Mechanical Systems and Signal Processing 23 (2009) 2435–2444

Contents lists available at ScienceDirect

Mechanical Systems and Signal Processing

journal homepage: www.elsevier.com/locate/jnlabr/ymssp

Laboratory-scale experiments on wind turbine nacelle movement estimation

Yoonsu Nam, Tai Jun Yoon *

Department of Mechanical and Mechatronics Engineering, Kangwon National University, 192-1 Hyoja-2-dong, Chunchon, Kangwon 200-701, South Korea

ARTICLE INFO

Article history:
Received 25 September 2008
Received in revised form
1 June 2009
Accepted 4 June 2009
Available online 18 June 2009

Keywords:
Kalman filter
Wind turbine
Nacelle motion estimation
Accelerometer
Strain gauge

ABSTRACT

The effect of nacelle motion should be considered when calculating the wind speed relative to the wind turbine structure, which is essential in wind turbine control and performance testing. A Kalman filter approach is applied to estimate the nacelle motion of a wind turbine. Information from several accelerometers and strain gauges which are installed on the wind turbine tower is combined with the Kalman filter. An optimization algorithm is used to choose the optimal locations for strain gauge and accelerometer installation. A laboratory-scale experimental rig which mimics the tower and nacelle of the wind turbine is constructed to evaluate the performance of the proposed estimator algorithm. The usefulness of the proposed algorithm is validated by these laboratory-scale experimental results.

1. Introduction

A wind turbine captures wind power by using rotating blades and converts it to electric power by a generator. The aerodynamic torque (T_a) and thrust (F_a), which are the source of the rotating motion of the drive train and the main cause of wind turbine tower vibration, are given by [1]

$$T_a = \frac{1}{2}\rho\pi R^3 \frac{C_p(\lambda,\beta)}{\lambda} v^2,$$
$$F_a = \frac{1}{2}\rho\pi R^2 C_t(\lambda,\beta) v^2, \tag{1}$$

where ρ is the air density, R the rotor radius, v the wind speed relative to wind turbine, β the blade pitch angle, $\lambda = \Omega R/v$ the tip speed ratio, Ω the rotor speed, C_p the power coefficient and C_t the thrust coefficient.

As can be seen in the above equation, the wind speed which is experienced by the rotor blades is a key parameter for determining the wind turbine's operational characteristics. If a nacelle is moving due to tower vibration, then this effect should be considered in calculating Eq. (1) and that is given by

$$v = v_w - \dot{y}(L,t), \tag{2}$$

where v_w is the wind speed, $\dot{y}(L,t)$ the nacelle velocity.

The estimation of a nacelle motion is also useful in the problem of tower load alleviation. Fatigue life of a wind turbine has to be more than 20 years, which means that the magnitude of mechanical stresses on wind turbine structure needs to

* Corresponding author. Tel.: +82 33 257 4190.
E-mail addresses: nys@kangwon.ac.kr (Y. Nam), endmyion@hanmail.net (T.J. Yoon).

0888-3270/$ - see front matter © 2009 Elsevier Ltd. All rights reserved.
doi:10.1016/j.ymssp.2009.06.002

be tightly controlled. Also, high level of wind-induced accelerations at the nacelle of wind turbine could result in unavailability of wind turbine [2]. To reduce this vibration, a tuned liquid-column damper is tried and its effectiveness is investigated [3]. The other way of reducing this vibration is using active control algorithms [4,5].

However, it is not possible to find a cost-effective sensor which measures the nacelle motion. A discrete Kalman filter which utilizes sensor information from accelerometers and strain gauges installed on a wind turbine tower in order to estimate the motion of a nacelle is introduced. As depicted in Fig. 1, accelerometers are placed on the tower top near the nacelle, and strain gauges are installed on the root area of the tower. Approaches similar to that proposed in this paper can be found in some references. The end point displacement of a flexible beam is estimated by combining a slowly refreshing vision system and a high-bandwidth accelerometer with a Kalman filter [6]. A rotational speed estimator of a servo motor based on a Kalman filter is designed by using an angular accelerometer and a rotary encoder and applied to the servo-motor velocity control [7]. Bridge dynamic motion and wind-induced response of high buildings are monitored by GPS and accelerometer [8,9]. In these applications, however, acceleration data are used just as reference data for GPS measurement and not for estimation. The other issue in this paper is to find the optimal placement of the strain gauge and accelerometer on the tower. Many research results in this area can be found. Much of this work is related to the control problems of a huge flexible structure [10,11]. Various optimization algorithms are applied to determine the best locations for sensor installation. A performance index such as maximization of the measurement resolution or accuracy of displacement of the node of interest in the flexible structure is chosen for this problem [11]. The minimum number of strain measurements and strain sensor placements to optimally reconstruct modal shapes of a cantilevered beam is found [12]. The strain gauge location and orientation are determined in order to extract vibration states of a disk drive suspension and to feedback this information for active vibration control [13]. In this research, a numeric search algorithm which maximizes the maximum singular value of the observability grammian of the suspension dynamics is developed. The strain gauge and accelerometer locations on the tower are chosen such that the sum of the diagonal elements of the error covariance matrix in Kalman filtering is minimized in this paper.

To verify a proposed algorithm, a small-scale experimental apparatus is made. This consists of a one-meter-long rod and a 10 kg concentrated tip mass, which represent a wind turbine tower and a nacelle. Mode shapes of the tower deformation are determined by FEM analysis and integrated with the estimator dynamics of the nacelle movement. The laboratory-scale experimental results on applying the Kalman filter to this laboratory-scale experimental device are introduced.

2. Estimator dynamic model

With the coordinate system of Fig. 1, the deflection of a wind turbine tower in the direction of the wind can be described by the approximation

$$y(x,t)=\sum_{i=1}^{n}\phi_i(x)q_i(t), \tag{3}$$

where $\phi_i(x)$ is the ith mode shape function, $q_i(t)$ the generalized coordinate, x the displacement from the ground.

The mode shape functions can be obtained from FEM analysis. If there are l accelerometers to measure tower acceleration, then the following relationship holds:

$$\ddot{Y}(t)=\begin{Bmatrix}\ddot{y}(x_1,t)\\ \vdots\\ \ddot{y}(x_l,t)\end{Bmatrix}=\begin{bmatrix}\phi_1(x_1) & \dots & \phi_n(x_1)\\ & \dots & \\ \phi_1(x_l) & \dots & \phi_n(x_l)\end{bmatrix}\begin{Bmatrix}\ddot{q}_1\\ \vdots\\ \ddot{q}_n\end{Bmatrix}=\phi\ddot{q}, \tag{4}$$

where x_i is the distance of ith accelerometer installation from the tower root, $\ddot{y}(x_i,t)$ the acceleration at $x=x_i$.

If we assume the state vector as $\mathbf{x}=[q\quad \dot{q}]^T$ and $l\geq n$, the above relation can be represented by using the state space form of

$$\dot{\mathbf{x}}=\begin{bmatrix}0 & I_n\\ 0 & 0\end{bmatrix}\mathbf{x}+\begin{Bmatrix}0\\ \phi^T(\phi\phi^T)^{-1}\end{Bmatrix}(\ddot{Y}+\xi)=A\mathbf{x}+Bu+B\xi, \tag{5}$$

where ξ is the accelerometer noise vector and $u=\ddot{Y}$.

With the assumption of m-strain-gauge installation, the measurement equation is given as

$$v=k_{AMP}V_SS_g\begin{Bmatrix}\varepsilon(x_1,t)\\ \vdots\\ \varepsilon(x_m,t)\end{Bmatrix}+\eta=k_{AMP}V_SS_gR_T\begin{bmatrix}\phi_1''(x_1) & \cdots & \phi_n''(x_1)\\ & \cdots & \\ \phi_1''(x_m) & \cdots & \phi_n''(x_m)\end{bmatrix}\begin{Bmatrix}q_1\\ \cdots\\ q_n\end{Bmatrix}+\eta=\psi q+\eta=[\psi\quad 0]\mathbf{x}+\eta=C\mathbf{x}+\eta, \tag{6}$$

where x_i is the distance of ith strain gauge installation from tower root, $\varepsilon(x_i, t)$ the strain of tower's outer surface at x_i, R_T the outer radius of tower, K_{AMP} the strain gauge AMP gain, S_g the strain gauge factor, V_s the strain gauge supply voltage and η the noise vector of strain gauge measurement.