A Numerical Study of Low-cost Wind Velocity Estimation using Extended Kalman Filter and Tethered, Spherical Helium Balloon

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Abstract

The objective of this work is to investigate the feasibility of low-cost wind-characterization using an inertial measurement unit (IMU) attached on a helium balloon. The balloon system acts as a measuring instrument for wind characterization. The wind velocity and direction are to be determined using only a standard set of on-board sensors (i.e., accelerometers, gyroscope, thermometer, and barometer). An Extended Kalman Filter (EKF) technique is implemented with the formulation of equations of motion describing the dynamics for the spherical balloon configurations (i.e., slung motion and free motion). The ability of the system to capture both a low frequency component and a turbulence component (i.e., high frequency variations) is determined. The effects of design parameters (such as balloon size and sensing errors) are investigated and analyzed with the use of numerical simulations. The feasibility of low-cost wind-characterization is found for the wind with a frequency lower than 0.05 Hz. It is found that the limitation is due to the error of gyroscope.

Keywords*:* Extended Kalman Filter, Wind Characteization, Estimation.

1. Introduction

Wind information can be crucial for many applications. Especially in the wind turbine applications, wind data can be used to optimize the design of wind turbine blade and structure as well as enable an improved fatigue-life modeling which could increase turbine lifetime and reduce costs at the same time. Since the variation of the wind speed is highly depended on the area and on the atmospheric conditions, corresponding wind information is required to be measured on-site and for a long period of time. To obtain wind information for a desired height in a specific area, many conventional methods (e.g., meteorological mast, weather station, tethered balloon, etc.) are available to be used. However, these conventional methods mostly require expensive structure, equipment, and sensors.

The fundamental objective of this study is to investigate the feasibility of using a tethered balloon with a standard, low-cost sensor set as a wind measuring instrument. The dynamic behaviors of a tethered helium balloon installed at desired height are interpreted for wind characterization. A standard set of on-board sensors (i.e., accelerometers, gyroscope, thermometer, and barometer) is installed on the balloon to capture the balloon dynamics for the wind characterization process. The extended Kalman Filter (EKF) technique is implemented to estimate the wind velocity corresponding to the sensor measurements. In this study, numerical simulation is utilized to determine the feasibility of low-cost wind-characterization using IMU on a tethered balloon and show the effects of design parameters. In this paper, the effect of balloon size and sensing errors in the wind characterization are focused. The following sections first describe the details of simulation models and the wind estimation model (EKF). Then, the discussion on numerical results and conclusion are presented.

2. Simulation Models

In this study, the physic behaviors of wind speed and tethered balloon motion are represented using mathematical models. An EKF with an imperfect model of the tethered balloon in the present of wind is then formulated.

2.1 Van der Hoven Spectrum Wind Model

The Van der Hoven Spectrum method divides the wind speed into two components; a low frequency component which presents slow variations in wind speed and a turbulence component which presents fast, high frequency variations. Figure 1 shows the Van der Hoven spectral model of wind speed in [2] which identifies the two components. The model also considers the turbulence component as a zero

average random process. The wind characteristics can be stored in the Van der Hoven Spectrum of wind speed.

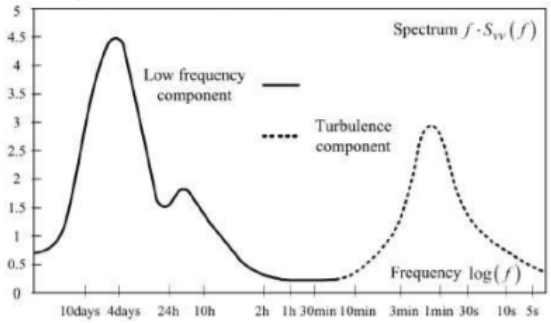

Fig. 1 Van der Hoven spectral model of wind speed [2].

To regenerating wind speed time series, one of the most common methods is by sampling the Van der Hoven spectrum. The wind speed is obtained by the combination of random processes from sampled spectrums and the mean wind speed [3]:

$$V(t) = V_0 + \sum_{i-1}^{m} A_i \cos(\omega_i t + \xi_i) \qquad (1)$$

where V_0 is the mean wind speed, ω_i discretized frequency of the sampled spectrum, $\xi_i \in [0,2\pi]$ is a randomly-generated variable, and A_i is defined by

$$A_i = \frac{2}{\pi}\sqrt{\frac{(S_{vv,i} + S_{vv,i+1})}{2}(\omega_{i+1} - \omega_i)} \qquad (2)$$

where S_{vv} is the sampled Van der Hoven spectrum.

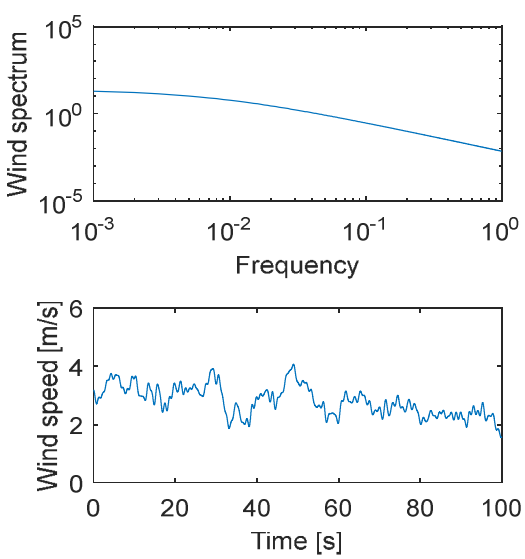

Fig. 2 Example of wind Spectrum (top), Regenerated wind profile (bottom)

Using Eqs. (1) – (2), the wind profile with similar characteristics to the wind data in the Van der Hoven spectrum can be regenerated. Figure 2 shows the example of wind spectrum and wind profile regenerated from the spectrum.

2.2. Dynamics of Tethered Balloon

To simulate the dynamics of tethered balloon, the balloon is considered as a rigid sphere with an elastic element attaching between the bottom of balloon to the ground station. Figure 3 illustrates the tethered balloon model. The forces acting on the balloon are the aerodynamic drag, the gravitational-buoyant force, and the rope interaction.

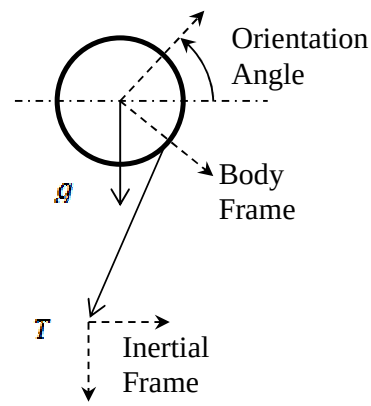

Fig. 3 The tethered balloon model

The aerodynamic drag is defined by

$$F_{aero} = \frac{1}{2} C_d \rho V^2 2r \qquad (3)$$

where C_d is the drag coefficient of the balloon, ρ is the air density, r is the radius of balloon, and V is the airflow speed.

The buoyancy force is defined by the replacement of air

$$F_{buoyancy} = \rho g \frac{4}{3}\pi r^3 \qquad (4)$$

where g is the gravitational acceleration.

When the rope is extended beyond its length, it is considered as an elastic element with no aerodynamic drag. This tension force points to the direction of ground station. When the rope has not reach its full length, it creates a downward force as

$$F_{rope} = \rho_{rope} g l \qquad (5)$$

where ρ_{rope} is the rope mass-per-unit-length, l is the length of the rope that is in the air.

The linear and angular motions of balloon then follow the Newton's law:

$$\sum F = m\ddot{X} \tag{6}$$

and

$$r \times F_{rope} - I\ddot{\Theta} \tag{7}$$

where m and I are the mass and mass moment of inertia of the balloon.

2.3 EKF with State Estimations of Balloon System

For the estimation model in the EKF, the balloon is considering as a point-mass object. Two estimation models are developed; one is for the free ascending configuration and the other is for the restricted radial motion configuration. When the position of the balloon indicates the maximum extension of the rope, the radial motion is limited. In this configuration, the orientation of the balloon is assumed to be equal to the orientation of the rope. Figure 4 illustrates the force and motion of the estimation model for tethered balloon.

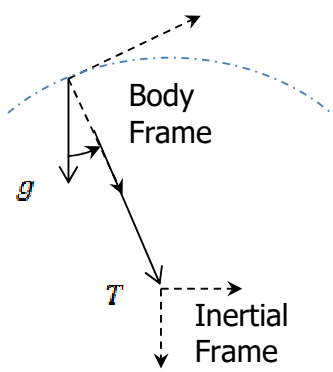

Fig. 4 Estimation model for the tethered balloon

The estimated states in the EKF include the balloon body velocity, position, angular rate, orientation, and wind speed (as shown in Eq. (8))

$$\mathbf{X}_k = [U^B, X^I, \Omega, \Theta, W^I]^T \tag{8}$$

The measurement for the state estimation includes the acceleration from accelerometers, the altitude from barometer, and the angular rate and orientation from gyroscopes.

$$\mathbf{Y}_k = [A^B, z^I, \Omega, \Theta]^T \tag{9}$$

3. Simulation Results and Analysis

To investigate the feasibility of the wind-measuring system described in previous section, design parameters must be identified. The parameters shown in Table 1 are the reference parameters for this study. Note that, in this study, it is assumed that the drag of rope is small (neglected), the wind is coming horizontally, and the change of balloon size is small (no change). Two intervals of time-step are used in the numerical simulation.

Table. 1 Reference Parameters

Description	Value
Air density [kg/m^3]	1.2
Helium density [kg/m^3]	0.2
Balloon skin and Avionics [kg]	1
Nylon rope [kg/m]	0.02
Balloon drag coefficient	0.3

From the parameters in Table 1, it is found that the size of balloon is the main design parameter. The balloon must carry the weight of rope as it ascends to the desired altitude. Therefore, the minimum size of balloon is depended on the desired height for the wind measurement. For example, the balloon for an altitude of 100 meters must carry an extra weight of 2 kilograms of rope. Then, the volume of this balloon must be at least 3 cubic-meters.

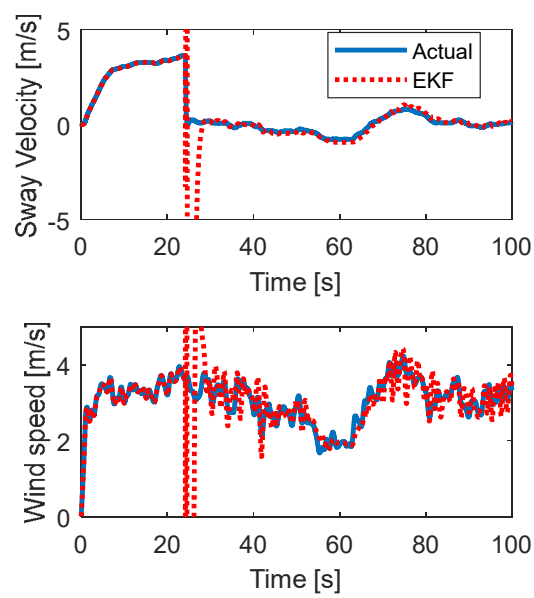

Fig. 5 Comparison between reference and estimating result; balloon inertial velocity (top), wind speed (bottom)

Figure 5 shows the comparison between actual and estimated speed for an example wind spectrum for the height of 100 meters and the mean wind speed of 3 meter-per-second. In the figure, the balloon starts a free-ascending motion from the ground station. The point which the rope reaches its maximum extension can be identified by the sudden change of sway velocity. The estimation in the free-ascending configuration is shown to be better than that in the restricted radial-motion configuration with an example set of sensors.

Table. 2 Parameters of sensing instruments

Description	Value
Acceleration (Accelerometers)	±0.01m/s^2
Altitude (Barometer)	±1m
Angular rate (Gyroscopes)	±1°/s
Orientation (Gyroscopes and accelerometers)	±1°

Table 2 presents the parameters of sensing instruments for an example low-cost sensor set. Figure 6 shows the simulation result of wind estimation and characterization. It is found that the estimation is working well for the wind with a frequency lower than 0.05 Hz.

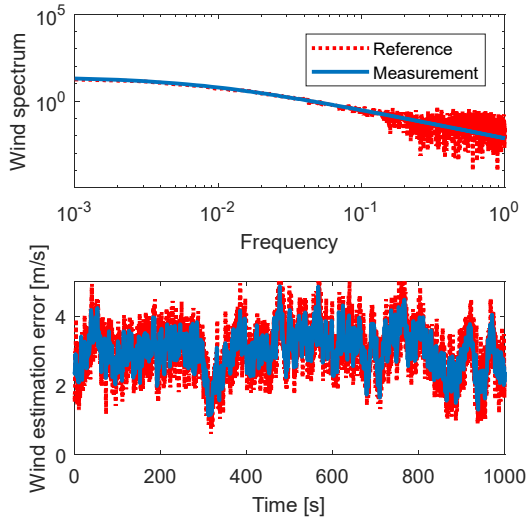

Fig. 6 Comparison between reference and estimating result; wind spectrum (top), wind speed (bottom)

3.1 Effect of Balloon Size

Figures 6 – 8 present the effect of balloon size in the wind estimation described in this study. Figure 7 shows the simulation result from a reduced-size balloon (all other parameters are the same as those of the result in Figure 6) while figure 8 shows the simulation result from an increased-size balloon (all other parameters are the same as those of the result in Figure 6). It is found that the reduction of balloon size results a decreased estimation performance as observed in figure 7. It is because the lifting force from a reduced-size balloon is not enough to keep the balloon in the circular motion. Therefore, an error occurs. For the increase of balloon size, an improvement of result cannot be observed.

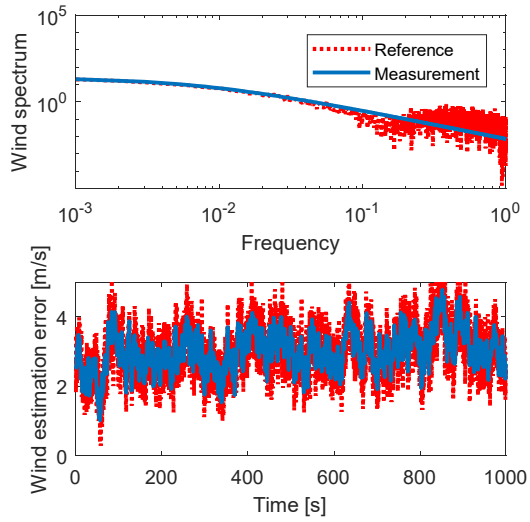

Fig. 7 Simulation result from a reduced-size balloon

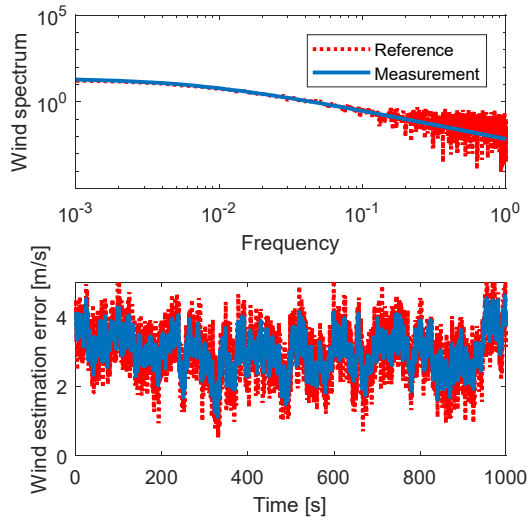

Fig. 8 Simulation result from an increased-size balloon

3.2 Effect of Accelerometer Error

Figure 9 shows the simulation result from an increased-performance accelerometer (all other parameters are the same as those of the result in Figure 6). From the numerical simulation, an improvement of estimation result cannot be clearly observed.

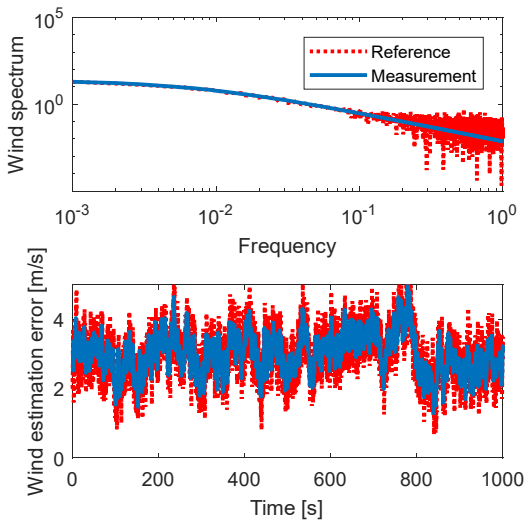

Fig. 9 Simulation result from an increased-performance accelerometer

3.3 Effect of Barometer Error

Figure 10 shows the simulation result from an increased-performance barometer (all other parameters are the same as those of the result in Figure 6). An improvement of result cannot be clearly observed for this change.

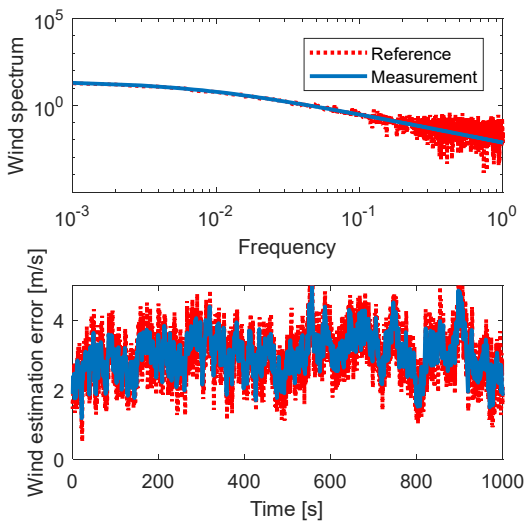

Fig. 10 Simulation result from an increased-performance barometer

3.4 Effect of Angular Rate Error

Figure 11 – 12 present the simulation results from an increased-performance gyroscope. Figure 11 show the simulation results when the angular rate measurement is improved. Figure 12 show the simulation results when the orientation measurement is improved. In these results, all other parameters are the same as those of the result in Figure 6. It is observed that the wind estimation performance is increased when the angular rate measurement is improved.

For an improved orientation sensing, an improvement of result cannot be clearly seen.

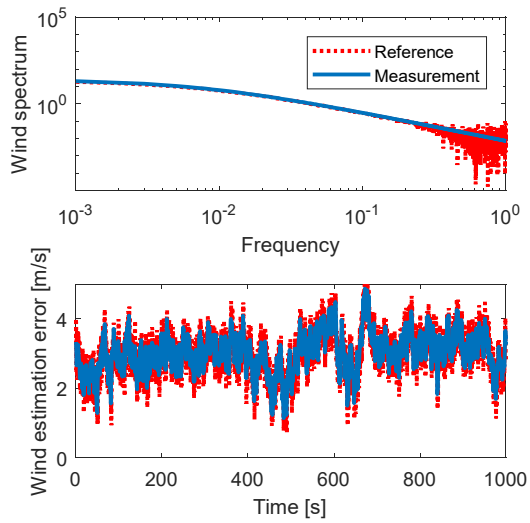

Fig. 11 Simulation result from an increased-performance gyroscope (angular rate)

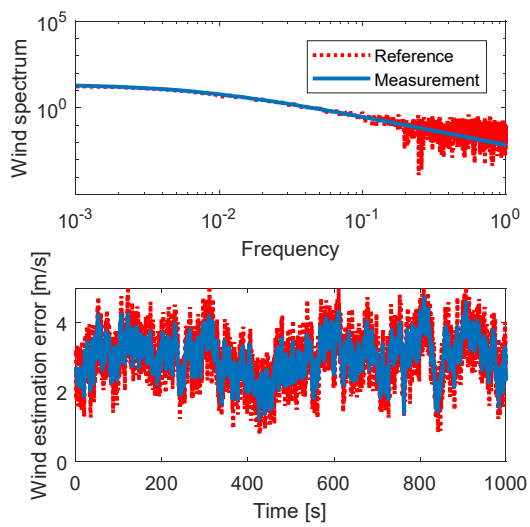

Fig. 12 Simulation result from an increased-performance gyroscope (orientation)

4. Conclusion

The feasibility of low-cost wind-characterization with an example set of sensors is found for the wind with a frequency lower than 0.05 Hz. It is found that the limitation is due to the angular rate error of gyroscope.

For a balloon with low lifting force, the estimation performance is poor due to the motion of balloon that does not follow the assumption. However, the estimation performance seems to be the same when the balloon lifting force is high enough.

5. Acknowledgement

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References

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