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REVIEW PAPER

State of the Art Review of Aerodynamic Effects on Bridges

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Abstract Nowadays, predicting aerodynamics phenomena on bridges with global climate change and enlarging span length, no doubt it isn't easy. One of the significant factors for designing long-span bridges is wind-induced vibrations (WIV). The major classifications of WIV based on wind mechanisms are Flutter, Galloping, Vortex, Buffeting, Rain & Wind, and Wake induced vibration. In the present scenario, the most challenging job is to mitigate flutter and buffeting response and eliminate vortex-galloping interaction in the aerodynamic field. This synopsis has highlighted the history, development of aerodynamic force evaluation methods, different types of failure of bridges due to divergent wind speeds, and state-of-the-art experimental and numerical methods. Furthermore, a review corresponding to the effect of aerodynamic vibration on bridges has also been addressed. Finally, this synopsis characterises the conclusions endorsed to adjust the different WIV.

Keywords Flutter · Galloping · Vortex · Buffeting · Computational fluid dynamics · Angle of attack

Introduction

The wind is the motion of air based on relative locations on the earth's surface and its energy. This perceptible natural movement in the form of velocity varies with time and space. It also depends upon the terrain and topography of the locations. The wind has an unpredictable nature. Hence, its effects are multi-directional based on the exposed surface over which it acts. Initially, its complex nature, behavior, and impact were overlooked in the research. An eye-catching development of the wind-resistant design was evolved after the Second World War. The expended economic trends and high demand for different infrastructures in the construction industry made that development. The wind-resistant design is also a vital issue for the bridges [1]. The modern concept of wind load in bridge decks is incomplete without aerodynamics, flow characteristics, fluid–structure interactions, diversified climate, structural mechanics, dynamics, and reliability [2]. Previously, 'the whole aerodynamic research world' concerning bridges was based on understanding the physics of aerodynamic force and analysis of structural responses. The elementary research factors were how this aerodynamic force acted and its devastating nature. At that time, several arsenals were the analytical, experimental, and numerical methods to complete the research. But at present, the mode of study and computational version has changed. Also, various advanced methods have been developed, such as Computational Fluid Dynamics (CFD), Field observation. Several counter measurements have already been designed to control the aerodynamic effect in this context. However, research with the typical structural and aerodynamic countermeasure approach has become inevitable. The structural countermeasure approach eliminates structural vibration, neglecting the vibration source (aerodynamic force). It also incurs extra maintenance costs. From the engineering point of view, the solutions having simplicity in construction and less cost is always given the highest priority.

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In contrast, the aerodynamic countermeasure approach is identical to eliminating the structural vibration source. Usually, the modified bridge deck shape and additional members (wind nose, deflectors, flaps, spoilers, etc.) are the weapons for remedying this aerodynamic problem. Like a structural countermeasure, each member is for specific aeroelastic issues, incurring extra maintenance costs. Therefore, one significant gap between understanding the aerodynamic problem and applying its solution is burning. The present literature upholds the details of this problem by segmentally addressing the WIV, which can enhance knowledge to any researches through a single platform.

In this paper, individual aspects of different wind mechanisms and past events of aerodynamic effect on bridges were consequently studied. Moreover, the development of aerodynamic force analysis in the present era has been intensely discussed by categorising the WIV in a different segment. Finally, the advancement in the intensification of the aerodynamic force evolution analysis is reviewed for the comparison purpose of better evolution process respect to recent time. Here, another important factor is the wind attack angle. A brief idea about its countermeasure is also evolved in this present literature.

Aerodynamic and Aeroelastic Forces

The fluid exerts aerodynamic force over an immersed body. This exertion happens mainly due to relative motion between fluid and body. In many aerodynamic (AD) problems, drag and lift forces are of interest. The perpendicular force to the flow direction is called lift, which occurs by the pressure on the body's exterior surface. The parallel force with the direction of the fluid flow is called drag. Aeroelasticity is a branch of Physics and Engineering that deals with fluid matters and flexible solid bodies. In this regard, both static and dynamic types of aeroelasticity are available. Static aeroelasticity is the science that deals with the mutual interaction between aerodynamic force (AF) and elastic forces (SF). On the other side, dynamic aeroelasticity involves inertial force (IF), AF, and SF interactions.

Further, a Collar Triangle is illustrated in Fig. 1 for the exact concept of aeroelasticity and aerodynamic force [3, 4]. The Collar Triangle defines the dynamic aeroelasticity for the investigations and designs of the mutual interaction IF, AF, and SF in the vertex of the triangle. This mechanism is required to be exposed within the air streams. The interaction of IF and SF in the structural domain, where mechanical vibration is a prominent phenomenon, is called structural dynamics (SD). Again, the bottom side of the triangle represents the static aeroelasticity which is the origin of divergence (D). The realm of dynamic aeroelasticity develops due to all the three forces simultaneously acting. Then, common failures like a flutter (F), buffeting (B), and other dynamic response (Z) in the form of a vortex, galloping, etc., take place.

Wind Induced Vibration

It was already discussed that aerodynamic stability problems arise with the interaction between IF and AF. For the study, the response of complex static and dynamic wind-structures interactions are categorised into several forms, as shown in Fig. 2. Again, WIV against different wind mechanisms was discussed broadly. Parameswaran elaborated on the wind-resistant design and estimation methodology [5]. The pressure coefficient (C_P) has shown below to understand those phenomena more elaborately, in terms of instantaneous wind pressure at a chosen point (P), atmospheric pressure (P_0) and dynamic pressure (q) (kinetic energy/unit volume) at some stagnation point on the deck surface [6].

$$C_P = \frac{P - P_0}{q} \tag{1}$$

Next, an important term is an aerodynamic moment, the product of said force and corresponding lever arm concerning the point of interest. The unsymmetrical pressure distribution around the section of the bridge deck generates these. The bridge components' non-dimensional aerodynamic coefficients (drag, lift, and moment) are based on empirical measurements collected from WTT of reduced-scale models. These coefficients are the functions of the angle of incidence (θ), Air density (ρ), Mean velocity of the incoming wind flow (U), Reference area (A) of the fluid, and distance to the centroid of section (D). Thus, the full description of aerodynamic load on a three-dimensional body (3D) is possible with six aerodynamic coefficients: three forces and corresponding three-moment components, as shown in Eqs. (2) to (7). The forces are Heave/Lift (F_L) perpendicular to the mean wind direction, Drag (F_D) along the wind direction and moment (M) concerning the centroid of the section. These coefficients can also be expressed to the structural coordinate. These

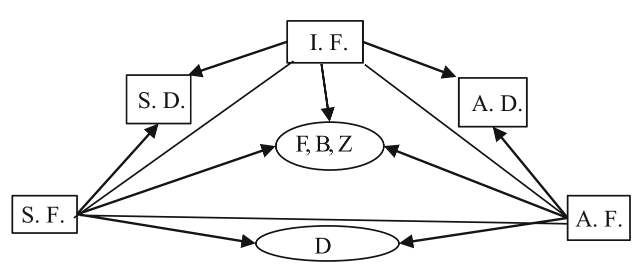


Fig. 1 Collar Triangle [3, 4]

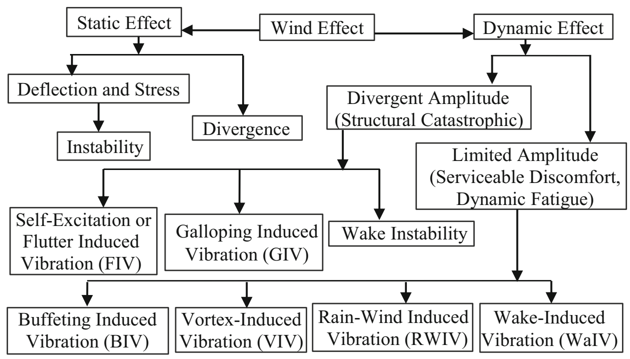


Fig. 2 Wind Effect [5, 7]

are vertical force (F_V) along with normal axes (NA), the horizontal or sway force (F_H) along with transverse axes (TA) and Side force or surge force in case of the ship (F_S) along longitudinal (LA) axes of the structure. Also, moments are Yaw (M_Y) about NA, Pitching/Torsional (M_P) about TA and Heaving/Bending (M_H) about LA axes of the structure [6].

$$\text{Lift Coefficient,}\quad C_L(\theta) = \frac{F_{L(\theta)}}{0.5\rho U^2 A} \tag{2}$$

$$\text{Drag Coefficient,}\quad C_D(\theta) = \frac{F_{D(\theta)}}{0.5\rho U^2 A} \tag{3}$$

$$\text{Side Coefficient,}\quad C_S(\theta) = \frac{F_{S(\theta)}}{0.5\rho U^2 A} \tag{4}$$

$$\text{Yaw moment Coefficient,}\quad C_Y(\theta) = \frac{M_{Y(\theta)}}{0.5\rho U^2 AD} \tag{5}$$

$$\text{Heaving/bending moment Coefficient,}\quad C_H(\theta) = \frac{M_{H(\theta)}}{0.5\rho U^2 \mathrm{A\ D}} \tag{6}$$

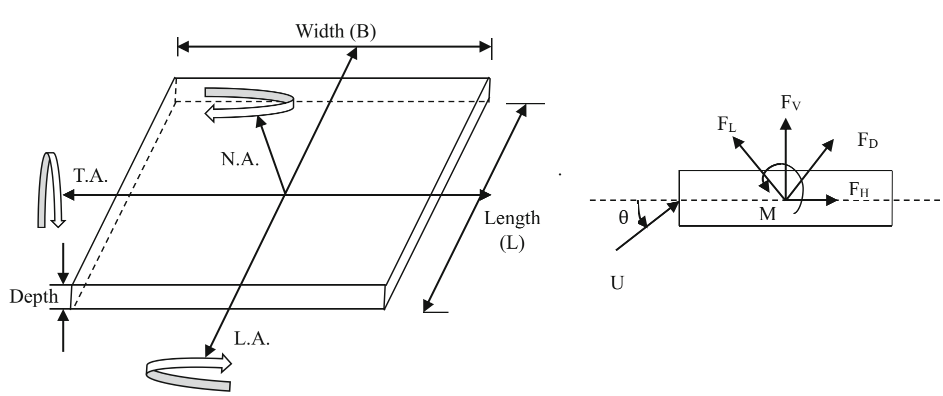
$$\text{Pitching/Torsional moment Coefficient,}\quad C_P(\theta) = \frac{M_{P(\theta)}}{0.5\rho U^2 \mathrm{A\ D}} \tag{7}$$

Further, it is often convenient to assume that bridge length is infinite for bridge girders. In that situation, two-dimensional (2D) calculations are sufficient to describe the said coefficients: C_L, C_D, and C_P [5, 8, 9]. A generalised section under the aerodynamic environment has displayed in Fig. 3. The WIV due to dynamic effects has been described below in continuation of Fig. 2 in Fig. 4. Self-excitations, VIV, and Buffeting Induced Vibration (BIV) are three significant responses against induced aerodynamic forces. Typically, self-excitation happens due to the interaction between wind and structure. At the same time, vortex-induced force (VIF) and flow fluctuation generate VIV and BIV, respectively. The bridge's total damping systems combine aerodynamic and aeroelastic damping that may be negative at tremendous wind speeds. If the effective structural damping fails to disperse input energy by the wind, the amplitudes of the oscillating structure increases and diverge. The velocity up to this decaying and diverging border is critical wind velocity. Up to the aeroelastic instability limit, aerodynamic damping is positive and reduces vibration [10]. Knowledge about this basic terminology is imperative and will be clear after visualising the history of bridge failure due to different WIV and its analysis history.

Ancient Literature in Bridge Failure

The observations of aerodynamic effects on bridges in laboratories are not good enough. Hence, evidence from a history of failures is compelling [12]. Dry burgh Abbey Bridge on January 1818 [10]; Brighton Chain Pier Suspension Bridge (BCPSB) in 1836 [10]; Tay Rail Bridge on 28th December 1879 [13]; etc., are the failure examples in the nineteenth century. Woefully, the failure patterns of these bridges are not clear due to a lack of information. Further, a list of the investigated response of bridges due to WIV is also shown in Table 1 (1 to 9: Suspension Bridge & 10 to 13: Cable Suspension Bridge). Both made a picture to understand the overview of failures. Moreover, the wind is comprehensively capable of changing dynamic and random phenomena. Time and space are the two independently

Fig. 3 Generalised section under aerodynamic environment



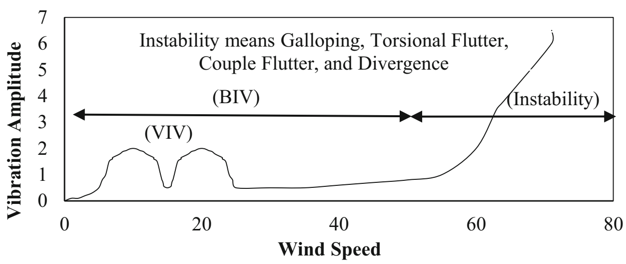


Fig. 4 Different forms of WIV [10, 11]

varying random factors influencing the structures and flow field. Therefore, fluctuating and time-averaged components are two significant factors that define wind speed. The total wind force acting on a bridge is the summation of the motion-induced, static and fluctuating wind force [11].

History of Aerodynamic Force Analysis

Fifty to seventy-year-old structures are comparatively massive due to higher safety factors for materials. For example, the 21 m first suspension steel bridge was constructed over Jacob's Creek in 1801 without considering the wind effect [25]. The first significant bridge failure due to severe wind gale was the first Dryburgh Abbey bridge in 1818 in Scotland [10]. Again, it was also reported that the longest radiating chain was broken down in the same incident. The two most apparent failures of long-span bridges due to WIV are England's BCPSB [12] in 1836 and the Tay Rail Bridge in Scotland in 1879 [13]. The key person for developing the "Firth of Forth Bridge" in Scotland was Baker, considering the wind effect [2]. Almost at the same time, Gustaf Eiffel designed the "Eiffel Tower" with a wind effect [2]. Again, from the perception of human discomfort, Rathbun in 1940 studied the response of wind vibration for the Empire State Building [26]. It is clear from the study that before 1930, the aerodynamic wind loading on structures in design was not compulsory. However, the induction of the skyscraper boom from the 1930s, lighter material, and increased span length for the bridge decks accomplish high consciousness to the wind. Nowadays, bridges are more lightweight and flexible due to advanced material and techniques attached to the appropriate analysis and design of the aeroelastic effects.

The 853 m span TNB, a suspension bridge in the USA, collapsed for wind in 1940 [13]. Karman was involved in studying the probable cause of the failure of TNB [27]. The study reported that the aerodynamic force due to the changes of wind motions was the primary cause of the said devastation. At that moment, the mechanism of failure of the TNB was not fully cleared. Later, several types of research were reported that both VIV and FIV type vibration occurred with TNB. It was predicted that low-speed torsional flutter might be repressed due to vortex-induced heaving vibration. Vortex convections are the main reason for this torsional flutter, which generally happens on the bridge deck's thickness face. Further, Billah and Scanlan demonstrated physically and mathematically that self-excitation due to the wind is the leading cause of ultimate bridge failure rather than resonance [28]. Stiffness, elasticity, rigidity, length, width, mass, and distance between hangers are the main factors on which the critical energy thresholds of the "nonlinear normal modes" of the bridges depend [12]. Arioli and Gazzola also addressed that the wind places sufficient energy to defeat the critical energy threshold of TNB's 9th "nonlinear normal mode" and creates destructive torsional oscillations by increasing internal resonance. Therefore, the investigation on the failure of TNB is one of the crucial openings for

Table 1 Investigated response of Bridges due to WIV

SN	Bridge Name	Built Year	Main Span (m)	Wind Induced Response
1	Tacoma Narrows Bridge (TNB), USA	1940	854	Vortex induced & flutter vibration [14]
2	Little Belt, Denmark	1970	600	Large Harmonic vortex-excited oscillations [15]
3	Bosporus, Turkey	1973	1074	First modal Frequency decrease [16]
4	Tsing Ma, Hong Kong	1997	1377	Vortex induced oscillation [17]
5	Humen, China	1997	888	Fatigue Crack [18]
6	Great Belt, Denmark	1998	1624	VIV [19]
7	Akashi-Kaikyo, Japan	1998	1991	Flutter instability and buffeting [20]
8	Runyang, China	2005	1490	Flutter [21]
9	Zhejiang Xihoumen, China	2008	1650	Flutter [21]
10	Normandy, France	1995	856	Buffeting Induced response [22]
11	Sutong, China	2008	1088	Cable vibrates at different amplitude [23]
12	Stonecutters, Hong Kong	2009	1018	Buffeting induced stress at larger corners [24]
13	Russky, Russia	2012	1104	Cable vibrates at different amplitude [23]

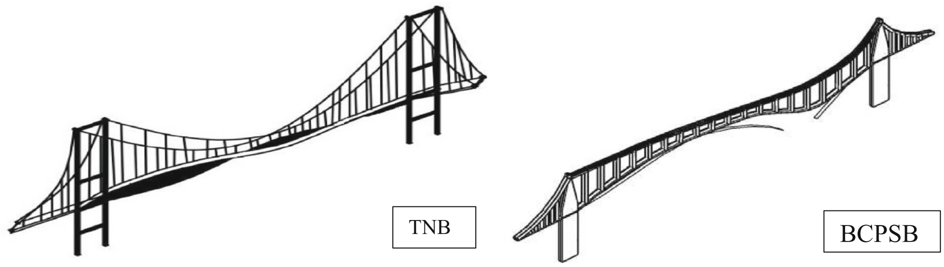


Fig. 5 Torsional motion of TNB and BCPSB

the initialisation of research on wind effects with bridges. Figure 5 has illustrated the torsional motion of the TNB and the BCPSB before the collapse by a schematic diagram [12, 29].

Scanlan and Miyata reviewed the improvement of aerodynamic force's history for predicting the responses of the bridges [30, 31]. Ge and Xiang outlined by configuring a few bridges' structural characteristics against aerodynamics in China [21]. The Great Belt East analysis, a famous bridge in Denmark, is also informative for understanding the aerodynamic effects [19]. Again, Xu prepared a list of the ten top longest cable-stayed and suspension bridges in the world to understand the then scenario [6]. Under smooth and turbulent flow, the aerodynamic stability analysis was explored with different yaw angles on the Third Nanjing Bridge [32]. The critical flutter speed has been derived after investigating the flutter performance with a large attack angle over Stonecutters Bridge [1, 33]. They also compared the results with Wind Tunnel Tests (WTT) and CFD simulation. This study improved several aerodynamic counter measurements in the Russky Bridge (Russia in 2012) and others. Finally, this aerodynamic history analysis proved that the self-excitation of the bridge is a primary cause of bridge failure, and the large attack angle is a vital factor to be considered. The overview of all WIV mechanisms will clear the concept against its effect on bridges. Now, the time to discuss different forms of WIV in detail.

Flutter Induced Vibration

The most crucial aerodynamic force is self-excitation only. Of course, this is for flutter and is directly related to the bridge decks' motion [21]. Flutter is a dynamic aeroelastic phenomenon. It can also be considered divergent vibration and may be the leading cause of catastrophic failure of structures [1, 34]. Flutter mainly happens due to the coupling of bridge deck motion with the wind. The well-known fact is that the torsional damping ratio of the bridge increases until maximal value with the increase of wind speed and then decreases toward negative. This fact is associated with divergent vibrations [35]. Again, mechanical damping of structural systems related to bridges can dissipate energy by the aerodynamic force due to high oscillation cycles. The vibration amplitude will grow if it is more extensive and can generate self-excited force. If this situation continues for some more time on the bridge, the collapse state is inevitable after the ultimate limit state [10]. The flutter varies as per the shape of the deck and the varying gap between the two decks [36, 37]. Flutter can be classified as damping and stiffness driven. The damping-driven flutter is associated with a single degree of freedom in the torsional direction. Stiffness-driven flutter is a coupling of vertical bending with the torsional degree of freedom (DOF). Generally, coupled flutter affects the modern cable-supported bridges [5, 38, 39].

Flutter Derivatives

A set of semi-empirical functions to identify flutter critical wind speed is called Flutter Derivative (FD). Scanlan and Tomko established the semi-experimental and semi-analytical approaches [40]. Again, these are the functions of wind velocity, structural configurations, and circular frequency [41]. In addition, the prediction of wind responses strongly depends on the derivative of classical pseudo-static force coefficients for long-span bridges: actually, these are FD [42]. Direct and cross FD can be found by single and two DOF tests [43]. Gu et al. expressed in their study on frequency domain analysis that vertical, bending, and torsional motion should be constrained to calculate direct derivatives [44]. The torsional and bending movement should have the same frequency for all the wind velocities for cross derivatives estimation. Further, Briseghella et al. used time-domain flutter analysis: a reliable alternative against frequency domain [45]. Here, structural nonlinearities and behavior of the models over time were considered. Although, Sepe et al. performed a more precise analysis for both frequency and time domain to assess the shape of flutter mode and critical wind speed [46]. Again, Zhang et al. expressed indicial functions of aeroelastic force for numerical problems related to time-domain flutter analysis [47].

The Eqs. (8) to (10) represent the self-excited forces on the bridge as illustrated in Fig. 3 [48] to extract the FD using WTT/CFD for lift (L_{se}) (vertical direction cross-wind), drag (D_{se}) (horizontal direction along-wind), and torsional moment (M_{se}) (acting nose-up). Critical conditions can be easily calculated by applying "Strip Theory" with the help of these formulations. Further, wind-bridge interaction is required to determine by a two-dimensional section. Here, the longitudinal axis of the bridge is normal to the direction of wind flow [5]. The possible influence of transverse displacement is not required for 2-DOF flutter analysis. This analysis is well organised in between bending and torsional mode shapes. Again, it influences the critical flutter wind speed in a greater quantity. Therefore, 3-DOF flutter analysis has been very widely adopted by researchers from the last three decades of the twentieth century [20, 37, 49–51]. 3-D FEM structures shall be directly considered by the researchers and apply the same over unsteady aerodynamic force in frequency and time domain. Again, in the 2nd way using the mode superposition method, assembled various vibration modes of the structure, taking the response separately.

$$L_{se} = 0.5\rho U^2 B\left[KH_1^*\left(\frac{h^{\cdot}}{U}\right) + KH_2^*\left(\frac{B\alpha^{\cdot}}{U}\right) + K^2H_3^*\alpha + K^2H_4^*\frac{h}{B} + KH_5^*\left(\frac{P^{\cdot}}{U}\right) + K^2H_6^*\left(\frac{p}{B}\right)\right] \tag{8}$$

$$D_{se} = 0.5\rho U^2 B\left[KP_1^*\left(\frac{p^{\cdot}}{U}\right) + KP_2^*\left(\frac{B\alpha^{\cdot}}{U}\right) + K^2P_3^*\alpha + K^2P_4^*\frac{p}{B} + KP_5^*\left(\frac{h^{\cdot}}{U}\right) + K^2P_6^*\left(\frac{h}{B}\right)\right] \tag{9}$$

$$M_{se} = 0.5\rho U^2 B^2\left[KA_1^*\left(\frac{h^{\cdot}}{U}\right) + KA_2^*\left(\frac{B\alpha^{\cdot}}{U}\right) + K^2A_3^*\alpha + K^2A_4^*\frac{h}{B} + KA_5^*\left(\frac{p^{\cdot}}{U}\right) + K^2A_6^*\left(\frac{p}{B}\right)\right] \tag{10}$$

where $K = \frac{B\omega}{U}$ = Reduced frequency

$\omega_{h,p,\alpha}$ = Circular natural frequency for the vertical, lateral, and torsional DOF, respectively

$H_i^*, P_i^*, \& A_i^*$, (i = 1 to 6) = FD and functions of K, determined experimentally/CFD techniques for the deck cross-section

α, h, & p = displacement against longitudinal, normal, and transverse directions, respectively

$\alpha^{\cdot}$, $h^{\cdot}$, & $p^{\cdot}$, = First Derivative of α, h, & p, respectively

Progressive Feature of Flutter Analysis

Many investigations were conducted on several aerodynamic mitigation measures to overcome the flutter instabilities after the dramatic failure of TNB. Sarkar et al. evolved a new method named Modified Ibrahim Time Domain over Scanlan derivative [43]. Again, this new system extracts all the aeroelastic parameters from the section model test associated with coupled motion displacement. Singh et al. developed a 3-DOF suspension system to determine the sway associated with FD for a streamline and bluff deck section [42]. Another mitigation path was explored for a long-span critical flutter, and the same can be increased by using tuned mass dampers (TMD) [52]. This critical flutter speed for the direct wind was compared with the skew wind [53]. At that time, study over laminar and turbulent wind flow was processed [22]. Further, different procedures were proposed [42, 54] to extract 18 FD and controls of the bridge deck from direct wind. Xu et al. studied the same for skew wind [55].

The analytical studies for the aeroelastic instabilities were started by solving problems related to aircraft flutter. Aerodynamic Admittances Function (AAF) and Aeroelastic Derivatives (AD) express aerodynamic and aeroelastic forces, respectively. The flutter characteristics for thin plate sections against aerodynamics force were studied experimentally [56]. They conducted the WTT with three viewpoints: flow structures, torsion heaving frequency ratios, and energy analysis. Sometimes, structures are impacted by simultaneous action of self-excited motion and turbulent wind. Therefore, based on the time domain, a vital function was generated in Quasi Steady (QS) formulation for AD and AAF solutions [54, 57, 58]. The spanwise correlation of those aerodynamic forces responsible for AAF and AD must be considered. Compared to the AAF and AD approximation, the frequency domain, time domain, and Fourier transform functions-based expressions were occupied in QS state formulation [59, 60].

Moreover, the study of the aeroelastic phenomenon for girders concludes that frequency characteristics could be a primary objective to indicate various flutter type differences [61, 62]. The nonlinear flutter response or torsional instability can occur due to geometric nonlinearity and fluid-bridge interactions. The critical flutter of wind speed might be estimated by extracting the FD as nonlinear functions. Different approaches were suggested to obtain various FD and critical flutter of thin plate, hangers, and bridge deck sections at various wind attack angles [63–68]. A model was analyzed using the linear fluid memory effect, named a modified hybrid model [69]. They compared this modified hybrid model with five existing models, i.e., QS theory, QS theory with some correction, QS theory with a linearisation process, semi-empirical linear theory, and hybrid model. Presently, some new approaches based on the pressures at each pressure point are introduced to establish the characteristics of pressure distribution patterns. Therefore, the Proper Orthogonal Decomposition (POD) method, a powerful statistical tool, was invented by removing the drawbacks discussed [8, 70, 71]. Further, Yang et al. measured the flow field by Particle Image Velocimetry (PIV) experimentally [56]. It is observed that with the increase of wind velocity, the scale of the vortex street becomes more significant. At the same time, the flutter instability of the thin plate is followed by bobbing movements of the vortex street. Again, a FEM-based fluid analysis methodology was proposed to predict the flutter velocity [72], and RANS-based models (Reynolds-averaged Navier–Stokes) was applied for aerodynamic characterisation [73, 74]. Finally, a firm idea for several mitigation measurements due to different flutter speeds was addressed [1, 20, 21, 47, 49, 52, 65, 72, 75, 76, 77]. This evaluation story of the flutter analysis from antiquity clarifies that time-domain analysis result via PIV WTT validation can positively affect the research domain but not enough to make a complete WIV view. For this, knowledge about galloping is essential. This galloping is another vibration due to divergent amplitude.

Galloping

Another significant self-excited oscillation is galloping to cause mechanisms and large oscillations of the structures. A dynamic instability caused by wind-induced self-excitation of slender structures with a large amplitude of the divergent response is galloping/bending flutter/crosswind galloping/translational galloping. Further, when the structures are subjected to vertical/torsional motion due to wind attacks at various angles, the same are undergone galloping. Galloping can be experienced mainly for the cables of cable-supported structures. The cables, whose cross-section is nearly constant, vibrate in the crosswind direction, and their amplitudes are more extensive than their cross-sectional dimension. Although, this is not so concerned during its occurrence in the bridge deck and girder. The galloping may take place due to any or combination of (i) formation of ice around the cable, (ii) effective attack angle due to torsional/vertical motion of structure (iii) structural negative damping in the crosswind direction. The sectional characteristics of structures play a massive role in galloping. The bluff body's propensity is considered the main factor for the gallop. A higher tendency to gallop comes for cross-flow with a smaller aspect ratio (depth/width), known as soft galloping. In contrast, hard galloping, the larger ratio, requires initial perturbation [11, 76, 77]. The rectangular cross-section is prone to gallop if the aspect ratio is less than five [5]. Finally, the tendency of galloping is indicated by the negative slope of the lift force. Galloping mainly depends upon the QS behavior of the structure. Therefore, QS aerodynamic theory plays a huge role in explaining galloping mechanisms [12]. Galloping generally occurs due to low wind speed, and slight amplification of wind speed make it another form of WIV that is VIV (Ref Fig. 4). Awareness is obligate against this vibration is discussed later.

Vortex-Induced Vibration

The vibration of long spans bridges due to fluid is VIV. A rotating region in a fluid about a central axis is a vortex. This axis is either an imaginary straight or curved line, depending upon the nature of the vorticity, mainly a vector. VIV is incapable of creating direct catastrophic failures of the bridges. But, significant concerns are endangering constructions, fatigue problems due to large oscillation amplitude, traffic safety, and bridge users' discomfort [11, 78]. The VIV mechanism is utmostly required to investigate the counter measurement that mainly varies according to the shape of the bridge decks. The physics of VIV is also fundamental. Hence, acceptable models for the calculation of VIV are a challenging job. Vortices are generated at the backside of a bluff body when fluid flow passes over the same. Again, the flow detaches periodically from either side of the body. Therefore, the downstream side of the object is influenced by an alternating low-pressure vortex. These periodic vortices are called Von Karman Vortex Street in the name of Von Karmann, who studied the same around 1910 based on Reynolds number, the geometry of the deck, and Strouhal number (S_t). A specific frequency (n) vibration is produced due to fluid flow to fill the low-pressure zone called shedding frequency. The typical dimensions of the bluff body (D), 'S_t' and 'U' are the factors on which the value of 'n' depends and is interlinked as below.

$$\mathrm{St} = \frac{nD}{U} \tag{11}$$

This 'n' has a significant concern when the structural natural frequency (n_s) coincides. This shows a tendency to resonate and produce harmonic oscillations driven by the energy of the flow. The 'n' synchronisation will occur in such conditions as the lock-in phenomenon, as represented in Fig. 6 [11, 78–82]. Matsumoto et al. classified VIV for bridges into three types [83]. First, the girders of long-span bridges are frequently subjected to single shear-layer type vortices. Second, double shear layer-related vortices are expected under downwind, including Karman Vortex Street. Last but not least is 3D-type vortices generated on the tips of the free pylon and inclined cable.

Progressive Feature of VIV Analysis

VIV is a motion-induced on bodies interacting with an external fluid flow produced by, or the motion having periodic irregularities on this flow, accompanied by multi-

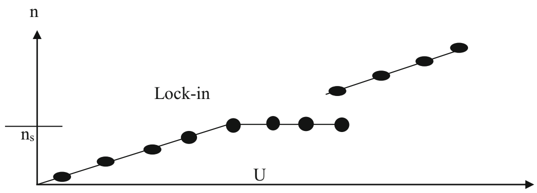


Fig. 6 Lock-in effect due to VIV [80]

parameters couplings due to its critical mechanisms. The attempts were made for the countermeasures of VIV by adding intermediate supports, natural frequency, etc., are more appreciable than changes of shape and TMD method [11, 84, 85]. The studies based on earlier mentioned approaches were done over cable-stayed [86], twin boxes [87], multi boxes [78, 88], parallel-twin cables-stayed [89], and parallel decks [79] bridges. The one shear layer vortex can be suppressed by stopping the vortex generation at the leading edge due to body motion. This idea can be applied successfully after modifying the borders of girders by the fairing, deflectors, flap plates, and wind noises. But, maintenance and installation add additional costs.

Therefore, changing the angle of the trapezoidal-shaped box-girder deck is becoming very famous in the modern day. This angle change is especially true for long-span bridges due to superior aerodynamic instability performance against flutter and VIV at low speed [90]. Again, amplitudes of the VIV strongly influence structural phenomena. Hence, vertical and torsional vortex shedding excitations must examine the VIV. The response shall be mitigated by developing a semi-empirical tool for the VIF with mode-by-mode vibration of complex flow fields [78, 87]. Shear flow consideration induced by aerodynamic force is essential for VIV experimentations [91]. A PIV technique was applied successfully upstream and downstream of the deck with an intermediate wind velocity range to investigate these complex flow fields [89]. Different spanwise correlations and frequency domain characteristics under smooth and turbulent flow fields on twin box decks were studied [92]. VIF perfectly correlates for both turbulent and smooth flowfields within the lock-in region. In contrast, if the turbulence intensities increase, the correlation decreases mildly. At the same time, in lock-in cases, Lupi et al. experimentally observed the quadrature components of the forces as an oscillation amplitude function [93]. However, several experimental techniques were carried out with different scales [88], spanwise correlation [92], and various mitigation tools [94] for the same purpose. In addition, beyond the experimental investigations of VIV over bridges may be computed using advanced simulation techniques named CFD and measured directly by field observation methods using Structural Health Monitoring systems [95]. The results from the above process look promising when these are compared with experimental/analytical results. Some examples of code-based investigations using CFD over bridges for VIV are Direct Numerical Simulation [96], Discrete Vortex Method [97], RANS-based model [98], and Large Eddy Simulation [99]. One crucial example of field observation is a stay cable vibration in 3D [86].

The WTT based on sectional models was conducted [100, 101] to identify the characteristics of the additional aeroelastic effects at the nonlinear stage during structural amplitude versus VIV. Further, Marra et al. considered both section and full-scale models for the yawed bluff body [102]. Chen et al. examined the VIV experimentally on flexible inclined cable and circular cylinder under shear and suction-based flow, respectively [91, 103, 104]. Again, Chen et al. studied the effect of VIV for different wind attack angles, speeds, and damping ratios over the bridge deck experimentally [88]. Liu et al. experimentally proved that the damped crossties' numbers and locations could affect the dynamic performance and control the efficiency of cables [94]. Further, Kim et al. examined the interactive behavior using field monitoring data [105]. Their conclusions are in acceptable agreement in terms of threshold wind velocity. Finally, more complex concepts of VIV mitigations were addressed [20, 78, 88, 89, 106–109], and CFD analysis with PIV WTT validation is more acceptable against those countermeasure mitigations. Sometimes, sudden shock WIV can attack a bridge rather than amplification in catastrophic stage (flutter) and periodic flow irregularities (VIV). A significant idea about this type of WIV (BIV) is vital.

Buffeting Induced Vibration

The vibration response in turbulent flow is called buffeting. More elaborately, buffeting is a high-frequency instability of airflow separations or shock wave oscillations due to the striking of airflow with objects. This random forced vibration is measured both in frequency and time domain. Thus, vibration modes and frequency range greatly influence the exact computation [24].

The study on the response theories due to wind-structure interaction on flexible bridges was developed in the last few decades [110]. Random vibration is generally non-deterministic or precisely unpredicted motions, typical to bridges. Therefore, the buffeting associated with horizontal and vertical pressure fluctuations in turbulent wind velocity is random bridge vibration [11, 64]. Buffeting forces are not responsible for disastrous failures like a flutter, but these are important for specific serviceability problems like fatigue [11].

Aerodynamic Admittance Functions (AAF)

One of the demanding issues for the bridges subjected to buffeting is aerodynamic admittance calculation. The transfer functions between the sectional forces and turbulent components in the frequency domain define AAF [11, 111]. Scanlan et al. described the relationship between FD and AAF in the time domain [53]. On the other hand, in QS conditions, buffeting forces are sometimes indispensable for accuracy [53]. The frequency-domain correction factors are multiplied with buffeting forces to modify the inaccuracy [110]. Moreover, the relationship between turbulent and smooth wind responses for the bridge decks can be characterised by AAF, which is used for all the force components induced by the wind [112].

Measurement of BIV

State of the art in analysing aerodynamic buffeting was started at the beginning of the twenty-first century. Sears established the earliest researches for the theoretical solutions of AAF in 1941, named Sears' Function [113]. Sears' function as 2D-AAF was developed to differentiate the vertical fluctuation in a two-dimensional wind field. Later, Liepmann addressed 3D-AAF by investigating the effect of turbulence on the airfoil [114]. The spanwise variations in 3D wind fields were also considered. Although, this force is inherently unsteady and was modeled conventionally using QS theory. Later, these AAF were redeveloped for unsteady behavior with six and eighteen components for normal and Yaw wind directions, respectively [53, 63, 115]. Simiu and Scanlan (1996) developed some formulations to obtain the complex AAF using the Fourier Transform component ($\Im$), as illustrated below following Fig. 3 [79, 112].

$$X_{\mathrm{L}} = \frac{\Im(L)}{0.5\rho V^2 BL\left(K_{\mathrm{L0}} + C_{\mathrm{D0}}\right)\Im(\theta)} \quad (12)$$

$$X_D = \frac{\Im(D)}{0.5\rho V^2 BL\left(K_{\mathrm{D0}} - C_{\mathrm{L0}}\right)\Im(\theta)} \quad (13)$$

$$X_M = \frac{\Im(M)}{0.5\rho V^2 B^2 L K_{\mathrm{M0}}\Im(\theta)} \quad (14)$$

where

$\Im(L, D, \&M)$ = Complex Fourier transform of lift, drag, and moment at wind oscillation frequency.

$K_{\mathrm{L0,\ D0,\ \&\ M0}}$ = derivative of the lift, drag, and moment curves around the mean angle of the deck, respectively.

$C_{\mathrm{L0,\ \&\ D0}}$ = Lift and drag coefficients with references to vertical and horizontal positions for smooth horizontal flow, respectively.

Progressive Feature of BIV Analysis

Several techniques were adopted for the measurements of AAF are incoming wind spectrum [116], FD [117], rational functions [59], indicial functions [56], single-frequency excitation [112], etc. At the same time, Chang et al. criticised the fruitful introduction of the TMD method, which is the mitigation measures of buffeting on suspension bridges [118]. Wang et al. examined the buffeting performance based on design and measured the spectrum after QS analysis in the time domain, considering aeroelastic effects [119]. The buffeting-induced stresses analysis was done where POD modes were used to get local stresses, global displacements, and acceleration responses of the bridges [120]. Again, these analyses were completed based on FE models under pressure modes. The POD of Wind-induced pressures is essential to obtain pressure modes. The time series turbulence was generated considering the spectral representation method to analyse buffeting performance on cable-stayed bridges [121]. This process was executed by developing FEM-based CFD using Fluid–Structure Interaction (FSI).

Moreover, to estimate AAF, Hejlesen et al. provided a valuable tool by finding a discrete vortex method under turbulence flow [97]. In contempt of the current developments, the time domain AAF formulations with complete understandings of the said forces in WTT have become challenging, requiring proper engineering judgments. Therefore, WTT has become essential for developing scenarios of buffeting responses [122]. Several experiments were conducted considering different parameters: skew wind [55]; oscillation effect [123, 124]; various turbulence wind fields [122]; etc. Moreover, Su and Li considered aspect ratio for their experimental investigations to evaluate integrated transfer functions for buffeting [125]. In brief, using the POD method with WTT validation is exhaustive for the BIV analysis. The time-domain analysis is equally considerable. Though conception of BIV is crucial as it is responsible for the fatigue effect, the knowledge of RIVW and WaIV is necessary to acquire the WIV concept ultimately.

Rain and Wind Induced Vibration

The study on RWIV for stay cables was started three decades ago. Many complex parameters sensitively covered this phenomenon to simulate in the laboratory [126]. The survey of these excess and unanticipated vibrations was initiated by considering rivulet patterns on the upper surface of cables. It includes vortex, wake-induced vibration, vortex shedding in the direction of the cable axis, and axial flow at low frequency. The assessments of the simultaneous actions of RWIV were observed by theoretical models using the QS assumption [127] and its theory [128]. Later, the same assessments were carried out by WTT and numerical simulations [129, 130], though the most exact method is a field observation. Finally, it was proposed to model this concurrent vibration due to wind and rain as a Van-der Pol oscillator [131]. This vibration is not destructive but is responsible for fatigue to the cables and causes damage to the anchorages. Hence, it becomes an important topic to worry about for long-span cable-stayed bridges. The various mitigation actions were suggested regarding structural and aerodynamic countermeasures [127–129, 131].

helan et al. studied the RWIV through field observation on a full-scale model. They concluded that velocity-restricted type response often triggers low wind speed, no rain, and wind direction normal to the plain [132]. Miyata et al. studied full-scale measurement data of a bridge deck during strong typhoons and then developed a correlation between longitudinal velocity fluctuations and power spectral density [133]. Further, Ni et al. set the correlation of wind velocities at different heights for different yaw angles of the bridge deck at different wind speeds [131]. Krarup et al. established the finite element (FE)-based dynamic structural model of the cable-rivulet system [128]. It was shown that the suppression capacity under RWIV of the model is more than the optimally tuned viscous damper. Again, Shen et al. studied the stay cable's performance statistically using long-term monitoring data [134]. Indeed, field measurement is the best solution for RWIV, along with some significant CFD or WTT validation.

Wake Induced Vibration

WaIV mainly happens under two closely placed parallel aligned decks of the bridge. The windward side produces a wake, and the leeward side is influenced by wake shear flow. WaIV is also generated due to the coincidence of the vortex shedding frequency of windward and leeward directions of the decks. However, this vibration is not responsible for the disastrous failures of structures like flutter and galloping. But, it causes only fatigue problems [5, 11]. Several studies on WaIV initiated with different approaches, including analytical methods [135, 136]. Again, Deng et al. have done the theoretical analysis over the hangers of the suspension bridges to study the physics of WaIV [137]. Moreover, CFD analysis is suggested for the WaIV with some strong validation.

Coupling of VIV and Galloping

The coupling of VIV and galloping is also an essential effect of wind. The structural elements exposed to wind may be the victim of catastrophic oscillation due to galloping and Karman vortex coupling. Both the vibrations occur in the direction of rotational degrees of freedom, which is a compassionate issue [81]. The first documentation on VIV-galloping interaction was presented in the paper of Parkinson & Sullivan [138]. Moreover, the coupling of VIV and galloping on prismatic towers was detected by Novak & Davenport [139]. An aerodynamically stable design under VIV-galloping interaction was provided using the response of divergent amplitude of footbridges. Further, Mannini et al. represented an engineering tool sensitive to the wind to estimate this coupled vibration, which is helpful for the initial design [81].

Aerodynamic Evaluation Method

The fundamental theory behind aerodynamics was addressed from Archimede's period and dated back to the work of Aristotle. Practically, quantitative approaches to aerodynamics were started from the beginning of the eighteenth century. World-famous scientist "Newton" derived the first theory of air resistance for low wind speed, honoured as the first aerodynamicist. In 1783, Bernoulli described the relation between velocity, pressure, and density for incompressible and inviscid flow. Later, the Euler equation was published for compressible flow. In the nineteenth century, the Navier–Stokes equation was extended from the Euler Equation for viscid flow [140].

Analytical and Experimental Method

The evaluation of aerodynamic force was started from the history-stage experimentally, analytically, and numerically [54, 141–143]. The analytical or mathematical method is insufficient to analyse aerodynamic forces as the ideal theory covers the same. Wardlaw identified specific gaps in the effects of turbulence with its terrain [144]. Simultaneously, significant progress in field and laboratory investigations was achieved in different countries, including Canada, Australia, Japan, and the United States. Since then, various researchers have experimented with several WTTs by making prototypes of natural bridges [145]. Moreover, Phelan et al. tested with rain-wind-induced cable stay vibration [132]. Zhang and Zhang investigated the relation between AAF and FD experimentally [146]. Furthermore, Park et al. suggested some reference data by conducting advanced WTT (i.e., PIV) for the predictions, validations and checking the accuracy of future models and or methods [147]. The classification of experimental methods is shown in Fig. 7. Notably, the modern WTT is advanced to develop results of different flowfields.

Field Observation and CFD Method

As described above, WTT is an essential method to study WIV, though the results depend on the tunnel size [149]. They understood the excitation and response features of WIV and validated those excitation mechanisms in the context of field measurement. Therefore, an innovative approach was adopted to directly measure the WIV and wind characteristics in the field. This method was developed with accelerometers, anemometers, displacement meters, thermometers, GPS sensors data acquisition systems, and other necessary tools [120].

CFD is the numerical simulation of governing equations of transport phenomena combined with applied physics, mathematics, and computational codes to visualise fluid flow characteristics of submerged objects. The 3D analysis of CFD simulation entirely depends on the processor's capacity and computational grids. Francis H. Harlow and his laboratory members probably performed the first simulation technique to model fluid flow using the Navier–Stokes equation at Los Alamos National Laboratory [150]. Therefore, this famous icon was acknowledged as one of the CFD developers. This group developed numerical simulation methods for 2D, transient, and incompressible fluid flow. The Fluid-in-cell method and Particle-in-cell method are two examples of this from 1957 to 1960. The CFD process is illustrated in Fig. 8. A new branch of engineering has come out in Computational Wind Engineering (CWE) to study the effect of wind with the help of CFD methodology in the year 1970.

Xu et al. established a dynamic 3D-FE model to study the interaction between vibration modes of the deck, cables, and towers, including the girder's main and side spans [16]. This model can also compute the mode shapes and natural frequency of bridges' vertical, lateral, torsional, and longitudinal vibrations. This study agrees with previous literature related to the above factors. Thomas and Williams showed the application of large-eddy simulation (LES) with a large grid of 10,000,000 nodes for a cube under turbulent flow [151]. Again, Zhu and Chen represented the reattachment and flow separation patterns on the surface of the girder by the same method [152]. Shimada and Ishihara used the K-€ Model based on RANS theory to predict separated and reattached type aerodynamic behavior [153]. The exact meaning of numerical simulations is to get solutions at discrete points within the domain. Therefore, Hybrid Model Approach, Continuous Torsional Motion Technique, Forced Oscillation Method, etc., were adopted by researchers to get an exact solution for complex problems. A few examples of the above complex problems are RWIV of stay cable, aerostatic Force coefficient of bridge decks, and VIV of inclined cables under different wind profiles [96, 154–156]. Over the years, many commercial codes like Ansys Fluent, Open Foam, LS Dyna, Console Multi-Physics, etc., have been established [9, 157–159]. Finally, it is required that research in this field is still going on for further development.

Comparison Between WTT and CFD

WTT is used for classical studies on the behavior of aerodynamic forces for the design of bridges. Nevertheless, these tests need time between planning and actual testing

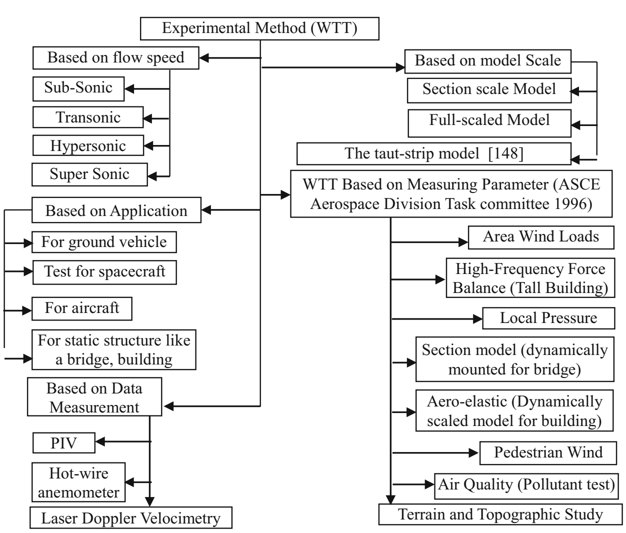


Fig. 7 Classification of Experimental Method

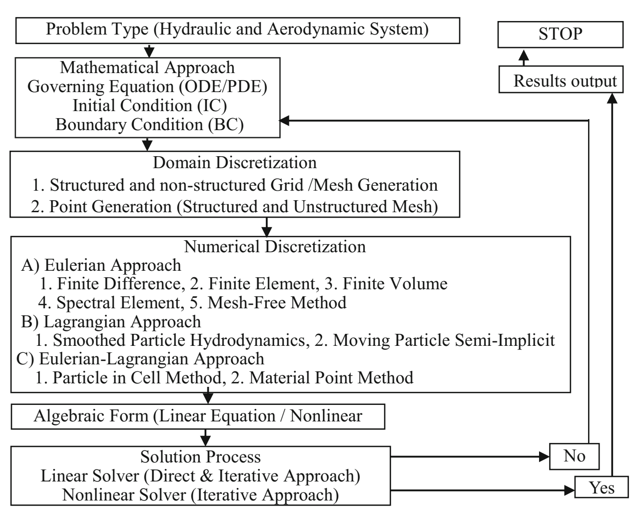


Fig. 8 CFD Process

and are expensive. The detailing of the WTT is easy, but any minor modification of the section requires remodeling. In the last two decades of the twentieth century, the development of an innovative technique has been achieved much more attention as an alternative to experimental and analytical methods. CFD application has been used to analyse the Aerodynamic Derivative, force coefficient, distribution of pressures, and flow visualisations. CFD techniques are in the leading position to understand the aerodynamic phenomena. Finally, there are some limitations by its nature and 3D complexity [9, 160]. Both Zhang and Ge and Tang et al. performed WTT and CFD simulations to evaluate flutter response on single and twin-box bridges' girders, respectively [1, 161]. The characteristics of static and dynamic flow fields changed at large attack angles. The substantial similarity in CFD and WTT results was noticed at a small attack angle. Further, the difference in result increases with the increase of attack angle.

Another critical issue is backflow, from the leeward side during WTT, should be considered to differentiate the result from CFD. Besides, Calautit et al. and Choi et al. studied the tall buildings with various corner shapes, multi-directional wind towers, etc., and compared the same with WTT [162, 163]. Finally, the iterative solutions have a different approach, but WTT is unique with no substitute for experimentation. The genesis of the relation between WTT and CFD is complicated. Nevertheless, CFD can give restricted, limited, and highly refined data for controlled and sophisticated simulations. The comparisons between WTT and CFD are shown in Fig. 9.

Wind Attack Angles

The attack angles are the angle between the relative motion of decks and chord lines. Han et al. investigated the response of decks under different wind attack angles [9]. Further, studies demonstrated that better construction convenience with proper economic measures could be possible by streamlining trapezoidal box girders (STBG) than truss girders. However, the change of the fairing angles of the girders has become popular as this STBG is affected by VIV when the wind speed is low [87, 98]. This problem was noticed on the Storebelt bridge [164] and Xiangshan harbour bridge [70, 152]. Noguchi et *al.* (2020) used a forced oscillation method for the above problem [156]. Further, Larsen and wall (2012) emphasised a more practical design of STBG without any appendages for the long-span bridge [102]. Moreover, Sato et al. ensured this application over superlong-span-slotted-box-girder bridges with flutter [165].

Effect of Sistem Identification Techniques (SIT)

Various operational and environmental loads are the daily operation factors in the existing bridge structure. These loads are also responsible for structural degradation and damages. The mitigation of this phenomenon is possible with Structural Health Monitoring (SHM). For instance, the powerful tools are Single Input Single Output (SISO) and Multiple Input Multiple Output (MIMO) SITs. The researchers have conducted several model-based studies and practical measures from the last four decades [166, 167]. But sometimes, it was impossible to analyse all the data, and at that time, the sake of computational efficiency came. Therefore, deep learning in this matter is one

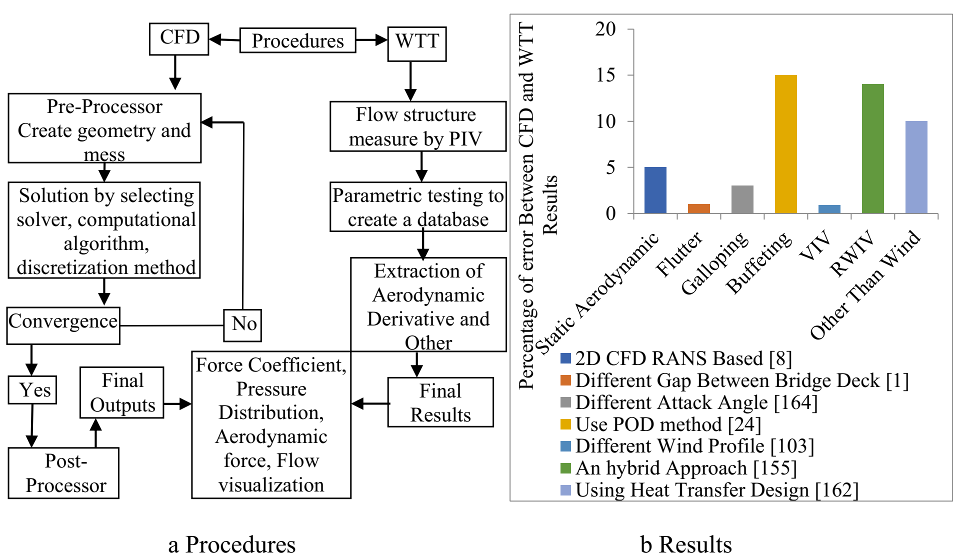


Fig. 9 Comparison between CFD and WTT (**a**) Procedures, (**b**) Results

Table 2 Short informative tabulation of this literature

Parameter/ Aspect		References	Key Contribution/ Observation
FIV	WIV	[1, 6, 7, 10, 11, 20–22, 34–74]	FDs are important constants for flutter measurement. Its mitigation measure truly depends on the flutter speed and bridge deck shape
GIV		[5, 11, 12, 76, 77]	The QS behaviour and sectional characteristic of the structure massively influence GIV
VIV		[11, 78–109]	One important countermeasure technique is changing the trapezoidal box girder deck angle after calculating span wise correlation and frequency domain characteristics under a smooth and turbulent flow field
BIV		[11, 24, 53, 55, 56, 59, 63, 64, 116–125]	Time-domain analysis and POD method with WTT validation is suggested for the BIV measurement
RWIV		[126–131]	Analysis for deck yaw angle is a significant future scope
WaIV		[5, 11, 135–137]	Shear flow plays a vital role
Analytical	Method	[5, 6, 26, 54, 132, 141–145]	Nonlinear structural models can be analysed by time-domain analysis
Experimental		[5, 7, 12, 19, 32, 36, 37, 147, 149]	PIV methods for experimentation is a catchy tool
CFD		[1, 7, 16, 96, 150–160]	The semi-analytical CFD method is the future of this aerodynamic domain, giving enhanced simulations
Full Scale		[68, 120, 132, 133, 149, 165]	One crucial tool is field measurement for full-scale experimentation. Local data is highly affected by this
SIT		[166–170]	SISO and MIMO SIT tools with AI help are new research venues

of the conspicuous topics representing the importance of Artificial Intelligence (AI) in this domain [168–170]. Table 2 shows the short tabulation of this literature.

Concluding Remarks

This review attempts to illustrate a short informative platform of WIV up to date. The effects of WIV can be reduced by changing the shape, type, mass, stiffness, damping, the proximity of parallel deck, etc., of the bridges. Moreover, the velocity, types, angle of attacks, etc., of wind are the key parameters to minimise the effects. Other mitigation parameters have also been addressed, including an overall solution for bridge decks. The stiffening methods are the best mitigations for both economic and long runs. Another critical issue is, though FIV is catastrophic, suppression of VIV, BIV, RWIV, and WaIV is the vital parameter because it causes discomfort and fatigue problems. The best choice is a bridge with the assemblage of the counter measurement of these effects. In this regard, the author suggests shape modification of course for streamlining bridge section considering the local force is considerable after testing with CFD and WTT. The critical observations on different types of WIV based on date, literature, existing models, and methods are addressed below:

1. The lift, drag, pitching moment, and bending moment are the primary phenomenon to characterise the bridge deck subjected to wind effect. The other moment and force components are essential for the other part (i.e., cable, pylon) of the bridge. The 2D analysis is more convenient as the bridge span length is slender.
2. The discussion about the various bridge responses against WIV gives the main idea from the investigated history: flutter is responsible for catastrophic accidents, and buffeting does not appear dangerous unless it produces shock waves.
3. The self-excited aeroelastic force is an actual cause of the collapse of decks, which makes the FD indispensable. Moreover, AAF of buffeting forces and analysis of VIV-galloping vibrations are essential for designs to avoid fatigue.
4. Computational effort and cost may be saved by adopting a suitable shape and or type of bridge deck under an aerodynamic environment.
5. The RWIV and WaIV are the crucial issues for the cables of the long and parallel deck of the bridges, respectively. These vibrations can be predicted by QS theory and models using Van-derpol oscillators.
6. For efficient and straightforward results, a frequency domain method is commonly adopted for linear structural models only, and time-domain methods are suggested for the nonlinear structural model.
7. WTT and or Full-scale experimental results are more reliable than those captured by CFD or analytical methods. But, this method is costly. Hence, it is suggested to prepare a scale-based model. The same is valid for analytical and CFD too. Again, CFD is a valuable alternative to WTT for preliminary design though it is developing. WTT is preferable for final designs if possible.

8. Literature with SISO and MIMO system identification techniques are powerful tools with continuous health monitoring of bridges in full-scale real-time, and prognostic analysis tools with AI techniques are many new research areas. This also helps to analyse these aerodynamic effects.
9. The future of aerodynamic analysis is applying a semi-analytical CFD method to simultaneously predict the effect of wind and ground vehicles over the bridges. Finally, it is essential to understand the climate change effects to predict wind engineering. El Nino and La Nina, these complex weather patterns help to understand the wind nature globally but anticipating nature is impossible. Still, understanding the climate changes can help to predict the wind responses on bridges.

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