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The Research Grants Council of Hong Kong
NSFC/RGC Joint Research Scheme
Joint Completion Report

(Please attach a copy of the completion report submitted to the NSFC by the Mainland researcher)

Part A: The Project and Investigator(s)

1. Project Title

Study on the Mechanism and Application of Energy Transfer in the Nonlinear Self-excited System for 10 MW Level Wind Turbine System

2. Investigator(s) and Academic Department/Units Involved

	Hong Kong Team	Mainland Team
Name of Principal Investigator *(with title)*	Professor Songye ZHU	Professor Shitang KE
Post	Professor	Professor
Unit / Department / Institution	Civil and Environmental Engineering / The Hong Kong Polytechnic University	Civil Engineering / Nanjing University of Aeronautics and Astronautics
Contact Information	songye.zhu@polyu.edu.hk	keshitang@163.com
Co-investigator(s) *(with title and institution)*	N.A.	Prof. Tong-Guang WANG / Nanjing University of Aeronautics and Astronautics

3. Project Duration

	Original	Revised	Date of RGC/ Institution Approval *(must be quoted)*
Project Start date	1 Jan 2018		
Project Completion date	31 Dec 2021		
Duration *(in month)*	48		
Deadline for Submission of Completion Report	31 Dec 2022		

Part B: The Completion Report

5. Project Objectives

5.1 Objectives as per original application

1. To quantify wind-induced nonlinear self-exciting forces on large-scale wind turbines;
2. To characterize the relationship between the generation and development of nonlinear self-excitation forces and the unsteady development of vortex flow fields;
3. To investigate the energy transfer mechanism due to internal resonance among different vibration modes (or elements) in nonlinear self-excited response; and
4. To develop internal-resonance-based vibration control measure by transferring energy to high vibration modes for large-scale wind turbines.

5.2 Revised Objectives

N.A.

6. Research Outcome

Major findings and research outcome
(maximum 1 page; please make reference to Part C where necessary)

A total of 62 publications were generated in prestigious peer-reviewed journals in this research project, including 15 papers published by the Hong Kong PI, 22 papers published by the mainland PI, 3 papers jointly published by the HK and mainland PIs, 2 papers currently under review and 1 paper under preparation. More detailed information on these articles can be referred to Part C. The major findings are summarized as follows.

(1) Large-scale WT systems are dynamically sensitive to the wind. An extreme loading effect can be generated under wind-sand and wind-rain combinations. The wind-induced sands and rains significantly alter the vortex characteristics and impose additional impact forces on the WT. The sands are mostly distributed in a range of 0-0.6 height of the tower due to the shadowing effect and the sand quantity considerably increases with increasing wind speed when the sand diameter is small, while it decreases with wind speed when the sand diameter is larger than a certain level. In addition, the blades and lower part of the tower are impacted by the wind-induced rains, and this effect is not evident by increasing the yaw angle.
(2) In the overlapping part of the tower and the RNA, the rotating blades have a significant influence on the wind flow above the nacelle, and intensive vortex shedding between the tower and blades is observed. In contrast, the disturbing effect caused by the rotating blades on the tower is very weak when the RNA is located at a high height (i.e., the tower is not shadowed by the blades).
(3) The first two vibration modes of the WT are the bending modes of the tower, which are not affected by the blades, and higher modes are the coupled vibrations between the tower, blades and nacelle. Typhoon-resistance design of large WT systems shall pay attention to multi-stage effects in local regions, and different vibration modes of the WT can be excited in different stages. For engineering practice, it is recommended that the wind vibration coefficient of the tower and blade should be taken at least as 2.15 and 2.40, respectively, considering multi-stage typhoon impact. Moreover, wind tunnel test results indicate that the internal resonance condition of the blades is strongly related to the azimuthal angle, pitch angle and wind speed.
(4) The wake effect in a wind farm considerably influences the aerodynamic loads, energy production, and fatigue life of downstream WTs. The wake-induced wind speed deficit, turbulence intensity increase, and meandering effects, together with the wind farm topology, should be considered when studying coupled dynamics of large-scale WT systems.
(5) Large-diameter monopile foundation significantly increases the excess pore water pressure in the soil medium, particularly at the pile toe. In general, the liquefaction risk of saturated soil weakens the foundation capacity and jeopardizes the whole system safety.
(6) Novel NESs with newly-designed track profiles combining quadratic and quartic polynomials were proposed. Piezoelectric material was attached to blades to improve structural functionality and safety. These control methods can redistribute the input energy from low to high modes, wherein energy dissipation is more pronouncedly, and they have great potential in mitigating structural responses of WTs with better control effectiveness and robustness.
(7) A function-enhancement energy harvesting circuit for dual-function devices was developed by using microcontroller units. The passive control and adaptive control strategies were validated experimentally and numerically. Moreover, the optimization consistency between maximization of damping power and minimization of structural kinetic energy was analytically confirmed. It provides an energy-efficient control strategy to wind turbines.

Potential for further development of the research and the proposed course of action *(maximum half a page)*

The accumulated wind power installations in the world reached 743 GW in 2020, out of which offshore wind energy accounts for 4.5%. The increasing share of offshore wind energy is mainly due to their promising characteristics against onshore wind farms. For example, wind resources in marine areas are more steady and stronger with less turbulence, and offshore wind turbines (OWTs) have less visual impact, less annoyance from noise, and do not occupy valuable land. With increasing offshore wind farms constructed in deep seas (water depth is normally larger than 50 m), multi-megawatt floating OWTs are generally adopted and designed with extremely long blades and slender towers to generate more power and dramatically lower the levelized cost of energy. For instance, the rotor diameter of the Haliade-X 14-MW OWT developed by GE are as high as 220 m. Meanwhile, deep waters are usually associated with complex wind and wave conditions. Consequently, it is expected that floating OWTs with large turbine sizes will have high demands on structural stability, integrity and dynamic behaviour. Therefore, it is imperative to enhance the serviceability and safety of floating OWTs in consideration of the coupled dynamics in the future. The principal investigators will actively seek potential opportunities to financially support in-depth research on floating OWTs.

7. The Layman's Summary

(describe in layman's language the nature, significance and value of the research project, in no more than 200 words)

Wind energy, as an important clean and renewable energy source, has been gaining popularity over the past decades. The cumulative installed capacity of wind power in China reached 282 GW in 2020, ranked first in the world. The China Wind Energy Development Roadmap aims to achieve a wind power installed capacity of 1,000 GW by 2050, which will contribute 17% of the total national power consumption. Research and development on large-scale onshore/offshore wind turbines (WTs) is recognized as a major challenging task to satisfy the rapidly growing demand for wind power. The increasing size or slenderness of WTs reduces their stiffness and frequency, make them exhibit apparent nonlinear behavior, and render them vulnerable to unsteady aerodynamic excitations. However, investigations on nonlinear vibrations of large-scale WTs has remained limited to date. The project team investigated wind-induced nonlinear vibrations of large-scale WTs through a combination of analytical, numerical and experimental studies. The complex mechanism of the nonlinear vibrations (including self-excitation and energy transfer through internal resonance) and the corresponding vibration mitigation strategies for large-scale WTs were systematically investigated in this project. The outcome of this project will provide useful knowledge to the research and development of next-generation super-large-scale WTs.

Part C: Research Output

8. Peer-reviewed journal publication(s) arising directly from this research project

(Please attach a copy of each publication and/or the letter of acceptance if not yet submitted in the previous progress report(s). All listed publications must acknowledge RGC's funding support by quoting the specific grant reference.)

Only journal publications from HK PI are listed here.

The Latest Status of Publications				Author(s) (***bold** the authors belonging to the project teams and denote the corresponding author with an asterisk**)	Title and Journal/ Book *(with the volume, pages and other necessary publishing details specified)*	Submitted to RGC *(indicate the year ending of the relevant progress report)*	Attached to this report *(Yes or No)*	Acknowledged the support of this Joint Research Scheme *(Yes or No)*	Accessible from the institutional repository *(Yes or No)*
Year of publication	Year of Acceptance *(For paper accepted but not yet published)*	Under Review	Under Preparation *(optional)*						
			Yes	Zhang J, Yuan GK, **Zhu S***, Gu Q, Ke S, Pei AG	Seismic analysis of 10-MW offshore wind turbine with large-diameter monopile in consideration of seabed liquefaction.		No	Yes	
		Yes		Zuo H and **Zhu S***	Development of novel track nonlinear energy sinks for seismic performance improvement of offshore wind turbine towers. Mechanical System and Signal Processing.		No	Yes	
		Yes		Zuo H, Zhang J, Yuan G and **Zhu S***	Wind- and sea wave-induced response mitigations of offshore wind turbines using track nonlinear energy sinks. Structural Control and Health Monitoring.		No	Yes	

2022				Cai Q and **Zhu S***	The nexus between vibration-based energy harvesting and structural vibration control: A comprehensive review. Renewable and Sustainable Energy Reviews		Yes	Yes	
2021				Zhang J, Zuo H, Yuan G, **Zhu S***	The effect of wake flows on the output power and fatigue behavior ofwind turbines. ACTA AERODYNAMICA SINICA. (in Chinese)		Yes	Yes	
2021				Wang B and **Zhu S***	Cyclic behavior of iron-based shape memory alloy bars for high-performance seismic devices. Engineering Structures.		Yes	Yes	
2021				Wang H, Shen W*, Zhu H, Kong F, **Zhu S**	Stochastic seismic analysis of base-isolated structures with electromagnetic inertial mass dampers considering different soil conditions. Bulletin of Earthquake Engineering.		Yes	Yes	

2021				Wang H, Shen W*, Li Y, Zhu H, **Zhu S**	Dynamic behavior and seismic performance of base-isolated structures with electromagnetic inertial mass dampers: Analytical solutions and simulations. Engineering Structures.		Yes	Yes	
2021				Cai Q and **Zhu S***	Applying double-mass pendulum oscillator with tunable ultra-low frequency in wave energy converters. Applied Energy.		Yes	Yes	
2021				Wang B, **Zhu S***, Casciati F, Chen K, Jiang H	Cyclic behavior and deformation mechanism of superelastic SMA U-shaped dampers under in-plane and out-of-plane loadings. Smart Materials and Structures.		Yes	Yes	
2021				Li JY and **Zhu S***	Tunable electromagnetic damper with synthetic impedance and self-powered functions. Mechanical Systems and Signal Processing.		Yes	Yes	

2020				Cai Q, **Zhu S*** and **Ke ST**	Can we unify vibration control and energy harvesting objectives in energy regenerative tuned mass dampers? Smart Materials and Structures.		Yes	Yes	
2020				Wang B, **Zhu S***, Chen K, Huang J	Development of superelastic SMA angles as seismic-resistant self-centering Devices. Engineering Structures.		Yes	Yes	
2020				Wang B, **Zhu S***, Casciati F	Experimental Study of Novel Self-Centering Seismic Base Isolators Incorporating Superelastic Shape Memory Alloys. Journal of Structural Engineering.		Yes	Yes	
2020				Wang H, **Ke ST***, Wang TG and **Zhu S**	Typhoon-induced vibration respone and the working mechanism of large wind turbine considering multi-stage effects. Renewable Energy.		Yes	Yes	
2020				Cai QL and **Zhu S***	Unified strategy for overall impedance optimization in vibration-based electromagnetic energy harvesters. International Journal of Mechanical Sciences. 165: 105198.	2019	No	Yes	

2019				Cai QL and **Zhu S***	Enhancing the performance of electromagnetic damper cum energy harvester using microcontroller: concept and experimental validation. Mechanical Systems and Signal Processing. 134: 106339.	2019	No	Yes	
2019				Li JY, **Zhu S*** and Shen J	Enhance the damping density of eddy current and electromagnetic dampers. Smart Structures and Systems, 24(1): 15-26.	2019	No	Yes	
2019				Shen W, **Zhu S*** and Zhu H	Unify energy harvesting and vibration control functions in randomly excited structures with electromagnetic devices. ASCE Journal of Engineering Mechanics. 145(1): 04018115.	2019	No	Yes	
2018				**Zhu S***, Zhu Z and Ke S	A review of failure analyses and structural health monitoring techniques for offshore wind turbines. Southern Energy Construction. 5(2): 47-59. (in Chinese)	2019	No	Yes	

2018				Li C, Xiao Y, Xu YL, Peng YX, Hu G and **Zhu S***	Optimization of blade pitch in H-rotor vertical axis wind turbines through computational fluid dynamics simulations. Applied Energy. 212: 1107-1125.	2019	No	Yes	

9. Recognized international conference(s) in which paper(s) related to this research project was/were delivered *(Please attach a copy of each delivered paper. All listed papers must acknowledge RGC's funding support by quoting the specific grant reference.)*

Month/Year/ Place	Title	Conference Name	Submitted to RGC *(indicate the year ending of the relevant progress report)*	Attached to this report *(Yes or No)*	Acknowledged the support of this Joint Research Scheme *(Yes or No)*	Accessible from the institutional repository *(Yes or No)*

10. Student(s) trained *(Please attach a copy of the title page of the thesis.)*

Name	Degree registered for	Date of registration	Date of thesis submission/ graduation

11. Other impact *(e.g. award of patents or prizes, collaboration with other research institutions, technology transfer, etc.)*

Patent:

Zhu S and Cai Q "A tunable low-frequency wave energy converter". China Model Utility Patent No.: CN212583871U, Grant Date: 23 February 2021.

Keynote Lecture:

Novel electromagnetism-based structural vibration control devices and strategies. The 8th National Conference on Structural Control and Health Monitoring (SVCHM8). Hefei, China. Nov 22-24, 2019.

Self-powered active vibration control of structures. The 2021 5th International Conference on Civil, Architectural and Structural Engineering (ICCASE 2021). Zhangjiajie, China. April 23-25, 2021.

The Nexus between Structural Vibration Control and Energy Harvesting Techniques. The Ninth Kwang-Hua Forum Innovations and Implementations in Earthquake Engineering Research: Engineering Resilience. Shanghai, China. December 10-12, 2021.

12. Statistics on Research Outputs *(Please ensure the summary statistics below are consistent with the information presented in other parts of this report.)*

	Peer-reviewed journal publications	Conference papers	Scholarly books, monographs and chapters	Patents awarded	Other research outputs (Please specify)
No. of outputs arising directly from this research project [or conference]	15 (HK) 22 (Mainland) 3 (Joint)	6 (Mainland)	0	1 (HK) 18 (Mainland)	0