geometry, and boundary conditions. As wind speed increases, the natural vortex-shedding frequency of a fixed body may approach one of these structural frequencies.

A particularly useful nondimensional parameter is the reduced velocity,

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$$U_r = \frac{U}{f_n D} \tag{4}$$

where $f_n$ is the structural natural frequency. Reduced velocity combines the characteristic fluid velocity, structural time scale, and structural length scale. It is therefore more useful than wind speed alone for organising VIV response.

As reduced velocity increases, the natural shedding frequency may first approach a structural frequency. The resulting aerodynamic force can increase structural motion. Once this motion becomes significant, it modifies the relative flow and changes the separation and wake process. The wake then modifies the aerodynamic force acting on the structure, completing the feedback loop.

The physical sequence can therefore be understood as flow separation producing vortex-induced force, vortex-induced force producing structural motion, structural motion changing separation and wake formation, and the modified wake producing a new aerodynamic force. Within a certain range of reduced velocity, the wake and structure can become synchronised. The structure is then in the lock-in region.

This means that lock-in is not simply a single wind speed where two uncoupled frequencies become equal. Instead, it represents a range of coupled behaviour in which the wake frequency is influenced by structural motion [1].

### 3.2. Mass ratio, damping ratio, and scruton number

Frequency proximity alone cannot predict the amplitude of VIV. Structural inertia and energy dissipation are also important.

The effect of structural mass is normally described through a mass ratio rather than absolute mass. The mass ratio compares structural inertia with an appropriate characteristic fluid mass. This is important because comparing the absolute mass of a bridge and a tall building would provide little information about their aerodynamic sensitivity.

The damping ratio, commonly represented by $\zeta$, describes how quickly vibration energy is dissipated. A structure with greater damping removes more mechanical energy during each vibration cycle, while a lightly damped structure can sustain larger responses under the same aerodynamic energy input.

Mass and damping are frequently combined into a mass-damping parameter, such as the Scruton number. Although different conventions exist, its general form is proportional to

$$Sc \propto \frac{m\zeta}{\rho D^2} \tag{5}$$

The Scruton number is particularly useful in wind engineering because it measures the combined resistance of structural inertia and damping to aerodynamic excitation. Studies of bridge VIV have shown that the Scruton number can strongly influence vibration amplitude and therefore needs to be considered when comparing experiments or full-scale structures.

Structural mass must also be considered together with fluid added mass, since the surrounding flow can effectively modify the inertia of the oscillating system. It is therefore inaccurate to state simply that a structure with lower absolute mass will always exhibit stronger VIV. The response depends on mass ratio, damping, added mass, geometry, and aerodynamic coupling together [1].

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### 3.3. Aerodynamic phase and energy transfer

Another important element of VIV is the phase relationship between aerodynamic force and structural motion. If the aerodynamic force is timed so that it performs positive net work on the structure during an oscillation cycle, energy is transferred from the flow into structural vibration and the amplitude can grow.

As the vibration amplitude changes, the wake pattern and the phase of the aerodynamic force can also change. Eventually the average energy supplied by the fluid may balance the energy removed by structural and aerodynamic damping. VIV therefore often develops into a self-limited finite-amplitude response, rather than an oscillation that increases without limit.

This energy-transfer interpretation also explains why VIV cannot be described using frequency matching alone. Forced-vibration CFD studies of bridge decks have shown that amplitude-dependent aerodynamic damping and phase relationships can be used to predict the final VIV response [5].

### 3.4. Difference between VIV, flutter, and buffeting

VIV, flutter, and buffeting all produce wind-induced structural motion, but their dominant physical mechanisms differ. VIV is primarily associated with organised wake dynamics and synchronisation between vortex shedding and structural motion. Flutter is a self-excited aeroelastic instability in which motion-dependent aerodynamic forces introduce more energy into the structure than damping can remove. Buffeting, in contrast, is mainly the forced response of a structure to turbulent fluctuations that already exist in the approaching wind.

These categories should not be treated as completely independent in real structures. A bridge can experience background buffeting while a narrow-band vortex-induced response develops, and motion-induced aerodynamic forces may alter the total damping during the same event. Engineers may therefore examine frequency spectra, force-motion phase relationships, aerodynamic damping, and amplitude dependence to determine which mechanism dominates a particular wind response.

## 4. VIV in bridges and tall buildings

### 4.1. VIV in long-span bridges

For a long-span bridge, the main aerodynamic body is normally the deck or main girder. Wind interacting with the bridge deck can excite vertical bending, lateral bending, or torsional modes depending on the geometry and structural properties.

Longer spans generally result in increased structural flexibility and lower modal frequencies, but a longer bridge is not automatically more likely to experience VIV. VIV requires the combination of wind speed, shedding characteristics, structural frequency, mass-damping properties, and geometry to enter a suitable synchronisation region.

Bridge VIV is highly sensitive to cross-sectional details. Railings, barriers, maintenance rails, fairings, guide vanes, and small changes in girder geometry can alter the separated shear layers and wake. Research on long-span bridge girders shows that practical VIV may involve several different vortex mechanisms, making the response more complicated than that of a simple bluff cylinder [4].

The engineering consequences of bridge VIV are often related to serviceability and fatigue rather than immediate structural failure. Significant vibration may cause driver or pedestrian discomfort,

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temporary traffic restrictions, and repeated cyclic stresses. The 2020 VIV event on the Humen Bridge, for example, caused a ten-day traffic closure despite not representing structural collapse [4].

### 4.2. Spanwise coherence in bridges

A bridge is not simply a two-dimensional cross-section. It can extend over hundreds or thousands of meters, meaning that aerodynamic forces may vary substantially along the span.

If the vortex-induced forces acting on different parts of the bridge are poorly correlated, their effects on a global structural mode may partially cancel. If the forces remain highly correlated over a large spanwise distance, the generalised aerodynamic force can become much larger.

This concept is referred to as spanwise coherence. It is important because a two-dimensional section model can reproduce local shedding behaviour accurately while still missing some of the three-dimensional response of the complete bridge. Studies comparing bridge section models with more complete aeroelastic models have shown that mode shape and spatial correlation can significantly alter predicted VIV amplitude.

Spanwise coherence therefore provides an important connection between local fluid physics and global structural dynamics.

### 4.3. Vortex-related response of tall buildings

Tall buildings experience wake-related phenomena but operate in a different aerodynamic environment. A tall building extends vertically through the atmospheric boundary layer, where mean wind speed, turbulence intensity, and turbulence length scale change with elevation.

Vortex shedding can generate significant across-wind motion, particularly in slender structures with low frequencies and relatively low damping. Experimental work by Kawai showed that classical vortex-induced response can occur in tall buildings even in turbulent boundary-layer flow under certain conditions [6]. Earlier research by Kwok and Melbourne also demonstrated lock-in behaviour in tall structures near critical reduced velocities [7].

However, not every across-wind vibration of a tall building should be classified as classical VIV. Real high-rise structures can simultaneously experience broadband turbulent excitation, motion-induced aerodynamic damping, torsion, higher structural modes, and coupling between along-wind and across-wind motion. The broader term aeroelastic across-wind response can therefore be more appropriate when a clearly defined narrow-band lock-in mechanism has not been demonstrated.

This distinction is particularly important when comparing tall buildings with bridge deck VIV. A bridge section often provides a relatively clear local aerodynamic body, while the building wake develops over a large vertical distance under continuously changing atmospheric conditions.

### 4.4. Vertical coherence and three-dimensional wake effects

Three-dimensional coherence is as important for tall buildings as spanwise coherence is for bridges. Different elevations of a building experience different mean velocities and turbulence conditions. Local vortex shedding can therefore have different frequencies, phases, or amplitudes along the building height.

If vortex-induced forces remain coherent over a large vertical distance, they can strongly excite a global structural sway mode. If coherence is poor, local forces may contribute much less to the total generalised force acting on the building.

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This principle also explains why tapering, setbacks, twisting, and changing cross-sections can reduce some vortex-related responses. These modifications alter the wake along the height and can reduce the ability of the vortex system to remain strongly correlated over a large portion of the structure.

### 4.5. Comparison between bridges and tall buildings

Long-span bridges and tall buildings share the same basic wake-structure feedback mechanism, but their engineering responses differ substantially. Bridge VIV is strongly controlled by the aerodynamic behaviour of the deck cross-section, angle of attack, attachments to the girder, vertical and torsional structural modes, and the coherence of aerodynamic forces along the span. Fatigue, traffic operation, and driver or pedestrian comfort are important design considerations.

Tall buildings, in contrast, experience a strong variation of atmospheric wind with height. Their major wind-sensitive modes commonly involve lateral sway and torsion, and human sensitivity to acceleration may become an important serviceability criterion even when structural strength is not threatened. Three-dimensional geometry and vertical wake coherence are therefore especially important.

The same fluid-mechanical mechanism can consequently produce different structural problems. This comparison demonstrates why VIV should be understood through the interaction of wake physics, structural dynamics, and the actual geometry of the engineering system rather than through vortex shedding alone.

## 5. Main factors affecting VIV

### 5.1. Reduced velocity

Reduced velocity is one of the most useful parameters for describing VIV because it combines wind velocity, structural frequency, and characteristic size. Strong VIV normally develops only over a particular range of reduced velocity rather than increasing continuously with wind speed.

As reduced velocity approaches a synchronisation range, the wake frequency and structural frequency can interact increasingly strongly. Structural vibration may then grow and alter the wake, leading to lock-in. Once the system leaves this synchronisation region, the VIV amplitude may decrease even though wind speed continues to increase.

This behaviour demonstrates why wind speed by itself is not sufficient to characterise VIV.

### 5.2. Reynolds number, geometry, and angle of attack

Reynolds number affects boundary-layer behaviour, separation, and wake formation. Its influence can also change the Strouhal number and aerodynamic coefficients. This is particularly important when model-scale wind-tunnel results are transferred to full-scale structures [3].

Structural geometry is equally important because it determines where and how the flow separates. For bridge decks, changes in angle of attack can significantly alter the behaviour of the upper and lower shear layers and therefore change VIV characteristics. Small external components such as barriers or railings can also modify the wake.

For tall buildings, corner geometry and building plan shape strongly influence separation and vortex formation. Rounded, chamfered, or recessed corners may weaken particular wake structures,

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although their effects depend on the specific geometry and wind direction. Aerodynamic modification should therefore not be assumed to be universally beneficial.

### 5.3. Mass-damping properties

The response of a structure to aerodynamic forcing depends strongly on its mass-damping characteristics. A lower mass ratio can allow fluid forces to have a greater influence on the motion, while higher structural damping removes more energy during each cycle.

The combined influence of mass and damping explains why parameters such as the Scruton number are widely used in wind-engineering studies. These properties must also be matched carefully in aeroelastic wind-tunnel models. A model may reproduce the geometry and wake reasonably well while still predicting an incorrect vibration amplitude if its mass or damping differs significantly from the prototype.

### 5.4. Incoming turbulence

Atmospheric turbulence can modify vortex formation and the coherence of aerodynamic loading. Turbulence may disturb an organised vortex street, but its effect is not always simply to reduce VIV. Depending on the structure, flow regime, and turbulence characteristics, it may change the lock-in region or interact with other components of the wind response.

This is especially important for tall buildings, which are exposed to atmospheric boundary-layer turbulence over their full height, and for long-span bridges in complex terrain where wind direction and turbulence can vary significantly along the span.

### 5.5. Spanwise and vertical coherence

The existence of local vortex shedding does not automatically imply a large global structural response. Aerodynamic forces must also have sufficient spatial correlation to project strongly onto a structural mode.

For bridges, this means considering spanwise coherence along the deck. For tall buildings, vertical coherence along the height becomes important. Low coherence can reduce the generalised aerodynamic force even when individual local sections show strong vortex shedding.

This distinction between local two-dimensional shedding and global three-dimensional response is one of the major challenges in transferring simplified experiments or simulations to real engineering structures.

## 6. Engineering methods for vibration control

### 6.1. Aerodynamic control of bridges

One method of reducing bridge VIV is to modify the aerodynamic behaviour of the girder. Fairings, guide vanes, spoilers, deck-edge modifications, and changes to barriers or other external components can alter the separation points, shear-layer development, vortex formation, and correlation of aerodynamic forces.

These modifications should not simply be described as "reducing excitation at its source." Their real function is to change the flow structure. A modification that reduces VIV at one angle of attack may have a different effect under another wind direction or may influence flutter and buffeting in an

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undesirable way. The performance of an aerodynamic modification therefore needs to be evaluated over a realistic range of wind conditions [4].

### 6.2. Aerodynamic control of tall buildings

Tall-building aerodynamic control applies similar principles at a larger three-dimensional scale. Rounding or chamfering building corners can change local separation, while tapering, setbacks, twisting, and openings modify the geometry along the height.

These strategies can reduce the coherence of vortex shedding and alter the distribution of fluctuating pressure forces. Wind-tunnel studies of tapered tall buildings have shown that tapering can reduce across-wind response under certain reduced velocities and damping conditions [8, 9].

However, no particular shape modification is universally optimal. Some corner modifications may suppress one form of vortex-related response while increasing aerodynamic loading under another wind direction or structural mode. Consequently, aerodynamic shaping must be tested as part of the complete wind-response design rather than treated as an automatically stabilising feature [8].

### 6.3. Passive structural control

Another way to reduce wind-induced vibration is to increase the amount of energy the structure can dissipate. One of the most common approaches is a tuned mass damper (TMD), which adds a secondary mass that is designed to move out of phase with the main structure. When the bridge or building begins to oscillate, the damper absorbs part of the vibration energy and reduces the motion of the main structure. Similar systems, such as tuned liquid dampers (TLDs), use the motion of liquid instead of a solid mass to achieve the same general effect. Other passive dampers can also be added to increase the effective damping of the structure. These systems are attractive because they do not require continuous external power, although their performance is usually best near the frequency range for which they were designed. If the structural frequency changes significantly or several modes contribute to the response, a single tuned device may become less effective.

### 6.4. Active and semi-active control

Active and semi-active control systems provide a more adjustable way to reduce vibration. Active systems use sensors to measure structural motion and actuators to apply forces that oppose the response. Semi-active systems usually do not apply large external forces directly, but instead adjust properties such as damping or stiffness in response to changing conditions. This allows the control system to adapt when wind speed or structural behavior changes. These methods can therefore perform well over a wider range of conditions than a purely passive device, but they also require more complicated sensors, control algorithms, power systems, and maintenance. Reviews of tall-building vibration control show that passive, active, semi-active, and hybrid systems can all be effective depending on the structure and the type of wind response being controlled [10]. Full-scale applications have also shown that active tuned mass dampers can noticeably increase the effective damping of important sway modes in very tall buildings [11].

### 6.5. Combining aerodynamic and structural control

Aerodynamic and structural control act at different stages of the VIV process. Aerodynamic measures change separation, wake structure, and force coherence, while structural control changes

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the response after aerodynamic energy has already entered the structure.

For this reason, the two strategies can complement one another. A bridge may use an optimised deck section together with additional damping, while a tall building may combine aerodynamic shaping with a tuned mass damper. The appropriate method depends on geometry, structural modes, wind environment, cost, and the required performance level.

## 7. Experimental and computational research methods

### 7.1. Wind-tunnel testing and similarity

Wind-tunnel testing remains one of the most important tools in bridge and building aerodynamics. Bridge section models allow researchers to study local girder flow and VIV behaviour under controlled wind speed and angle of attack, while complete aeroelastic models can represent global structural modes and three-dimensional effects.

Tall-building wind-tunnel experiments may use rigid pressure models, force-balance models, or aeroelastic models depending on whether the objective is to measure local pressure, overall loading, or structural response.

Accurate model testing requires more than geometric similarity. VIV is sensitive to reduced velocity, mass ratio, damping ratio, frequency ratios, turbulence characteristics, and, in some cases, Reynolds number. Matching all of these parameters simultaneously is difficult. This means that wind-tunnel results must be interpreted with an understanding of the limitations of model similarity rather than transferred directly to the prototype.

### 7.2. Fixed-body CFD

In fixed-body CFD, the structure remains stationary while the surrounding flow is solved numerically. This approach is useful for studying flow separation, pressure distributions, wake development, vortex shedding, lift and drag, and the effects of Reynolds number or geometric modification.

Fixed-body CFD can therefore estimate the natural shedding frequency of a stationary structure and provide detailed visualization of vortical flow structures. It is particularly useful during the early stages of aerodynamic design.

Its main limitation is that the structure cannot respond to the aerodynamic force. It therefore cannot directly reproduce the two-way feedback that produces lock-in.

### 7.3. Forced-vibration CFD

Forced-vibration CFD represents an intermediate level of coupling. Instead of keeping the body stationary, the simulation prescribes a particular structural motion, such as a sinusoidal oscillation with a specified amplitude and frequency.

The surrounding flow then responds to this imposed motion. Researchers can calculate motion-dependent aerodynamic forces, force-motion phase relationships, aerodynamic damping, energy transfer, and amplitude-dependent changes in wake structure.

Forced-vibration CFD is particularly useful for determining whether the aerodynamic force adds or removes energy from a structural mode. Wang and Chen used this approach to extract amplitude-dependent aerodynamic damping of a bridge deck and predict steady VIV amplitudes with promising agreement against free-vibration wind-tunnel results [5].

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The key limitation is that the structural motion is prescribed rather than calculated from the fluid force. The fluid responds to the structure, but the fluid does not determine the structural trajectory during the simulation.

### 7.4. Fully coupled fluid-structure interaction simulation

In a fully coupled FSI simulation, aerodynamic pressure and forces from the fluid solver are transferred to a structural model. The structural solver then calculates displacement and velocity, and this motion modifies the fluid domain before the next flow solution is performed.

This creates a numerical version of the full VIV feedback process. Fluid forces produce structural motion, structural motion changes the wake, and the modified wake produces new forces.

Fully coupled FSI is therefore the most direct numerical method for predicting synchronisation and lock-in without prescribing the response in advance. It is also much more computationally expensive and difficult to implement. Accuracy depends on fluid mesh quality, dynamic mesh treatment, structural parameters, turbulence modelling, time-step size, coupling strategy, and numerical convergence.

For large three-dimensional bridge or building models, the computational cost can become substantial. This is why simplified two-dimensional, forced-vibration, and reduced-order approaches remain important even when full FSI is theoretically more complete.

### 7.5. Full-scale monitoring

Full-scale monitoring provides information that cannot be reproduced perfectly by scaled experiments or numerical simulations. Real bridges and tall buildings can be equipped with accelerometers, anemometers, displacement sensors, pressure sensors, and structural-health-monitoring systems.

The major advantage is that the actual structure operates at its true Reynolds number, mass, damping, mode shapes, and atmospheric environment. Field measurements can reveal spanwise wind variation, turbulence, spatial coherence, and structural responses that are difficult to reproduce exactly in a laboratory.

The disadvantage is that full-scale experiments provide little control over the environment. Researchers cannot select the wind speed or turbulence condition, and significant VIV events may occur only rarely.

For this reason, the strongest understanding normally comes from combining wind-tunnel experiments, CFD or FSI simulations, and full-scale observations. Each method provides information that compensates for limitations in the others.

## 8. Conclusion

Vortex-induced vibration is fundamentally a coupled fluid-structure phenomenon, rather than simply a periodic wind load acting at a structural natural frequency. For a stationary bluff body, the Strouhal relationship provides a useful estimate of the natural vortex-shedding frequency. Once significant structural motion begins, however, the moving structure alters flow separation and wake dynamics. This feedback can cause vortex shedding to synchronize with structural motion over a finite range of reduced velocities, producing lock-in.

The resulting vibration is controlled by several interacting quantities, including reduced velocity, Reynolds number, mass ratio, damping ratio, Scruton number, structural geometry, incoming

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turbulence, aerodynamic phase, and the spatial coherence of vortex-induced forces. These parameters also explain why bridge and building VIV cannot be treated as identical problems.

Long-span bridges are particularly sensitive to deck geometry, angle of attack, vertical and torsional modes, spanwise force coherence, fatigue, and traffic serviceability. Tall buildings operate in a strongly height-dependent atmospheric boundary layer and may experience vortex-related across-wind motion together with buffeting, motion-induced aerodynamic forces, torsion, and higher-mode effects. Classical lock-in can occur in tall structures, but not every across-wind vibration should automatically be classified as VIV.

In practice, engineers usually choose between changing the airflow around the structure and changing the way the structure responds to that airflow. Aerodynamic modifications can weaken or reorganise vortex formation, while devices such as tuned mass dampers and tuned liquid dampers help dissipate the vibration energy that still reaches the structure. Neither approach works equally well under every wind direction, vibration mode, or operating condition. For this reason, the most effective designs often combine aerodynamic and structural control and then verify their performance through wind-tunnel tests, numerical simulations, or full-scale measurements.

Future research will likely focus on connecting these different methods more closely. Three-dimensional CFD and fully coupled FSI simulations can provide detailed information about wake formation, force coherence, and energy transfer, while monitoring real bridges and tall buildings can show how well those models represent actual atmospheric conditions. One of the main challenges is still the gap between simplified section models or two-dimensional simulations and the much more complicated three-dimensional behaviour of full-scale structures. As computational methods, turbulence models, and structural monitoring continue to improve, engineers should be able to predict VIV more reliably and design vibration-control systems that are better matched to the specific behaviour of each bridge or building.

## References

[1] Williamson, C. H. K., & Govardhan, R. (2004). Vortex-induced vibrations. *Annual Review of Fluid Mechanics, 36*, 413–455. https://doi.org/10.1146/annurev.fluid.36.050802.122128

[2] Zhu, H., Du, X., & Dong, H. (2025). Vortex-induced vibration of separated box girders for long-span cable-supported bridges: A review. *Structures, 71*, 107889. https://doi.org/10.1016/j.istruc.2024.107889

[3] Wang, B., Hao, S., Xu, Y.-L., Liu, Y., & Li, Y. (2023). Modelling of vortex-induced force and prediction of vortex-induced vibration of a bridge deck using the method of multiple scales. *Journal of Wind Engineering and Industrial Aerodynamics, 241*, 105533. https://doi.org/10.1016/j.jweia.2023.105533

[4] Gao, D., Deng, Z., Yang, W., & Chen, W. (2021). Review of the excitation mechanism and aerodynamic flow control of vortex-induced vibration of the main girder for long-span bridges: A vortex-dynamics approach. *Journal of Fluids and Structures, 105*, 103348. https://doi.org/10.1016/j.jfluidstructs.2021.103348

[5] Wang, Y., & Chen, X. (2022). Extraction of aerodynamic damping and prediction of vortex-induced vibration of bridge deck using CFD simulation of forced vibration. *Journal of Wind Engineering and Industrial Aerodynamics, 224*, 104982. https://doi.org/10.1016/j.jweia.2022.104982

[6] Gu, M., Su, L., Quan, Y., Huang, J., & Fu, G. (2022). Experimental study on wind-induced vibration and aerodynamic mitigation measures of a building over 800 meters. *Journal of Building Engineering, 46*, 103681. https://doi.org/10.1016/j.jobe.2021.103681

[7] Lu, W.-T., Phillips, B. M., & Jiang, Z. (2023). Effects of side and corner modification on the aerodynamic behaviour of high-rise buildings considering serviceability and survivability. *Journal of Wind Engineering and Industrial Aerodynamics, 233*, 105324. https://doi.org/10.1016/j.jweia.2023.105324

[8] Catania, M., Pomaranzi, G., & Zasso, A. (2024). The role of permeable double skin façades on the onset of VIV on high-rise buildings. *Journal of Wind Engineering and Industrial Aerodynamics, 253*, 105831. https://doi.org/10.1016/j.jweia.2024.105831

[9] Lu, W.-T., Phillips, B. M., & Jiang, Z. (2024). Aerodynamic responses of tall buildings with cross-section modification through additive- and subtractive-based strategies. *Journal of Wind Engineering and Industrial*

DOI: 10.54254/2753-8818/2026.37892

*Aerodynamics, 250*, 105762. https://doi.org/10.1016/j.jweia.2024.105762

[10] Jafari, M., & Alipour, A. (2021). Methodologies to mitigate wind-induced vibration of tall buildings: A state-of-the-art review. *Journal of Building Engineering, 33*, 101582. https://doi.org/10.1016/j.jobe.2020.101582

[11] Zhou, K., Zhang, J.-W., & Li, Q.-S. (2022). Control performance of active tuned mass damper for mitigating wind-induced vibrations of a 600-m-tall skyscraper. *Journal of Building Engineering, 45*, 103646. https://doi.org/10.1016/j.jobe.2021.103646