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Design Optimisation of Shroud-Augmented Dual-Rotor Exhaust Air Energy Recovery Wind Turbine Generator Using Hybrid Non-destructive Evaluation Approach

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Abstract

An innovative system for recovering exhaust gas is created to recycle the energy from industry cooling tower waste. Two Vertical Axis Wind Turbines (VAWTs) with enclosure are positioned at a specific position at the outlet of cooling tower to harness the wind energy for electricity generation. From structural dynamics aspect, adding two VAWTs or dual-rotor with enclosure can contribute extra burden to the cooling tower. This has changed the dynamic characteristics of the cooling tower. Therefore, a hybrid non-destructive evaluation approach is proposed to investigate the dynamic behaviour and reliability of this new design. From this approach, it was found that the overall vibration of the cooling tower increased from 3mm/s to 26mm/s after the installation of the VAWTs with enclosure. The VAWTs are not operating at its optimum speed due to energy loss in vibration. The operating speed of VAWTs (i.e. 7.5Hz) was found close to one of the natural frequencies of VAWT (i.e. 7.0Hz). This indicates structural dynamic weakness which causes high vibration as recorded. Structural Dynamic Modification (SDM) is performed on the new design in the attempt to reduce the vibration at VAWTs and improve the reliability of VAWTs with enclosure in order to ensure optimum operation of VAWTs. The SDM is expected to shift the natural frequency away from the operating frequency with around 81% of reduction in vibration level which leads it to safe and unrestricted long-term operation. In addition, reducing vibration at VAWTs also recovers the energy loss of 419 Joules and subsequently maximises the efficiency of wind turbine.

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Keywords: cooling tower; design optimisation; energy recovery; waste energy; vibration

1. Introduction

With the increasing of population growth, global energy consumption is increasing tremendously. In fact, ExxonMobil's outlook energy foresees that the need for electricity supply is expected to increase by 90% from 2010 to 2040 [1]. In Malaysia, the electricity generation is mainly depend on fossil fuels such as oil, natural gas and coal which contribute about 94.5% of the electricity generation [2]. With the limited supply of fossil fuels as it is non-renewable energy and the impact of the consumption of fossil fuels to the environment, sustainable energy system is highly demanded for a greener future. Chong, W.T., et al.proposed a sustainable energy system for electrical power

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generation. The system is able to recover energy from wasted exhaust air of cooling tower to generate clean electricity[3].

The exhaust air energy recovery system design comprises of two Vertical Axis Wind Turbines (VAWTs) or dual-rotor with enclosure, which are installed on top of an exhaust outlet in cross wind orientation to harness the discharged wind energy [4]. A lab scale of this system has been built for various testing purposes as shown in Fig. 1.

Fig. 1. Exhaust Air Energy Recovery System in Lab Scale.

From the aspect of structural dynamics, adding two VAWTs with enclosure can contribute extra burden to the entire structure as additional mass is added on the cooling tower. This has changed the dynamic characteristics, namely natural frequencies, mode shapes and damping, of the cooling tower and may cause unexpected change in dynamic behaviour. According to the first law of thermodynamics, energy can be neither created nor destroyed, i.e., the energy is conserved [5]. When a part is vibrating, energy is either dissipated into heat or radiated away and cause energy loss [6]. This indicates that the mechanical energy has been converted to thermal energy due to vibration.

One of the dynamic characteristics, damping is present in all oscillatory systems to remove energy from the system. Damping is generally concerned in terms of system response. In steady-state forced vibration, the loss of energy is balanced by the energy that is supplied by the excitation.At natural resonance frequency, the energy dissipated per cycle is given by,

$$W_d = 2\zeta\pi kX^2 \quad (1)$$

whereW_d refers to dissipated energy; ξ is damping ratio; k is stiffness; and X is amplitude.

In this study, a hybrid non-destructive evaluation approach is proposed to investigate the dynamic behaviour and reliability of this new design, which looks into the possible causes of high vibration and rectifies the vibration issue. By rectifying high vibration issue using this hybrid approach, the system will operate at optimum condition with relatively lower possibility of failure. In addition, more energy which will otherwise be dissipated due to damping force can be recovered and utilized by the system.

2. Methodology

The hybrid non-destructive evaluation consists of experimental and computational analyses. Experimental analyses include Operating Deflection Shape (ODS) analysis and Experimental Modal Analysis (EMA) using Frequency Response Function (FRF) measurement technique. ODS analysis is a study used to determine the response of the whole structure by analysing the signal of the mechanical vibrations that occur at the points of interest on the operating structure[7, 8]. EMA is a technique used to determine the dynamic characteristics of the structure[8]. EMA is conducted under non-operational condition in order to avoid any unaccounted excitation force induced into the system and substitute by measureable impact or random forces for the excitation force [9]. The time history of excitation force and response are measured and the FRF are estimated through signal processing technology [10]. Computer Aided Design (CAD) and Finite Element Analysis (FEA) were the computational tools for this research.

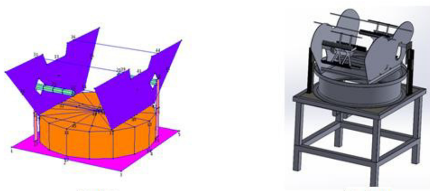

2. (a) 2. (b)

Fig. 2. (a) Wire-Mesh Model and (b) CAD Model of the Exhaust Air Recovery System

Initially, measurement points were identified and marked. All the points were linked to obtain a wire-mesh model to represent the whole structure of exhaust air recovery system as shown in Figure 2(a). ODS and EMA were then conducted on the real structure. Hence, both results were linked to the wire-mesh model to animate the actual motion of the system and its mode shape at particular natural frequencyrespectively. Concurrently, a CAD model was developed for the system's structure as shown in Fig. 2(b). The FE model was built according to the geometrical properties, boundary conditions and material properties of the system. FE modal analysis was conducted to determine the dynamic characteristics of the system.

The integrity of the FE model is validated and correlated using measured EMA result. Vibration assessment is then conducted to identify the root cause of vibration problem. If one or more of the modes are found to be within the operating range than the system is known as structural dynamic weakness problem. Further rectification is then performed with Structural Dynamic Modification (SDM) in virtual domain. SDM can identify the changes required in a structural system to modify its dynamics characteristics in the desired direction [11].The design criterion is that the natural modes of vibration are outside the operating frequency region. SDM allows a large number of design modifications without having the unnecessary physical cycles of 'modify-and-test'. Conceptually, it is intended to save the unnecessary time and money by 'get-first-time-right' during fabrication.By changing the dynamic characteristics of the structure away from the operating frequency, the vibration level is expected to reduce and subsequently it reduces the energy dissipation due to damping force. After obtaining positive results, the modification and fabrication is then performed on the real structure.

3. Results and discussion

From the ODS analysis, it is observed that overall vibration of the cooling tower was recorded at 3mm/s before the installation of VAWTs with enclosure. After the installation of VAWTs with enclosure, it is observed that the vibration increased to 26mm/s. According to ISO 10816-1 for motor and fan and VDI 3834 for wind turbine, these components should be running below 6mm/s for unrestricted long-term operation. High vibration of 26mm/s is considered unsatisfactory for long-term continuous operation and may cause severe damage to the system. Figs. 3(a)& (b) showed the overall vibration spectral before and after the installation of VAWTs with enclosure.

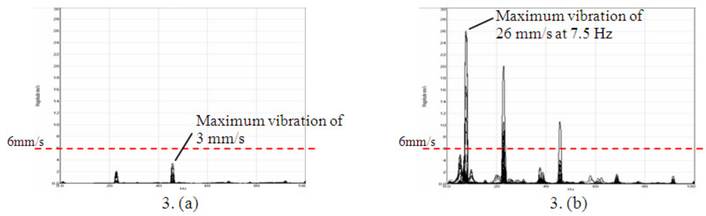
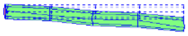


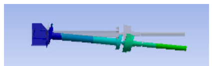
Fig. 3. ODS Spectral of the Cooling Tower (a) before and (b) after the Installation of VAWTs with Enclosure

In order to identify the root cause of this high vibration issue, EMA was performed. From EMA, it is observed that the operating frequency of VAWTs at 7.5 Hz coincided with its natural frequency at 7 Hz. Therefore, this explains the high vibration on the structure especially at VAWTs. The VAWTs are considered dynamically weak and it is classified as resonance problem. This has caused the VAWTs unable to operate at their optimum condition. Figs. 4(a) and (b) showed the VAWT bending mode at 7Hz of EMA and 7.35 Hz of FE modal analysis. Close correlation between EMA and FE modal analysis implies that the FE model is good for further analyses.

To rectify this structural dynamic weakness problem, SDM was performed by utilising FEA to inspect the effectiveness of the SDM prior to modification and fabrication. From the correlation results, it showed that the connection between VAWTs and supports are weak and modifications are needed at these components. SDM was performed by strengthen the connection between VAWTs and their supports in order to allow the system to operate at its optimum condition. It is recommended to add extra screws to tighten the connection or direct weld the wind turbine to the support. By doing so, the natural frequency of structure is expected to be shifted to 9.7 Hz as shown in Fig. 5. By assuming the damping maintains at same level, the amplification factor in FRF is expected to reduce from 0.21 m/s^2N to 0.04 m/s^2N or 81% reduction of vibration level. Therefore, it is estimated that the vibration of the system to be reduced to 5 mm/s which is acceptable for unrestricted long-term operation. With the law of energy conservation, it is believed that this reduction of vibration energy is converted to the mechanical energy for the wind turbine operation instead of being dissipated as thermal energy. Eventually, the electric power generated by the wind turbine can be increased.Assuming the dual-rotor wind turbine operates 16 hours per day, from equation (1), design optimisation on the dual-rotor wind turbine generator is expected to recover419 Joules of energy loss due to vibration.



4. (a)



4. (b)

Fig. 4. (a) VAWT Bending Mode at 7 Hz from EMA (Top View); (b) VAWT Bending Mode at 7.35 Hz from FE Modal Analysis

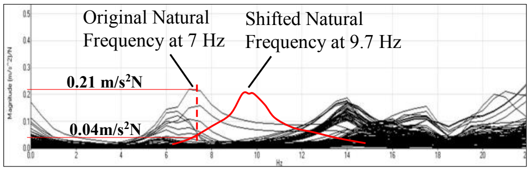


Fig. 5. Estimated Shifting of VAWTs Natural Frequency

4. Conclusion

From the hybrid non-destructive evaluation approach, the connection between VAWTs and supports are found weak and subsequently causing high vibration problem. Energy is lost due to vibration and it affects the efficiency of the VAWTs. By performing SDM, the natural frequency of the VAWTs is expected to be shifted to 9.7Hz and away from the operating frequency. The vibration level is expected to be reduced by 81% which leads the VAWTs for safe and unrestricted long-term operation. In addition, this reduction of vibration at VAWTS is expected to recover the energy loss due to damping force subsequently maximises the efficiency of wind turbine.Estimated extra recovery is 419 Joules for 16 operating hours per day.Future study could be focused on further improvement in energy recovery from the reduction of vibration and experimental validation of the calculated energy recovered.

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References

[1] ExxonMobil, The Outlook for Energy: A View to 2040. 2014.
[2] Ali, R., I. Daut, and S. Taib, A review on existing and future energy sources for electrical power generation in Malaysia. Renewable and Sustainable Energy Reviews, 2012. 16(6): p. 4047-4055.
[3] Chong, W.T., et al., Exhaust Air Energy Recovery System for Electrical Power Generation in Future Green Cities. International Journal of Precision Engineering and Manufacturing, 2013. 14(6): p. 1029-1035.
[4] Chong, W.T., et al., Early development of an innovative building integrated wind, solar and rain water harvester for urban high rise application. Energy and Buildings, 2012. 47: p. 201-207.
[5] Cengel, Y.A., M.A. Boles, and M. Kanoğlu, Thermodynamics: an engineering approach. Vol. 5. 2011: McGraw-Hill New York.
[6] William, T.T. and D.D. Marie, Theory of vibration with applications. New Jersey, 1998.
[7] Kromulski, J. and E. Hojan, An application of two experimental modal analysis methods for the determination of operational deflection shapes. Journal of Sound and Vibration, 1996. 196(4): p. 429-438.
[8] Rahman, A.G.A., Chao, O.Z., and Ismail, Z. (2011). Effectiveness of Impact-Synchronous Time Averaging in determination of dynamic characteristics of a rotor dynamic system. Measurement, 44(1): p. 34-45.
[9] Rahman, A.G.A., Z.C. Ong, and Z. Ismail, Enhancement of coherence functions using time signals in Modal Analysis. Measurement, 2011. 44(10): p. 2112-2123.
[10] Zhang, Y. and W.Z. Cai, Application of Experimental Modal Analysis Method in Researching of Mechanical Structure Dynamic Characteristics. Manufacturing Process and Equipment, Pts 1-4, 2013. 694-697: p. 370-373.
[11] Sestieri, A., Structural dynamic modification. Sadhana-Academy Proceedings in Engineering Sciences, 2000. 25: p. 247-259.

Biography

Dr. Ong Zhi Chao is a senior lecturer in University of Malaya. Dr. Ong has published more than 10 technical papers on vibration research. He is actively involved in more than 30 industrial projects on machinery vibration at on-shore and off-shore oil and gas processing plants in Malaysia.