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Generation of a mountain-valley wind in an atmospheric boundary wind tunnel: a gust-wind generator study

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Abstract

Appropriate modeling of an experimental technology is necessary in order to estimate the aerodynamic characteristic of railway trains and infrastructure (e.g., bridges). Simulation of the earth's wind characteristics of nature is a well-established practice by using an atmospheric boundary wind tunnel. However, in the mountainous area, the wind characteristics are strikingly different from those of the plain area, the amplitude variation of wind is related to complex terrain. Compared with atmospheric boundary layer winds, which are customarily treated as stationary, winds associated with gust winds originating from mountain areas exhibit rapid changes during a short period. A lack of available field test data and testing techniques has hindered such knowledge of the effect of mountain wind on railway-related applications. To simulate the characteristics of gust winds and prepare for follow-up studies of the impact on the railway-related structures, a gust wind generator was developed in an atmospheric boundary wind tunnel — the CSU wind tunnel. Further, the performance of the gust-wind generator was studied and analyzed under the condition of the combined operation between a gust-wind generator and a wind tunnel.

Keywords: Atmospheric boundary wind tunnel, Gust wind, Railway, Aerodynamics

1 Introduction

Over the past 10 years, the volume of railway operations increased by more than 52,000 km and the high-speed railways have more than tripled, ranking first in the world. A high-speed expansion of railway construction in and around cities has made this development trend even more evident in recent years. By the end of 2021, the mileage of China's railways has breaking 150,000 km and high-speed railways reaching 40,000 km (Zou et al. 2022a). Geography is a vital environmental factor that must be considered for the intensive exploitation of railway transport, and the developing trend of railway networks puts a high demand on design and construction. Especially the complicated topographic features of mountainous areas pose multiple threats to the railway, and one of the significant effects is from the wind environment. In addition, the expanding railway network is a consequence of the need to pursue speed and convenience; therefore, train shuttles through various terrain scenes have become widespread. The safety of the vehicle and wind-sensitive infrastructures (e.g., bridges, towers) need to pay more attention to the wind environment of mountain-valley areas. However, the wind characteristics of the mountainous area are very different from those of the urban, countryside and seaside (Xing et al. 2021).

To study the wind characteristics in mountainous areas, field measurements, wind tunnel tests and numerical simulations are the three main methods frequently used (Li et al. 2017, b; Zhang et al. 2020, c; Jing et al. 2020). There is no doubt that field measurements are a reliable method for providing first-hand information about wind characteristics of the mountain area, however, the high cost and limited points lead the field measurements to be prohibitive. Hence, the other two approaches are more commonly seen in the research on wind characteristics in mountain terrains. Moreover, numerical simulation is a good idea for obtaining wind field information, and numerous researchers have contributed to the understanding of the wind characteristics of mountains areas (Han et al. 2018; Ren et al. 2018; Huang et al. 2018; Hu et al. 2018). However, the accuracy of the numerical algorithm and the requirement of computing resources for high-precision computation limited the progress of wind characteristics in mountain district studies.

For the simulation of the atmospheric boundary layer (ABL), a wind tunnel is a well-established practice. Several investigations have been conducted to figure out the experimental techniques to reproduce the wind field identical to that in mountain areas. Li et al. (2017a) studied the wind characteristics in three different types of upstream terrains and found that wind speeds along the bridge deck are mainly affected by the local topography. Zhang et al. (2020, b) investigated the wind characteristics in complex terrain using wind tunnel tests. The sheltering effect of the mountain was discussed since the wind fields are uneven and very different from that of flat terrain. Li et al. (2010) performed a wind tunnel experiment to investigate wind characteristics in the mountainous valley terrain. The velocity speed-up effect was observed by measuring the simulated atmospheric neutral boundary layer on the valley models. Song et al. (2020) found that shielding and channeling effects contribute to wind deceleration and acceleration respectively, and the speed-up of the valley and mountaintop is obvious. Recently, the effects of mountains terrain have been a wide concern, especially the boundary layer developed on the surface of terrain and wind distribution at bridge sites (Hu et al. 2015, 2018; Mattuella et al. 2016; Zou et al., 2022; Wang et. al., 2022).

Physical modeling for railway aerodynamics is usually classified into two similarity requirements: (1) reproducing the main properties of natural winds and (2) criteria for similarity of wind effects (He and Zou 2021a, b). The design of the wind tunnel tests and study of railway aerodynamics should meet both essential criteria as much as possible. First, the inspection analysis of simulated wind fields in the boundary-layer wind tunnel applied to the equations expressing basic conservation laws applicable to the lower atmosphere yields a significant set of criteria for simulating natural wind in the ABL. Then, various types of wedge interference generate different ABL wind profiles in the wind. Furthermore, spire, fence, and floor roughness are common fittings for simulating the wind field of local terrains. However, many previous studies showed that these experimental techniques have good applicability for sustained wind speeds, but some problems still exist in simulating the wind field of mountain areas in a wind tunnel. For example, the significant feature is the strong gust of wind compared to the other terrain (Jiang et al. 2021), as shown in Fig. 1. Gust winds in mountainous areas are transient winds with the typical non-stationary characteristics of varying wind speeds and directions and strong suddenness (Li et al. 2017a; Zhang et al. 2020a; Ren et al. 2021).

In summary, conventional wind tunnel approaches can obtain the wind field information about mountain areas by using terrain models and employing a combination of passive devices (e.g., wedge, floor roughness) to generate boundary layers of the same scale as the geometric scaling of structural models placed in them. However, the study of gusts in mountainous areas is still in the primary stage and the available information regarding the aerodynamics of railway vehicles and infrastructures subjected to gust winds in mountainous areas is much lacking. Significantly, the limitations of wind tunnel experimental techniques and the dilemma of scale ratio of terrain and structures lead to restrain the further study of railway aerodynamics in mountainous areas.

To address the issues, some solutions have been developed to reproduce gust wind and related effects on the structures in the laboratory using active devices over the years. Some new wind tunnels have emerged with added features, such as passive or active wind farm systems and simulators with vortical flows (Kobayashi et al. 1994; Cao et al. 2002). The new experimental technique has enabled many efforts and contributions toward understanding aerodynamics, fluid-structure interaction and relevant mechanisms. Hence, practical and rational experimental simulation technology is necessary, and the design of a new device to produce high resolution and high stabilization of the wind field has become the key technology used in wind tunnels.

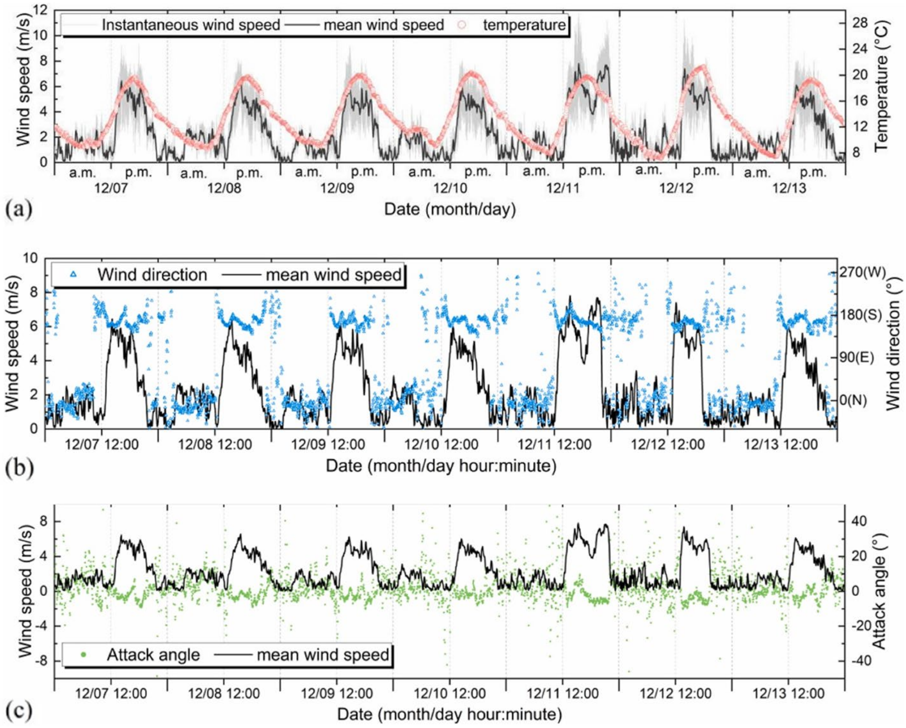


Fig. 1 Typical time history of wind speed in mountain areas (Li et al. 2022)

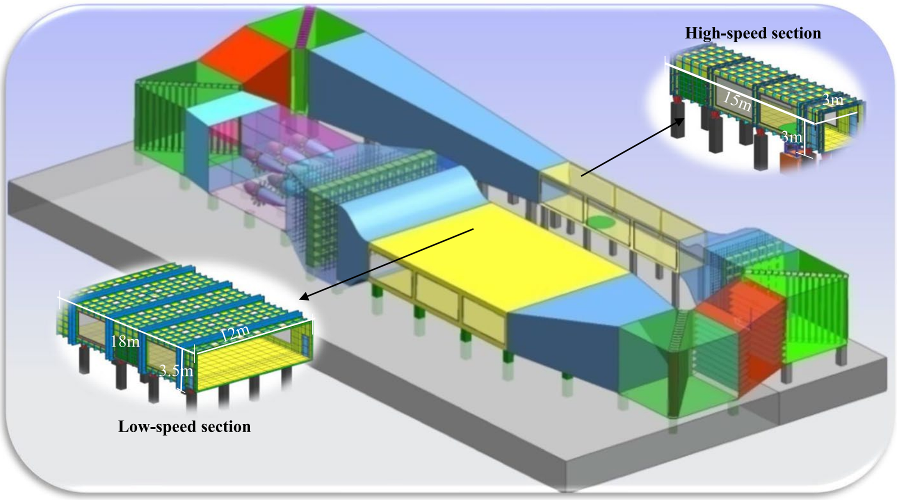


Fig. 2 Wind tunnel at Central South University (He and Zou 2021a)

Gust encounters are among the most critical load cases for railway aerodynamics and threaten running safety seriously. For example, a major accident occurred in India in 1981 when a train fell off a bridge after being hit by a strong gust of wind, causing more than 800 casualties among the passengers (Montenegro et al. 2022). In a more recent one in 2006 in Japan, a train hit by a lateral gust overturned at a low running speed (25 km/h) (Tamura 2009). In China, more than 100 vehicles flipped on the Lanzhou-Xianjiang railway line, where the wind gusts often reach 40–50 m/s (Zhang et al. 2013; Guo et al. 2015). All these wind-induced accidents indicate that the gust winds may pose a significant threat to the train's safety and should be studied in detail. Therefore, considering that gust winds conditions are significantly different from traditional boundary-layer flows, a wind tunnel at Central South University (CSU) equipped with a gust-wind generation mechanism has been developed as part of a research program on wind engineering and railway aerodynamics.

2 CSU wind tunnel

The CSU wind tunnel is one of the experimental platforms in the National Engineering Research Center for Construction Technology of High-Speed Railway at Changsha and is highly dedicated to civil engineering and railway-related aerodynamics model testing. The CSU wind tunnel is a largeclose-circuit wind tunnel, as illustrated in Fig. 2.

The CSU wind tunnel is currently being designed to accommodate 2 test sections (12 m × 3.5 m and 3 m × 3 m), which are connected to the contraction, settling, and diffuser sections. Two closed test sections (the two "yellow" areas) are available (Fig. 2). The good flow quality is adequate for wind engineering and industrial aerodynamic testing (the turbulence level is less than 0.3%). The wind tunnel is equipped with six large fans (3 × 2) that supply the power for the airflow movement. The airflow is streamlined by passing through turning vanes and contraction sections to the relatively large test section (12 × 3.5 m), named the low-speed section, which is controlled in velocity (from

0 m/s up to 20 m/s). On the other side, a smaller square section with dimensions of 3×3 m is named the high-speed section (due to the maximum velocity of 94 m/s). Furthermore, except for the wide scope of wind speed and the relatively large size, another advantage of the CSU wind tunnel is that it is convenient to adjust and maintain.

3 Design of gust-wind generating system

Compared with boundary-layer winds generally regarded as stationary, gust winds exhibit distinct non-stationarity, that is, rapid wind speed changes during a short time interval. The goal of the experimental facility was to generate gust winds in the wind tunnel test sections with the capability of large magnitude velocity changes within the shortest possible time. However, with the traditional setup of conventional wind tunnels, reproducing wind fields, testing loads and more in a general aerodynamics-related mountain-valley area inside an atmospheric boundary wind tunnel is always a challenging problem, especially when the focus of the testing activity is trying to reproduce gust wind flow and induced-effects over the structural models being analyzed. Therefore, the stationary wind model typically used in boundary-layer winds may not be valid for gust winds described in terms of time-varying parameters (Kwon and Kareem 2009). A solution has been easily found by designing, realizing and installing a gust-wind generator right at the front end of the wind tunnel test section (Kobayashi and Hatanaka 1992; Butler and Kareem 2007). As shown in Fig. 3, the proposed gust generator device is composed of 10 vanes, characterized by a symmetric airfoil. Flapping of the 10 vanes generates redirected airflow, and if the redirected airflow is controlled effectively, it is possible to generate either a gust of wind or air turbulence.

The square frame is made of rectangular steel and extruded profiles and is designed to be fixed to the wind tunnel with a cross-section 450 mm deep (i.e., along the direction where the airflow is moving downstream). The frame is joined using bolts, T-slot nuts, brackets, and specially designed attachment plates and supports the gust vanes and the actuators.

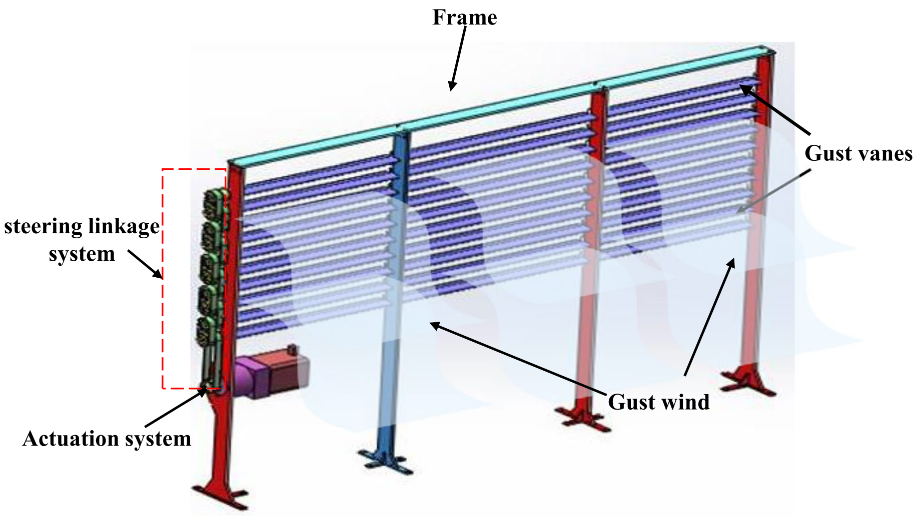
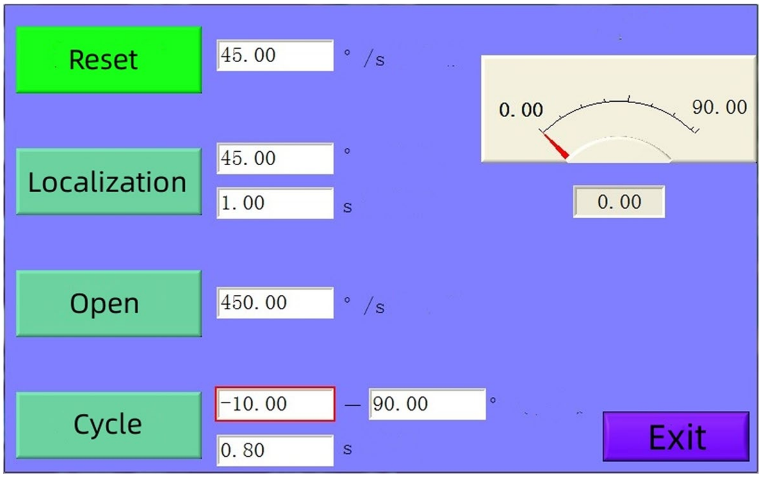


Fig. 3 Design sketch of gust wind generator



Reset 45. 00 ° /s

Localization 45. 00 °

1. 00 s

Open 450. 00 ° /s

Cycle -10. 00 — 90. 00 °

0. 80 s

0. 00

Fig. 4 Control graphical interface

Each gust vane is made of light steel. This material allows for a lightweight design and offers good machinability. The surface is impregnated with epoxy resin to increase its toughness and smoothness. During the gust-wind generator working, the gust vanes need to bear strong inertial and aerodynamic forces. Hence, the vanes must be ensured that no bend or twist excessively in the course of the experiments to prevent detrimentally affecting the flow quality. Therefore, the airfoil-shaped vanes are hollow with a certain thickness so that an aluminum alloy tube can be embedded to provide the required strength, stiffness, and stabilization. The vanes are 2.88 m long to cover the full width of the wind tunnel section and allow connection with the actuation system.

The actuation system and vanes are connected by a special coupling joint named "steering linkage system", which ensures high torsional rigidity. Moreover, the usage of an independent PID regulator, to avoid possible inconsistency of inertias, frictions and shape between the 10 vanes, guarantees the best mechanical rhythm to move the 10 gust vanes. Finally, a "steering linkage system" mechanism transforms the power imparted by the actuator into a vertical translating motion of 10 equally spaced 100 mm flat plates (vanes). The airflow will continue downstream, mostly uninterrupted when the vanes are parallel to the wind tunnel floor; the airflow will be blocked when the vanes are perpendicular (vertically orientated) and redirected at an angle when the vanes are slightly rotated.

The gust-wind generator device, with specifically developed software and hardware is capable of reproducing the gust-wind phenomenon that is required and can easily be tuned by means of a few parameters. As depicted in Fig. 4, the vanes' swing speed, angle, and frequency can be controlled by setting the control parameters in the control system. The redirection of the flow leads to an initial uniform flow oscillating up and down and produces an expected non-stationary flow.

In order to achieve the goal of simulated gust wind, the vanes of the gust-wind generator device, starting from an initial position with a "closed state" 90° angle of attack, are rapidly angled downward to an "open state" as 0° angle of attack (i.e., counter-clockwise in Fig. 3). The transience of the flow (and thus the non-stationarity of the "mean"-wind velocity) is mimicked by returning the vanes to their original position and returning the flow to its most uninterrupted state. These actions produce a signal marked by periods of sudden temporal changes in wind velocity. Owing to the advantages of the actuation system, vanes can be successfully operated at a maximum initial value, corresponding to the configuration wherein the vanes are parallel to the floor with the device in its "open state." Moreover, the system supports the usage of the generator in this configuration, enabling the vanes to reciprocate to swing up and down.

4 Experimental study of gust generator performance

In order to assess the performance of the gust-wind generator, experiments were conducted at the National Engineering Research Center for Construction Technology of High-Speed Railway at the railway campus of Central South University. The gust-wind generator was installed at the upstream high-speed section of the CSU wind tunnel to provide as much space for the flow and formation of gust wind as possible, as shown in Fig. 5. Vanes installed on the gust-wind generator were able to rotate through a full 90°, with 0° corresponding to the flat plate horizontal to the approaching flow and 90° corresponding to the flat plate perpendicular to the oncoming flow, imposing up to 40% blockage of the initial flow region.

4.1 Measurement devices

The system to measure the gust-wind velocities uses a Cobra Probe (Turbulent Flow Instrumentation), coupled with a pitot tube. The Cobra Probe is a four-pressure-hole probe with a high-frequency response capable of measuring velocities in three directions and mainly sensitive to flow variations normal to the probe with an accuracy of 0.5 m/s and a range of 0-60 m/s (Zou et al. 2022a, b, c), as shown in Fig. 6. Meanwhile, the probes are mounted on a traverse system, allowing measurements at different locations

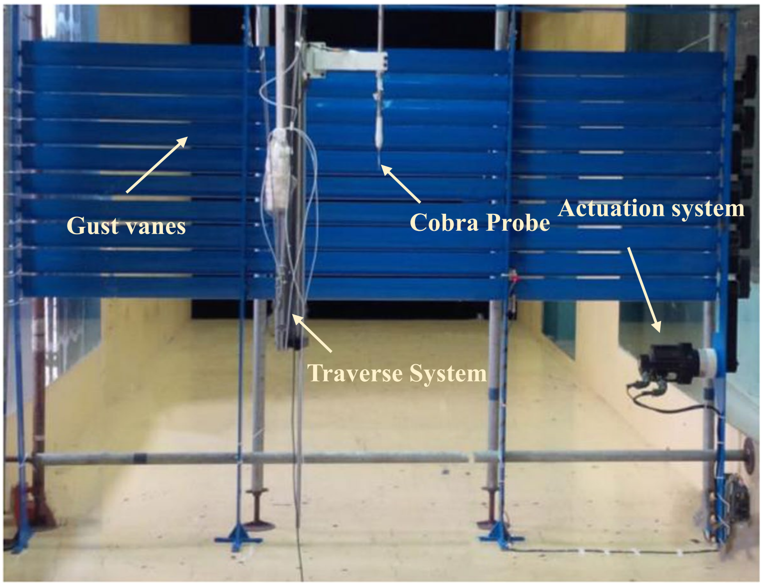


Fig. 5 Layout of gust-wind generator

Fig. 6 4-hole cobra probe manufactured and calibrated by Turbulent Flow Instruments (http://www.turbulentflow.com.au/)

in space. By positioning the probe parallel to the free stream flow, the velocities induced by the gust-wind generator can be measured. The Cobra probe was placed downstream of the wind tunnel and behind the gust-wind generator to contribute to the development of oncoming flow. In this study, measurements are conducted at the center of the test section after a series of tests done for a range of flow speeds, actuation frequencies, vane deflection amplitudes and locations to provide suitable gust-wind results.

4.2 Data processing

The measurements with the Cobra probe are recorded over 30 seconds at a sampling frequency of 2 kHz. Due to the initial measurements having a low signal-to-noise ratio, three techniques for obtaining the time-varying, non-stationary (slowly-varying) mean velocity, U, of the gust-wind flow are first compared and analyzed: (1) moving average (MA), and (2) decomposition using discrete wavelet transform (DWT).

The "moving average" is characterized by less computation and high significance, which is a more popular approach that has been utilized by previous studies to filter measurement records and extract the "mean" velocity from the time-varying, non-stationary winds (Yang et al. 2004; Belu and Koracin 2013). Recently, the other method of discrete wavelet transformation (DWT) has been proposed for the non-stationary "mean" extraction of time-varying flow velocity data (Kijewski and Kareem 2003; Wang and Kareem 2004). The algorithm of DWT operates by decomposing a signal into an approximation component that captures low-frequency contents contributing to the time-varying mean and a detail component that contains high-frequency contents. A series of high and low pass filters were used to progressively find the wavelet coefficients from the highest level to the mean value level. The reliability of the DWT in the identification and characterization of non-stationary random signals was verified and has been applied in ocean, wind and earthquake engineering (Gurley and Kareem 1999).

4.3 A sudden change in wind velocity

A close look at the literature reveals that the main properties of mountain-valley winds must be achieved to generate realistic non-stationary gusts. The two primary factors considered were the magnitude of the gust wind speed and the time scale of the velocity increase. For mountain area-related gust winds, Simiu and Scanlan (1996) summarize ranges of gust wind magnitudes afrom 3 m/s to 30 m/s and gust wind durations from a few minutes to 20 min or more. Hence, the average speed of wind

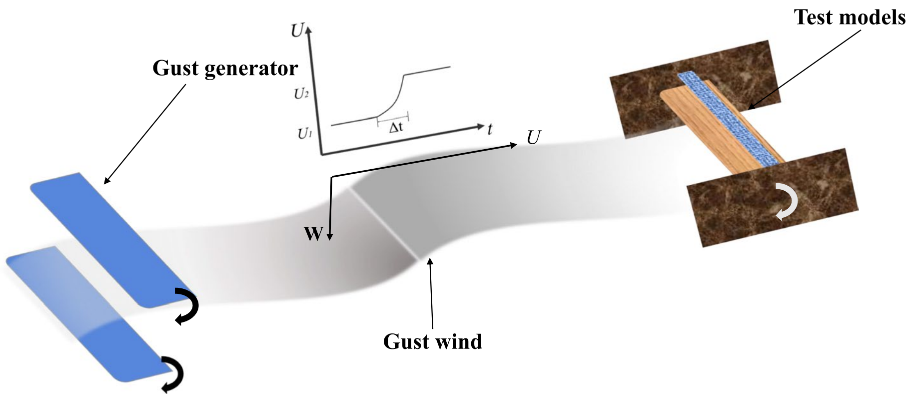


Fig. 7 A sudden change of wind velocity

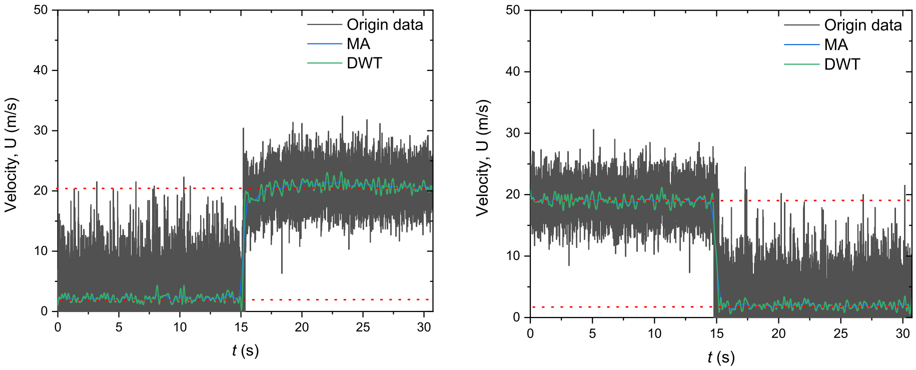


Fig. 8 Wind speed time series sample

mutation is one of the characteristics of gust wind, and the average wind velocities undergo at least one change in a short period. In order to highlight this characteristic of gust wind, the status of wind speeds before and after changes are defined as U_1 and U_2, and a time of radical changes in wind velocities is expressed as $\Delta t = T_2 - T_1$ (T_1 is the ending point of U_1 and T_2 is the beginning point of U_2), as shown in Fig. 7. To generate the sudden-change airflow, the wind tunnel was first started up until the wind velocity U_1 reached the stable state, after that, the wind velocity will be changed U_2 in the shortest period Δt until it reached the stable state again.

Figure 8 shows the 2 sample decomposition of wind speed records simulated by the gust-wind generator. The overlay of the total time history of the sudden change flow record confirms that interdependently of the choice of averaging methods, the computed non-stationary mean follows the temporal trend of the velocity. The "mean" values of wind velocity vary significantly with time. Both approaches display similar changing rules of mean-wind velocities with time, and the local peaks vary between 1.40% and 6.61% percentage difference, the peaks from the DWT approach tend to be slightly larger in magnitude by 0.24% than those from the running mean.

Figure 8a shows that the wind velocity accelerated from 2.31 m/s to 20.23 m/s and when an action potential is initiated, the gust vanes go from the closed state to the open state. The airflow can pass through in an instant and the accelerating time Δt was

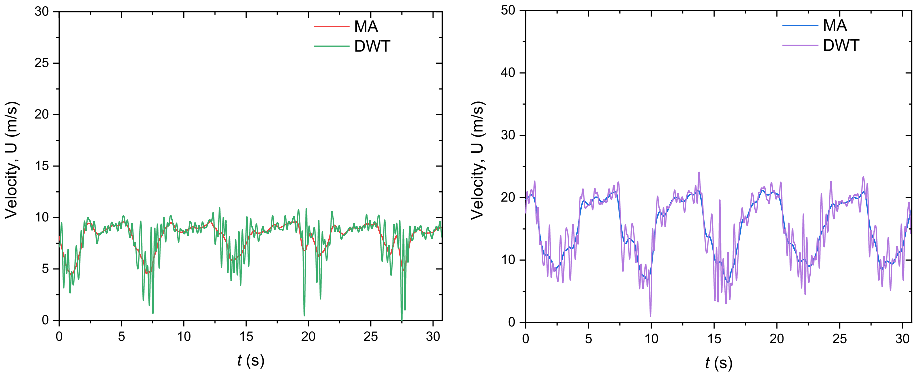


Fig. 9 Time history of the wind velocity of a single pseudo harmonic

defined as 0.33 s, and the corresponding acceleration was 54.30 m/s^2. Meanwhile, the gust-wind generator can negatively control operation, as shown in Fig. 8b, the wind velocity decelerated from 19.66 m/s to 1.76 m/s and when an action potential is initiated the gust vanes go from 0° to 90 °. The airflow stopped in an instant and the decelerating time Δt was defined as 0.44 s, and the corresponding acceleration was 40.68 m/s^2.

4.4 Continuous gust

For a sinusoidally oscillating flow, the continuous sinusoidal mode of the gust wind generator was tested for a range of amplitudes and frequencies for two tunnel-free-stream velocities. The initial velocity in a wind tunnel is $U_1 = 12$ and $U_1 = 25$, respectively. The time histories in Fig. 9 indicate the reciprocating characteristic of the oncoming flow. As expected, the amplitude of the induced gust is increases with larger gust vane deflections. The oscillatory pattern is visible for all combinations of amplitude and frequency, however at higher frequencies for the low wind speed amplitude case, the pattern becomes less sinusoidal with distorted peaks. Pure sinusoidal waves, especially for vertical turbulence, can hardly be generated because the attenuation of turbulence along the test section and the wind tunnel wall interference are complex. However, the sinusoidal type transient gust is another type of unconventional wind flow, which is normally observed in mountain areas and cannot be generated in a traditional boundary layer wind tunnel, as mentioned above in Fig. 1. By comparison in the relation curves Figs. 1 and 9, wind speed varies with time generated in the CSU wind tunnel are similar to that obtained in a mountain area.

5 Conclusion

A new gust-wind generator at the Central South University (CSU) wind tunnel is utilized to simulate gust winds in mountain areas. The system is worked through an advanced control system and a technology basis of theoretic to identify vanes movements leading to the target wind speed time history. The system is capable of generating applicable transient nature of wind speed and the current study simulated two kinds of typical mountain-valley wind. In the next step, the gust-wind generator will be improving and launching projects on other types of non-stationary winds and their effects on railway-related structures.

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Authors' contributions
Simin Zou performed the experiment and the data analyses and wrote the manuscript; Xuhui He helped perform the analysis with constructive discussions, financially supported, and was a major contributor to writing the manuscript. All authors read and approved the final manuscript.

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Availability of data and materials
All data generated or analyzed during this study are included in this published article.

Declarations

Competing interests
Xuhei He is an editorial board member for Advances in Bridge Engineering and was not involved in the editorial review, or the decision to publish, this article. All authors declare that there are no competing interests.

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References

Belu R, Koracin D (2013) Statistical and spectral analysis of wind characteristics relevant to wind energy assessment using tower measurements in complex terrain. N. p., Country Web
Butler K, Kareem A (2007) Physical and numerical modeling of downburst generated gust fronts. In: Proceedings of the 12th international conference on wind engineering, Cairns, Australia, pp 791–798
Cao S, Nishi A, Kikugawa H, Matsuda Y (2002) Reproduction of wind velocity history in a multiple fan wind tunnel. J Wind Eng Ind Aerodyn 90(12–15):1719–1729
Guo WW, Xia H, Karoumi R, Zhang T, Li X (2015) Aerodynamic effect of wind barriers and running safety of trains on high-speed railway bridges under cross winds. Wind Struct 20(2):213–236
Gurley K, Kareem A (1999) Applications of wavelet transforms in earthquake, wind and ocean engineering. Eng Struct 21:149–167
Han Y, Shen L, Xu G, Cai CS, Hu P, Zhang J (2018) Multiscale simulation of wind field on a long-span bridge site in mountainous area. J Wind Eng Ind Aerodyn 177:260–274
He XH, Zou SM (2021a) Advances in wind tunnel experimental investigations of train–bridge systems. Tunn Undergr Space Technol 118:104157
He X, Zou S (2021b) Crosswind efects on a train–bridge system: Wind tunnel tests with a moving vehicle. Struct Infrastruct Eng. https://doi.org/10.1080/15732479.2021.1966056
Hu P, Han Y, Xu GJ, Li YL, Xue FR (2018) Numerical simulation of wind fields at the bridge site in mountain-gorge terrain considering an updated curved boundary transition section. J Aerosp Eng 31(3):04018008
Hu P, Li YL, Huang GQ, Kang R, Liao HL (2015) The appropriate shape of the boundary transition section for a mountain-gorge terrain model in a wind tunnel test, wind and structures. Wind Struct 20(1):15–36
Huang GQ, Cheng X, Peng LL, Li MS (2018) Aerodynamic shape of transition curve for truncated mountainous terrain model in wind field simulation. J Wind Eng Ind Aerodyn 178:80–90
Jiang FY, Zhang MJ, Li YL, Zhang JY, Qin JX, Wu LH (2021) Field measurement study of wind characteristics in mountain terrain: focusing on sudden intense winds. J Wind Eng Ind Aerodyn 218:104781
Jing H, Liao H, Ma C, Tao Q, Jiang J (2020) Field measurement study of wind characteristics at different measuring positions in a mountainous valley. Exp Thermal Fluid Sci 112:10999
Kijewski T, Kareem A (2003) Wavelet transforms for system identification in civil engineering. Comput Aided Civ Infrastruct Eng 18:339–355
Kobayashi H, Hatanaka A (1992) Active generation of wind gust in a two-dimensional wind tunnel. J Wind Eng Ind Aerodyn 42(1–3):959–970
Kobayashi H, Hatanaka A, Ueda T (1994) Active simulation of time histories of strong wind gust in a wind tunnel. J Wind Eng Ind Aerodyn 53(3):315–330
Kwon DK, Kareem A (2009) Gust-front factor: new framework for wind load effects on structures. J Struct Eng 135(6):717–732
Li CG, Chen ZQ, Zhang ZT, Cheung JCK (2010) Wind tunnel modeling of flow over mountainous valley terrain. Wind Struct 13(3):275–292
Li Y, Xu X, Zhang M, Xu Y (2017b) Wind tunnel test and numerical simulation of wind characteristics at a bridge site in mountainous terrain. Adv Struct Eng 20(8):1223–1231
Li YL, Hu P, Xu XY, Qiu JJ (2017a) Wind characteristics at bridge site in a deep-cutting gorge by wind tunnel test. J Wind Eng Ind Aerodyn 160:30–46

Li YL, Jiang FY, Zhang MJ, Dai YY, Qin JX, Zhang JY (2022) Observations of periodic thermally-developed winds beside a bridge region in mountain terrain based on field measurement. J Wind Eng Ind Aerodyn 225:104996
Mattuella JML, Loredo-Souza AM, Oliveira MGK, Petry AP (2016) Wind tunnel experimental analysis of a complex terrain micrositing. Renew Sust Energ Rev 54:110–119
Montenegro PA, Carvalho H, Ortega M, Millanes F, Goicolea JM, Zhai W, Calcada R (2022) Impact of the train-track-bridge system characteristics in the runnability of high-speed trains against crosswinds – part I: running safety. J Wind Eng Ind Aerodyn 224:104974
Ren HH, Laima SJ, Chen WL, Zhang B, Guo AX, Li H (2018) Numerical simulation and prediction of spatial wind field under complex terrain. J Wind Eng Ind Aerodyn 180:49–65
Ren WM, Cheng P, Ma CM, Li ZG, Wang Q, Chen F (2021) Field measurement study of wind characteristics at different measuring positions along a bridge in a mountain valley. J Wind Eng Ind Aerodyn 216:104705
Simiu E, Scanlan RH (1996) Wind effects on structures: fundamentals and applications to design (Vol. 688). Wiley, New York
Song JL, Li JW, Flay RGJ (2020) Field measurements and wind tunnel investigation of wind characteristics at a bridge site in a Y-shaped valley. J Wind Eng Ind Aerodyn 202:104199
Tamura Y (2009) Wind-induced damage to buildings and disaster risk reduction APCWE-VII. In: The seventh Asia-Pacific conference on wind engineering, Chinese Taiwan
Wang L, Kareem A (2004) Modeling of non-stationary winds in gust-fronts. In: Proceedings of the 9th ASCE specialty conference on probabilistic mechanics and structural reliability PMC2004, Albuquerque, New Mexico, USA, July 26-28, 2004
Wang Z, Zou YF, Yue P, He XH, Liu LL, Luo XY (2022) Effect of topography truncation on experimental simulation of flow over complex terrain. Appl Sci 12(5):2477
Xing LF, Zhang MJ, Li YL, Zhang ZJ, Yin DG (2021) Large eddy simulation of the fluctuating wind environment at a bridge site in the mountainous area. Adv Bridge Eng 2:26
Yang K, Koike T, Fujii H, Tamura T, Xu XD, Bian LG, Zhou MY (2004) The daytime evolution of the atmospheric boundary layer and convection over the Tibetan Plateau: observations and simulations. J Meteorol Soc Jpn 82(6):1777–1792
Zhang J, Zhang M, Li Y, Qian Y, Huang B (2020a) Local wind characteristics on bridge deck of twin-box girder considering wind barriers by large-scale wind tunnel tests. Nat Hazards 103(1):751–766
Zhang J, Zhang M, Li Y, Qin J, Wei K, Song L (2020b) Analysis of wind characteristics and wind energy potential in complex mountainous region in Southwest China. J Clean Prod 274:123036
Zhang MJ, Zhang JX, Li YL, Yu JS, Zhang JY, Wu LH (2020c) Wins characteristics in the high-altitude difference at bridge site by wind tunnel tests. Wind Struct 30(6):548–557
Zhang T, Xia H, Guo WW (2013) Analysis on running safety of train on bridge with wind barriers subjected to cross wind. Wind Struct 17(2):203–225
Zou SM, He XH, Hu L, Wang HF, Kareem A (2022a) Characteristics of the velocity field in slipstream induced by a CR 400 high-speed train leading-carriage. Measurement 196:112205
Zou S, He X, Wang H (2022b) Moving model experimental analysis of the slipstream produced by a simplistic square-back high-speed train. Adv Struct Eng 13694332221127771.
Zou YF, Yue P, Liu QK, He XH, Wang Z (2022) Wind field characteristics of complex terrain based on experimental and numerical investigation. Appl Sci 12(10):5124

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