Wind and Structures, *Vol. 29, No. 3 (2019) 195-207*
DOI: https://doi.org/10.12989/was.2019.29.3.195

Wind turbine testing methods and application of hybrid testing: A review

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(Received July 16, 2018, Revised June 5, 2019, Accepted June 17, 2019)

Abstract. This paper presents an overview of wind turbine research techniques including the recent application of hybrid testing. Wind turbines are complex structures as they are large, slender, and dynamic with many different operational states, which limits applicable research techniques. Traditionally, numerical simulation is widely used to study turbines while experimental tests are rarer and often face cost and equipment restrictions. Hybrid testing is a relatively new simulation method that combines numerical and experimental techniques to accurately capture unknown or complex behaviour by modelling portions of the structure experimentally while numerically simulating the remainder. This can allow for increased detail, scope, and feasibility in wind turbine tests. Hybrid testing appears to be an effective tool for future wind turbine research, and the few studies that have applied it have shown promising results. This paper presents a literature review of experimental and numerical wind turbine testing, hybrid testing in structural engineering, and hybrid testing of wind turbines. Finally, several applications of hybrid testing for future wind turbine studies are proposed including multi-hazard loading, damped turbines, and turbine failure.

Keywords: wind turbine; hybrid testing; wind tunnel; shaking table; multi-hazard

1. Introduction

There is a scientific consensus about the global threat of climate change, which calls for a reduction in carbon emissions through the use of renewable energy generation. Wind turbines are a promising source of clean energy that can be used in lieu of non-renewable energy sources. As a result, the use of wind turbines throughout the world has greatly expanded; in 2017 alone the global wind energy capacity was increased by 52GW, to a total of 540GW (GWEC 2017).

One consequence of this large expansion of wind power is the required use of higher risk locations for wind farms. Near-shore and offshore turbines typically face higher typhoon and hurricane risks, and onshore turbines are prevalent in seismic-prone areas such as northern China, California, and Japan. High-intensity wind events such as typhoons are responsible for the majority of the numerous wind turbine failures each year (Chou and Tu 2011) and are likely to increase in intensity in the future due to climate change (Haldar and Basu 2016). Research has also shown that earthquake loading may govern for turbines in high-seismic areas (Diaz and Suarez 2014, Mardfekri and Gardoni 2015). Furthermore, since identical turbines are often used in a given wind farm, mass failure is risked in single extreme events. Many of the most common wind turbine design codes (IEC 2015, Risø 2002, GL 2010) lack explicit guidelines for certain aspects of design (Diaz and Suarez 2014, Katsanos *et al.* 2016) and the structural design codes of some countries will result in unsafe wind turbine designs (Song *et al.* 2013, Stamatopoulos 2013). Overall, the wind turbine industry faces serious challenges from structural failures, and given the growth of this industry, further studies of wind turbines will be of great value.

From an engineering perspective, wind turbines are challenging structures to study, which limits the possible testing available to researchers. Wind turbines are large, slender, hollow, and uniquely shaped structures with little redundancy and whose behaviour will greatly vary depending on operational states as well as loading type and direction. Due to their high flexibility, their lifespan is limited by fatigue failure from dynamic wind and (for offshore turbines) wave loading, which is difficult behaviour to model and test. Additional structural damping is often added to turbine towers to combat fatigue loading – a summary of the mainstream vibration control methods for wind turbines can be found in Rezaee and Aly (2016) – which can further complicate testing.

Individual structural engineering tests are traditionally performed either experimentally or numerically. Experimental (or physical) testing analyses full-sized or scaled-down physical models to determine structural behaviour. This type of testing can accurately capture nonlinear or poorly-understood behaviour by testing real replicas of the structure, but the maximum scale of the model is often restricted by test budgets and equipment limitations, and smaller-scale models often struggle to accurately simulate structural properties. Alternatively, numerical (or analytical) testing, typically performed via

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http://www.techno-press.com/journals/was&subpage=7 ISSN: 1226-6116 (Print), 1598-6225 (Online)

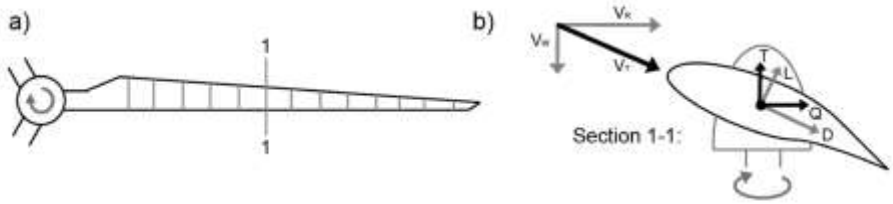

Fig. 1 Conceptual explanation of the BEM theory. (a) The propeller blade is divided into airfoil cross-sections and (b) The lift (*L*) and drag (*D*) of each cross-section due to the wind speed (V_T) are transformed into the thrust (*T*) and torque (*Q*), which are then summed along blade length for the total blade loads

computational analysis, allows for structures to be modelled at full scale with no real cost or equipment restrictions, however unknown or complex behaviour is difficult to capture as incorrect or flawed models will produce inaccurate outputs. Due to this, complimentary experimental or field research is often used to validate new numerical models, and cheaper and repeatable numerical testing can be used to design experimental tests. The advantages and challenges of both experimental and numerical testing are present in wind turbine research: the large size of turbines means that experimental tests are either extremely costly or heavily scaled down, and the complex behaviour of turbines can present challenges in numerical modelling. However, an alternative research method exists that appears quite promising for wind turbine studies: hybrid testing.

Hybrid testing (or hybrid simulation) combines experimental and numerical testing by modelling portions of the structure that undergo nonlinear or poorly-understood behaviour experimentally while the remainder of the structure is captured in numerical models. As a result, hybrid testing allows for accurate physical simulation of complex behaviour, such as nonlinear damping or failure, at large scale with reduced costs and equipment requirements. Hybrid testing may enable wind turbine research that is poorly suited for numerical only or experimental only studies.

This literature review will explore wind turbine research and the possible application of hybrid testing in five sections. The first two sections will present a review of numerical and experimental wind turbine studies respectively and discuss the advantages and challenges of each method. Subsequently, the development and capabilities of hybrid testing for general structural engineering research will be presented. The final sections of this review paper present the few instances of wind turbine research that have applied hybrid testing and propose possibilities for future research.

2. Numerical wind turbine studies

Numerical testing involves applying loading to a numerical wind turbine model which is typically developed using energy methods, multi-body dynamics, or finite element modelling (FEM). The level of detail of a model will be determined by the scope of the research: degrees of freedom (DOF) not relevant to the study will often be ignored to reduce the computational cost of the model. Though this distinction does not exist in practice, for the purpose of organising this section numerical turbine models will be generalized as either low-detail (such as models developed using energy methods, multi-body dynamics, or beam elements) or high-detail (such as those made from shell elements). In general, low-detail models are more concerned with the global behaviour of the structure, whereas high-detail models are used for more specific analysis of local structural behaviour. The numerical studies presented here are additionally summarized in Table 1 at the end of this section.

The Blade Element Momentum (BEM) theory (Glauert 1935) is used to numerically calculate wind-induced turbine blade loads. It consists of dividing the turbine blade along its length, determining the torque and thrust for each airfoil slice, and summing these for the total blade responses. The torque and thrust loads represent the side-to-side and fore-aft loads on the nacelle respectively; these are derived from the lift and drag loads on the blades which are relative to the blade chord. Fig. 1 explains this visually. BEM theory has since been widely used in numerical wind turbine research, though due to its simplicity, the initial theory could produce significant error in blade force estimates. Consequently, many researchers have tried to improve the method by suggesting and validating modifications to the BEM theory (Maheri *et al.* 2006, Madsen *et al.* 2007, Macquart *et al.* 2012), including combining several previous modifications into a single method that showed large improvements in accuracy (Liu and Janajreh 2012). BEM theory has been introduced here as it is a fundamental component of numerical turbine testing and is applied in the majority of the research discussed in this section.

Low-detail models are commonly used in wind turbine research due to their reduced complexity and computational costs. Several examples of this type of research are summarized here: Murtagh *et al.* (2008) used a multi-body dynamic turbine model to determine vibration reduction from tuned mass dampers. Similarly, Van der Woude and Narasimhan (2014) studied the effect of a turbine tower with vibration isolator subjected to seismic loading using a beam element model. Kessentini *et al.* (2010) used energy methods to develop a turbine model to study tower-blade coupling. Adhikari and Bhattacharya (2011) and Rong *et al.* (2017) developed analytical solutions for estimating the first natural frequency of wind turbine towers when

Table 1 Summary of numerical wind turbine studies

Authors	Year	Turbine Type	Load Cases*	Testing Indices	Numerical Model
Zhao *et al.*	2019	Onshore	HW	Tower failure	Shell model
Zhang *et al.*	2019	Onshore	EQ	Top response	Beam model
Ebrahimi and Mardani	2018	Turbine blade	SW	Blade velocity and drag	High detail CFD
Wang *et al.*	2018	Onshore	SW	Power generation	Beam model in FAST
Amirinia and Jung	2017	Onshore	HW	Base moment	Beam model in FAST
Dai *et al.*	2017b	Onshore	HW	Tower stress and failure	Shell model
Ke *et al.*	2017	Onshore	HW	Displacement, modal frequencies, tower failure	High detail CFD
Nunez-Casado *et al.*	2017	Onshore	SW	Fatigue damage	Beam model
Rong *et al.*	2017	Fixed offshore	AR	Modal frequencies	Beam model
Berny-Brandt and Ruiz	2016	Onshore	SW	Fatigue damage	Shell model
Bukala *et al.*	2016	Micro turbines	SW	Power generation	Beam model in FAST
Chen and Xu	2016	Onshore	HW	Blade and tower failure	Beam model
Smith and Mahmoud	2016	Onshore	SW, EQ	Shear, power, stress, fatigue	Beam and shell model
Chen *et al.*	2015a	Onshore	HW	Blade and tower failure	Beam model
Dai *et al.*	2015a	Onshore	EQ	Modal frequencies, shear	Beam model
Do *et al.*	2015	Onshore	SW	Fatigue damage	Beam model
Mardfekri and Gardoni	2015	Fixed offshore	SW, HW, WV, EQ	Base shear and moment	Beam model in FAST
Diaz and Suarez	2014	Onshore	SW, EQ	Blade and tower stress	Beam model
Van der Woude and Narasimhan	2014	Onshore	SW, EQ	Top response	Beam model
Zhang *et al.*	2014a	Onshore	HW	Base stress	Shell model
Wang *et al.*	2013	Onshore	HW	Top response, base stress	Shell model
Adhikari and Bhattacharya	2011	Onshore	AR	Modal frequencies	Beam model
Kessentini *et al.*	2010	Onshore	AR	Modal frequencies	Beam model
Murtagh *et al.*	2008	Onshore	SW	Nacelle displacement	Beam model
Ishihara *et al.*	2005	Onshore	HW	Base moment, tower failure	Shell model

*Load Cases: 'SW' refers to service wind loading, 'HW' refers to high-intensity refers to high-intensity wind loading, 'WV' refers to wave loading, 'EQ' refers to seismic loading, 'AR' refers to artificial static or harmonic loading

considering the effect of soil-structure interaction. Diaz and Suarez (2014) used a multi-body dynamic model to compare the wind- and seismic-induced responses of a wind turbine. Do *et al.* (2015a, b) used a beam element model to assess the fatigue life of wind turbine tower bases under wind loading and applied this model to design site specific foundations. Dai *et al.* (2015a, 2017a) developed methodologies using beam element models paired with field measurements to allow for improved assessment of the seismic resistance and structural health of in-service wind turbines. Nunez-Casado *et al.* (2017) used beam element models to estimate fatigue build up in turbine towers and suggested assembly strategies for mitigation. Zhang *et al.* (2019) adopted lumped mass beam model for wind turbine vibration control technology study.

High-detail models are typically used to reveal very specific information about wind turbines such as structural yielding or failure behaviour. Ishihara *et al.* (2005) matched numerical failures to the real failures of three turbines in a wind farm using shell element models subjected to measured wind speeds. Similar results were found when Wang *et al.* (2013) used a shell element model to study turbine responses under different wind loading directions. Zhang *et al.* (2014a) used a shell element model to gauge the importance of soil-structure interaction on turbine behaviour as well as to conclude that tower base buckling is the most likely failure behaviour of a turbine in a typhoon. This is supported by failure studies (Chen *et al.* 2015a, Chen and Xu 2016) investigating real turbine damage from typhoons using beam element models subjected to the measured wind speeds. Smith and Mahmoud (2016) used a similar type of turbine model to estimate tower yielding from multi-hazard loading. Berny-Brandt and Ruiz (2016) used a shell element model to study turbine reliability and lifetime likelihood of fatigue failure. Dai *et al.* (2017b) and Zhao *et al.* (2019) used a detailed shell element model to study the plastic yielding and failure of turbine towers, finding results that agree with previous loading direction and failure location studies. Finally, Ebrahimi and Mardani (2018) used a high-detail model with computational fluid dynamics to study turbine blade modifications to reduce the aero-acoustic noise production of wind turbines, which has been shown to be a concern in current designs (Dai *et al.* 2015b).

The development of computer-aided engineering (CAE) tools for numerical testing of turbines has been an asset for this type of research as they allow for faster and more accurate testing of turbines. While there are dozens of CAE tools for turbine design (Luhur *et al.* 2016), for brevity applications of only one of the more prominent programs will be presented here. The CAE tool FAST (Jonkman 2018) has been expanded since its release to include subroutines for seismic (Prowell *et al.* 2010) and hydrodynamic (Jonkman 2009) loads, as well as improvements to the BEM theory (Ning *et al.* 2015). As a result, it has been applied in many recent studies including when Mardfekri and Gardoni (2015) used it to model offshore turbines under multi-hazard loading in high-seismic and high-wind areas, developing probabilistic models of their reliability and concluding that seismic and wind loading govern respectively. Bukala *et al.* (2016) used a FAST model to perform detailed testing of small wind turbines, which allowed for more design variations to be studied than would have been feasible in experimental testing. Amirinia and Jung (2017) used FAST to compare turbine responses in hurricane and conventional wind spectra, and Wang *et al.* (2018) used FAST to test a newly designed turbine control system that improved power generation and power output.

Similarly, the development of computational fluid dynamics (CFD) has expanded the capabilities of numerical testing. CFD is a modern numerical analysis method that simulates fluid flow and is often used for structural analysis of wind loaded structures – a review of which can be found in Dagnew and Bitsuamlak (2013). As a very modern research tool, it has seen only limited application in wind turbine study, such as when Ke *et al.* (2017) used CFD to study the effect of blade position after shutdown on the tower response and stability and concluded that that it can greatly modify the lower natural frequencies of the turbine, which may affect the displacement and failure wind speed of the structure.

Numerical modelling is an extremely effective method of performing wind turbine research. Its relatively low cost allows for large quantities and a large variety of testing, the data gathered from which is crucial for identifying weaknesses in current turbine design requirements and suggesting improvements. It excels at the preliminary and design stages of research. The advent of modern CAE tools and CFD continues to further improve the quality and ease of numerical testing. The main weakness of this type of modelling is that it is challenging to develop and test models that accurately capture highly nonlinear responses such as detailed failure behaviour and complex dampers. For wind engineering, these structures are immersed in the lower turbulent atmospheric boundary layer which can be challenging for numerical wind simulations. In these cases, alternative forms of research, such as experimental testing, can be of great value to validate these numerical models.

3. Experimental wind turbine studies

Experimental testing, the other commonly used method of wind turbine research, has the primary advantage of accurately capturing nonlinear behaviour. It can also be used to determine structural properties for use in numerical models (Chou and Tu 2011, Ishihara *et al.* 2015, Lee and Bang 2012), as well as validate new numerical models. However, given the large size of modern wind turbines, test budgets and equipment limitations mean that models typically require significant scaling, which makes it difficult to accurately maintain the dynamic characteristics of the structure. The problem of cost is further exacerbated when performing failure testing, as it limits the number of allowable tests. Due to these issues, experimental testing makes up only a minority of wind turbine studies (Katsanos *et al.* 2016). Notable modern examples of experimental turbine testing that consider seismic, wave and particularly wind loading will be presented here, and are summarized at the end of this section in Table 2.

Experimental seismic testing of structures is typically performed using shaking tables. Famously, Prowell *et al.* (2009) experimentally tested a full-scale 65kW wind turbine on a large shaking table, and compared the results to equivalent numerical FEM models. The structural damping was calculated, additionally it was concluded that the FEM models showed good agreement. Similarly, Chen *et al.* (2015b) tested a 1/13 scale model of a 3.3MW turbine on a shaking table to study the effect of a tuned liquid column damper (TLCD) on the dynamic response of an offshore wind turbine subjected to wind-wave and earthquake loads. Thus, an equivalent accelerogram of wind-wave loading was developed and applied to the turbine model via the shaking table. The testing concluded that TLCD’s were effective at reducing the fatigue load and structural response from both loadings, and the results were used to validate numerical models. Mao *et al.* (2018) have further tested this turbine model by subjecting it to seismic loading from different directions.

Experimental testing of turbines under wind loads is typically performed in a wind tunnel. Interestingly, Sim *et al.* (2014) instead simulated the wind-induced blade loads on a full-scale 22 m turbine tower using an actuator. This model was tested to failure and was used to validate a numerical shell element model. Ma *et al.* (2015) similarly tested a 1/15 scale model of a 100 m tall prestressed concrete wind turbine tower to determine structural properties and assess possible advantages of concrete towers compared to traditional steel ones.

Wind tunnel testing is effective for large-scale airfoil design of turbine blade sections (Selig and McGranahan 2004), but wind tunnel tests of full turbines face scaling challenges compared to typical bluff bodies. Eq. (1) shows the Reynolds number (Re) which is a dimensionless parameter used to predict flow behaviour, and for accurate results in certain experimental tests the Re value must remain the same between the full-scale structure and scaled model. In wind tunnel testing, u is the wind velocity, L is the characteristic length, and ν is the kinematic viscosity of air. In most structural wind tunnel tests, Reynolds

Table 2 Summary of experimental wind turbine studies

Authors	Year	Turbine Type	Load Cases*	Testing Indices	Experimental Model
Mao *et al.*	2018	Onshore	EQ	Tower displacement, shear and moment	1:20 65 m turbine on shaking table
Abdelkader *et al.*	2017	Onshore	HW	Base loads	1:150 90 m turbine in wind tunnel
Bayati *et al.*	2016	Floating offshore	SW, WV	Top response	1:75 120 m turbine in wind tunnel & wave basin
Campagnolo *et al.*	2016	Onshore	SW	Power	6x 1.1 m turbines in wind tunnel
Chen *et al.*	2015b	Fixed offshore	SW, WV, EQ	Top response	1:13 100 m turbine on shaking table
Ma *et al.*	2015	Onshore	AR	Top response and tower stress	1:15 100 m turbine using actuator
Navalkar *et al.*	2015	Onshore	SW	Blade loads	Small scale 120 m turbine in wind tunnel
Kimball *et al.*	2014	Floating offshore	SW, WV	Blade loads, platform pitch	1:50 90 m turbine in wind tunnel & wave basin
Sim *et al.*	2014	Onshore	AR	Top response	22 m turbine using actuator
Imraan *et al.*	2013	Turbine blades	SW	Blade loads	0.5 m small blades in wind tunnel
Prowell *et al.*	2009	Onshore	EQ	Modal frequencies, tower response	22 m turbine on shaking table
Selig and McGranahan	2004	Turbine blade	SW	Blade loads	Large scale blade sections in wind tunnel

*Load Cases: ‘SW’ refers to service wind loading, ‘HW’ refers to high-intensity wind loading, ‘WV’ refers to wave loading, ‘EQ’ refers to seismic loading, ‘AR’ refers to artificial static or harmonic loading

number scaling is not feasible to maintain; for example, assuming unchanged air density and temperature, a 1:50 scale model would require wind tunnel wind speeds to be increased by 50x to maintain Re similitude – an infeasible speed for many tests. Fortunately, when testing bluff body structures, it may not be necessary to maintain Reynolds number scaling similarity. Beyond a minimum threshold, the wind loads are typically assumed to be independent of the Reynolds number of the flow for bluff bodies. Conversely, turbine blade loads are heavily dependent on the Reynolds number of the flow (Burton *et al.* 2002) and thus wind turbine blades can’t merely be geometrically scaled down in wind tunnel testing.

$$Re = \frac{uL}{\nu} \tag{9}$$

$$\lambda = \frac{\omega R}{u} \tag{10}$$

$$Fr = \frac{u}{\sqrt{gL}} \tag{11}$$

Instead, when wind tunnel tests of turbine models are performed, the tip speed ratio is typically used for scaling (Stein and Kaltenbach 2016) and different turbine blades which are designed for lower Reynolds number flow are used to accurately simulate thrust and torque loads (McTavish *et al.* 2013). The tip speed ratio (λ) is shown in Eq. (2), where ω is the rotor rotational speed, R is the rotor radius, and u is the wind speed in wind tunnel tests. Systems have been developed to optimize turbine blades for different Reynolds number flows, allowing for easier wind tunnel turbine test design in modern research (Ge *et al.* 2016). Examples of wind tunnel tests of scaled turbines with redesigned low-Reynolds-flow blades include Imraan *et al.* (2013) testing the power output of telescopic turbine blades and proposing a loss-correction factor for BEM theory to allow for numerical modelling of them. Navalkar *et al.* (2015) tested a scaled turbine model with independent active blade pitch control to validate the efficiency improvement provided by a developed blade control system. Campagnolo *et al.* (2016) tested six scaled turbines together in a large wind tunnel to study two wake control methods for wind farms. Abdelkader *et al.* (2017) tested a rigid turbine model in a wind tunnel to generate base loading due to wind for use in foundation design, and produced useful load time histories after correcting for resonance and the Re number difference.

Wind tunnels equipped with wave basins are capable of experimentally testing offshore turbines. However, this further complicates small-scale tests as Froude scaling is used to accurately model hydrodynamic loads. The Froude number (Fr) is a dimensionless parameter often used in hydrodynamic study to determine the behaviour of submerged objects in water. It is shown in Eq. (3), where u is the flow speed, g is the acceleration due to gravity, and L is the characteristic length in a wave basin. Since u and L have opposite ratios in Eqs. (1) and (3), it can be seen that Froude scaling is fundamentally incompatible with Reynolds scaling. Redesigned blades can once again be used to improve the accuracy of wind loads, but research suggests that it is impossible to accurately model both the blade thrust and torque response on a turbine model when using Froude scaling (Kimball *et al.* 2014). Thus, the current practice is to ensure thrust coefficient matching, as it has a larger impact on turbine response, while accepting small amounts of error from torque mismatch. Bayati et al. (2016) used this technique when they tested a scaled floating turbine with modified blades designed for thrust matching in a wind tunnel with a wave basin, concluding that accurate responses were still obtained despite scaling challenges.

Experimental testing of wind turbines shows great promise for testing failure behaviour as well as a form validation for numerical models. However, this type of testing is held back by the structures' large size and the challenges of model scaling. As a result of the scaling challenges, wind tunnel tests of wind turbines remain uncommon for a structure so heavily governed by and designed around wind loading. Hybrid testing, alternatively, may reduce these challenges by numerically modelling most of the structure, allowing for increased testing scale and scope.

4. Structural engineering applications of hybrid testing

Hybrid testing combines experimental and numerical methods. As previously presented, experimental testing excels at capturing complex nonlinear behaviour, but full-scale testing is often infeasible and small-scale testing presents challenges. Opportunely, complex structural behaviour is typically restricted to small portions of the structure, which allows for more affordable numerical simulations to be used to model the remainder of the structure. This is the conceptual basis for hybrid testing. Here, the historical development of hybrid testing is summarized (based on McCrum 2015) and several representative examples of modern hybrid testing are presented.

An understanding of the use of purely numerical integration for structural analysis is required to describe hybrid testing. In numerical structural analysis, a structure is simplified into a series of DOF's based on the scope of the research. Connections between DOF's represent structural properties. A simple example could be to approximate a water tower as a single degree of freedom lumped mass structure, connected to a fixed base via a beam with stiffness and damping. To solve for structural response due to loading, the equation of motion (EOM) of the structure is developed [Eq. (4)] and solved progressively. In Eq. (4), i is the time step, M is the mass matrix, $\ddot{x}_i$ is the nodal acceleration vector, C is the damping matrix, $\dot{x}_i$ is the nodal velocity vector, K is the stiffness matrix, x_i is the nodal displacement vector, and F_i is the external applied force vector. Using a numerical integration algorithm, the subsequent nodal displacement vector (x_{i+1}) is calculated, followed by the rest of the response for the subsequent time step. This process is continued for all time steps to determine the time history of the structural behaviour.

$$M\ddot{x}_i + C\dot{x}_i + Kx_i = F_i \tag{4}$$

Pseudo dynamic testing (PDT) was the original form of hybrid testing. It was conceived by Hakuno *et al.* (1969) and developed by Takanashi *et al.* (1974), as explained in a summary by Takanashi and Nakashima (1987). Originally, the entirety of the structure was modelled both experimentally and numerically. The same numerical integration process described previously occurs, however, the EOM [Eq. (5)] is slightly modified by the presence of R_i: the restoring force vector. The numerical simulation of the structure still predicts x_i, but these displacements are then applied to the physical structure by actuators. The measured resisting force of the physical model, R_i, is returned to numerical model, used to predict x_{i+1}, and the process is repeated for subsequent time steps. Fig. 2 illustrates this process using the previous water tower example – the numerical model predicts the displacement that is applied to the experimental model which, in turn, returns the restoring force. Pseudo dynamic testing has improved structural stiffness estimation as R_i is more accurate than Kx_i, particularly for plastic behaviour. Since this loading is performed quasi-statically (i.e. loads are applied slowly such that the velocity and acceleration of the physical structure are essentially zero), the inertial and damping forces of the structure are exclusively simulated in the numerical model, and thus the experimental component of pseudo dynamic testing is not appropriate for testing structures with velocity- or acceleration-dependent behaviour such as vibration dampers.

$$M\ddot{x}_i + C\dot{x}_i + R_i = F_i \tag{5}$$

The development of real-time hybrid testing (RTHT) was an important leap for hybrid simulation as it greatly expanded the capabilities of the research method. Since this type of testing is run at real-time, velocity- and acceleration-dependent behaviour can be captured in the physical model which improves accuracy and allows for additional types of structures to be tested. In RTHT, the restoring force measured from the physical model may include stiffness, damping and/or inertial forces, depending on the test. Historically, the first example of real-time hybrid testing was performed by Nakashima *et al.* (1992). Real-time hybrid testing faces new challenges compared to PDT, primarily that the numerical model must now be sufficiently lightweight and must be run on sufficiently powerful equipment to perform in real time. For some testing, this has meant a required numerical integration speed of 1ms per time step (Li *et al.* 2017). Both real-time hybrid testing and pseudo dynamic testing still see wide use in structural engineering research, as will be shown below.

The final major evolution of hybrid testing was the development of substructuring by Dermitzakis and Mahin (1985). Substructuring allows multiple partial sections of the structure to be tested separately from one another to optimize testing. Typically, this means that the experimental substructures will consist of sections of interest of the structure where nonlinear behaviour will occur, while the rest of the structure is numerically modelled. Fig. 3 shows a theoretical substructured hybrid test, similar to the test performed by McCrum and Broderick (2013), consisting of a multi-bay steel frame with a single braced bay, where the

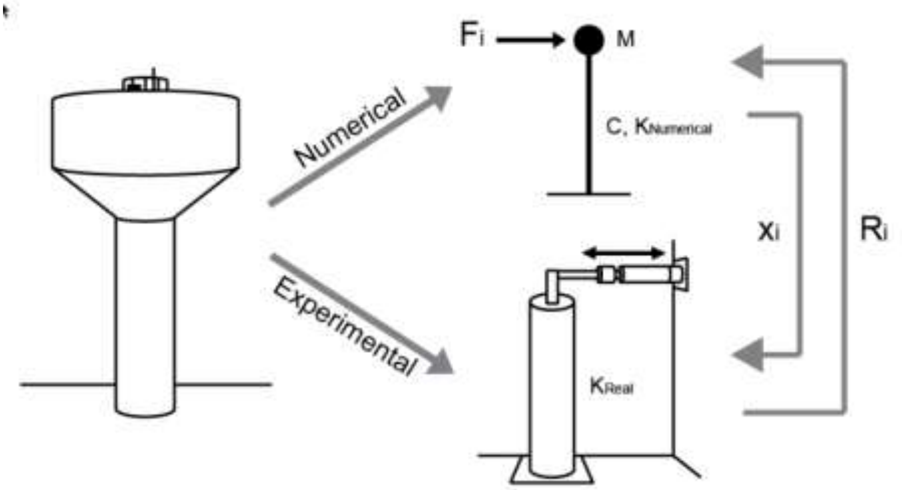

Fig. 2 Theoretical pseudo dynamic test of a water tower

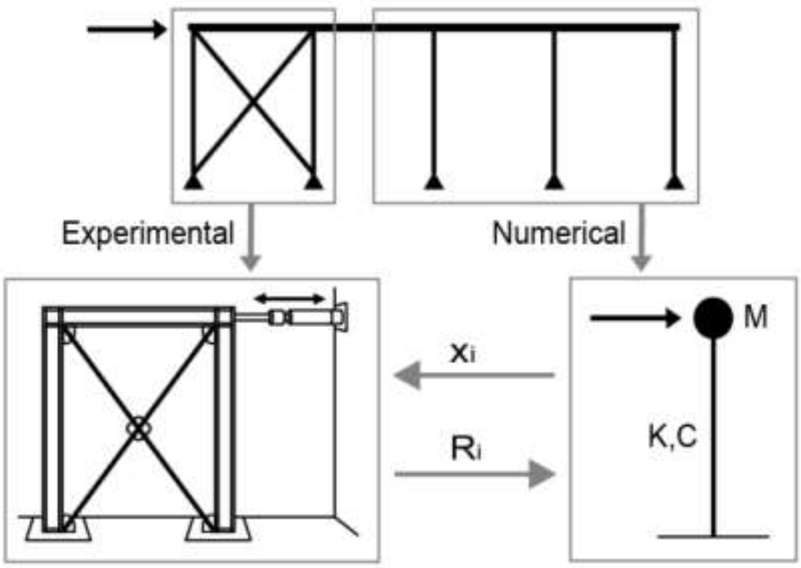

Fig. 3 Theoretical substructured hybrid test of a one-story braced frame

braced bay is physically modelled and the rest of the frame is modelled numerically. Both substructures are tested simultaneously and information is passed between them. Substructuring allows hybrid testing to be used to perform large-scale experimental tests without physically modelling the entire structure, thus unlocking the full potential of the testing technique. As a result, substructuring is employed in nearly all examples of modern hybrid testing. Distributed hybrid testing is a specialized form of substructuring that tests multiple substructures simultaneously in separate facilities, which allows researchers to take advantage of specialized equipment available at multiple different sites (Watanabe *et al.* 2001, Spencer *et al.* 2004, Wang *et al.* 2008, Ojaghi *et al.* 2014).

This hybrid testing process is its most common form and can be referred to as displacement control: target displacements are applied to the experimental substructure and the resulting restoring force is measured and used by the numerical model. However, hybrid testing can also be performed via force control: where a target force is applied to the experimental substructure via actuators and the resulting displacement is measured and returned to the numerical model. A comparison of the equations of motion of the structure using these two methods can be found in Plummer (2006). Force control can result in more precise control of actuators (Yalla and Kareem 2007) which is critical for fields such as robotics, but is also applied in civil engineering such as in the control of some shaking tables. Still, the vast majority of hybrid testing research uses displacement control as it is simple to implement and is more stable (Shao *et al.* 2011). Force control is typically only used when experimental limitations of the hybrid test requires it, such as when Shao *et al.* (2011) performed hybrid testing of a structure on a shaking table with additional actuation; since the shaking table was force-controlled, the additional actuation also had to be for stability purposes. Recently, Vilsen *et al.* (2019) and Ueland *et al.* (2018) performed hybrid tests of horizontally moored barges. Force control was used to more easily apply the tension loading to physical cables, as well it being easier to measure the displacement and acceleration of the floating models compared to the restoring force.

Error control for hybrid testing is continually being improved. To minimize error in hybrid tests, appropriate numerical integration algorithms and actuator controllers must be selected. The stability and explicitness of a numerical integration algorithm will determine its applicability to a given hybrid test; forms of the Newmark-beta method (Newmark 1959) are the most commonly used integration techniques, though numerous researchers have proposed alternatives (Ahmadizadeh and Mosqueda 2007, Chen *et al.* 2009, Kolay *et al.* 2015, Tang and Lou 2017, Kolay and Ricles 2017). Actuator controllers are required to minimize experimental error in hybrid testing by compensating for actuator response lag. Many researchers have developed actuator controllers for this purpose (Mosqueda *et al.* 2007, Lim *et al.* 2007, Phillips and Spencer 2012a, Phillips and Spencer 2012b, Chae *et al.* 2013), though seemingly none have become the standard. The selection of numerical integration algorithm and actuator controller is an important step to control error when designing a hybrid test.

There have been hundreds of applications of hybrid testing in structural engineering research, thus this paper will present summaries of only a few recent studies with the aim of displaying the capabilities of this testing technique. Friedman *et al.* (2014) studied the effect of magnetorheological (MR) dampers on the vibration response of a nine-story steel frame subjected to seismic loading, and used to results to validate a numerical model. A three-story damped steel frame acted as the physical substructure while the remainder was numerically simulated. Two papers (Tian *et al.* 2015, Jennings *et al.* 2015) used pseudo dynamic testing to study the effectiveness of retrofits on the seismic resistance of older residential homes. Numerical analysis was not an option for this study as the material properties of these older structures were not well known. Ramos *et al.* (2016) studied the failure behaviour of a four-story steel frame under seismic loads using pseudo dynamic testing, using the results to validate numerical models, and concluding that hybrid testing was an effective way of capturing this behaviour with limited budget and equipment. Hashemi *et al.* (2017) used pseudo dynamic hybrid simulation to test carbon fiber reinforced polymer (CFRP) repair of seismically damaged reinforced concrete columns. The base column of a five-story moment-resisting frame was loaded to failure, repaired, and its fragility was analyzed. Hybrid testing was chosen as the properties of CFRP-repaired columns are not well known. Finally, Murray and Sasani (2017) used pseudo dynamic testing to analyse the failure of a seven-story concrete frame building, determining detailed failure behaviour of the experimentally substructured columns as well as the global post-failure behaviour. This behaviour was captured with reduced experimental costs due to the application of hybrid testing.

Ultimately, hybrid testing can improve the scalability and fidelity of experiments, reduce equipment requirements, and validate numerical models. It excels at testing nonlinear behaviour, such as from complex vibration dampers or member failure, as well as unknown behaviour. However hybrid testing also has drawbacks: even with proper integration algorithm and actuator controller selections, some research suggests that hybrid testing continues to include fundamental modelling errors (Drazin *et al.* 2015). Additionally, as hybrid testing was originally developed for earthquake engineering, the vast majority of hybrid tests consider no other forms of loading, though a few hybrid tests of wind-loaded structures will be presented in the following section. Even with these concerns, due to fundamental limitations of experimental and numerical wind turbine tests, hybrid testing remains a promising candidate for future wind turbine research.

5. Hybrid testing of wind turbines

There have been some examples of the application of hybrid testing to wind turbine studies. As previously discussed, experimental testing of offshore turbines is particularly challenging due to a scaling mismatch between aerodynamic and hydrodynamic forces. Partially as a result of this, the majority of turbine research employing hybrid testing has studied offshore turbines.

There are several examples of studies on the development and optimization of hybrid testing techniques for turbines. Two studies (Bachynski *et al.* 2015, Karimirad and Bachynski 2017) examined the effect of limited actuation of wind loading in hybrid tests of floating and fixed offshore wind turbines, finding which DOF's were required to accurately model wind response and which could be safely ignored. Hall *et al.* (2014) ran numerical simulations in FAST of various floating turbine designs under different loading conditions to predict the required performance specifications of test equipment to ensure minimal error in theoretical hybrid tests of offshore turbines. Additionally, Koukina *et al.* (2015) developed a custom loading device for applying numerical wind loads to a floating offshore wind turbine during a real-time hybrid test, allowing for more accurate loading in this specific case.

Even with this preparatory research, there are only a few examples of actual hybrid testing of floating offshore wind turbines. Azcona *et al.* (2014) generated wind loads numerically and applied them to a physical floating turbine model using a fan, though the accuracy of this loading method was quite low. Additionally, Chabaud (2016) developed a framework to test floating offshore wind turbines. Numerically calculated wind loads were applied using a custom 6-DOF actuator while wave loads were applied using a wave basin, which avoided the scaling problem between hydrodynamic and aerodynamic loads.

There also exist two notable cases of hybrid testing of wind turbines. Brodersen *et al.* (2016) performed RTHT of a shallow water offshore turbine equipped with a hybrid damper. The goal of the study was to determine the vibration reduction effect of hybrid dampers, which involved the development of a simplified numerical turbine model. The physical substructure consisted of the hybrid damper, thus real-time testing was used for accurate loading. The hybrid damper was shown to surpass passive dampers when tuned correctly, and the results of the hybrid test showed good agreement with a concurrent numerical test.

Similarly, Zhang *et al.* (2016) released a detailed paper analyzing two large wind turbines equipped with tuned liquid dampers (TLD) using RTHT. This paper details the real-time hybrid testing of a TLD aligned to reduce the across-wind vibration of the nacelle and compares the results of this hybrid test to those from an equivalent numerical simulation. The TLD was physically modelled while a previously developed (Zhang *et al.* 2014b, Zhang *et al.* 2015) turbine model was numerically simulated. TLD's are very challenging to model numerically due the nonlinear behaviour of liquids, such as waves breaking or splashing, though models with reasonable accuracy have been developed using simplified assumptions (Tait *et al.* 2008). It was shown that the TLD's were effective in reducing across-wind vibrations, and that there was good agreement with the numerical model for less nonlinear behaviour but less agreement when behaviour was more nonlinear – such as when the wind speed was high and the TLD included screens. This research simultaneously highlights two uses of the hybrid testing method: to verify numerical models and to more accurately model the nonlinear behaviour of a vibration damper.

Hybrid testing has been applied to a handful of types of turbine research to good effect. Both conceptually and in practice, hybrid testing allows for research whose accuracy would otherwise suffer in numerical testing, and would be infeasible using experimental testing. That being said, these projects are exploratory in nature, designing and applying brand new turbines tests, and many possible applications of hybrid testing for wind turbines remain to be attempted.

6. Conclusions

This paper has presented literature collections of past wind turbine research and hybrid tests with the goal of exploring the potential application of hybrid testing to future wind turbine research. Modern wind turbines are unique structures which can be challenging to study. Despite this, previous wind turbine studies have successfully applied both numerical and experimental research techniques. Each of these forms of testing have advantages and disadvantages such as experimental models capturing nonlinear behaviour well but face financial and equipment limitations, while numerical testing can struggle to model this same behaviour but excels in terms of cost, versatility, and repeatability. Since nonlinear behaviour is often restricted to small sections of structures, substructured hybrid testing can be used to physically model only these areas while the remainder is numerically modelled. Alternatively, structures subjected to multi-hazard loading can apply certain loads experimentally and others numerically. Several examples of the capabilities of hybrid testing, including modelling of structural failure, damped structures, and materials with unknown structural properties, have been presented.

The complexity and scaling issues of wind turbines make them prime candidates for the application of hybrid testing for analysis. Other researchers agree with this observation as both preparatory research and actual hybrid tests of wind turbines have been recently performed. Two studies were presented of hybrid testing of damped fixed offshore turbines where the damper was physically substructured; these were excellent examples of the utility and feasibility of hybrid testing for wind turbine research.

This field of study remains in its infancy and thus there remain many possible uses and avenues of future research of wind turbines using hybrid testing. Several of these are proposed here:

- **Offshore turbines:** Floating offshore turbines are strong candidates for the use of hybrid testing as it addresses the issue of the fundamental scaling mismatch between aerodynamic and hydrodynamic loads. Preparatory research, including determining performance specifications and actuation requirements, has been performed, but there are few published examples of actual hybrid testing of these structures.
- **Multi-hazard loading:** Hybrid testing can be used to subject wind turbines to multi-hazard loading, including wind, wave, and seismic. Previous numerical research has shown that coupling between wind and seismic loading (Asareh and Volz 2013), as well as wind and wave loading in offshore turbines (Tran and Kim 2017, Calderer *et al.* 2014) plays an important role in determining the structural response of turbines but also introduces unique challenges. Experimental testing can struggle to simultaneously apply multiple loading types, but hybrid testing could allow for some loading to be experimentally modelled for greater accuracy while other loading is applied to the numerical model, as has been performed previously for some floating structures (Vilsen *et al.* 2019, Ueland *et al.* 2018, Koukina *et al.* 2015).
- **Damped turbines:** Dampers are often used to improve the service life and ultimate resistance of turbines. With the growing use of more complex, nonlinear dampers such as tuned liquid or magnetorheological, hybrid testing can be used physically test the damper while numerically modelling the turbine. Tests such as these are very common uses of real-time hybrid testing as the simulation technique allows for cost-effective experimental damper research.
- **Turbine failures:** Hybrid testing can be used to further study blade or tower failures of turbines, as it allows for failure testing that uses precise numerical loading and applies it to generate accurate experimental failure behaviour, while using a minimalist physical model that is less costly to replace than a purely experimental test.

In addition to these specific proposals, hybrid testing can also be used to validate complex numerical turbine models. These possible avenues of future research are in no way all-encompassing, but merely propose some of the more conspicuous applications of hybrid testing for wind turbine research. This is not to say that hybrid testing should be applied in all future wind turbine research; it is merely one more highly useful tool to add to a researcher's repertoire. Future research of wind turbines will be used to help design safer and more efficient turbines.

Acknowledgements

The authors would like to acknowledge the support from National Natural Science Foundation of China (51878426); International Collaboration Program of Science and Technology Commission of Ministry of Science and Technology, China (2016YFE0105600); International Collaboration Program of Science and Technology Commission of Shanghai Municipality and Sichuan Province (16510711300 & 18GJHZ0111); and the Fundamental Research Funds for Central Universities of China.

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