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Wind speed turbulence system identification and signal generator

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1 Introduction

Many mechanical systems operating outdoors, such as parabolic antennas are continuously disturbed by wind turbulence. The study was conducted to improve the tracking performances of mobile antennas developed by Safran Data Systems [5]. Indeed, antennas require a lot of precision where wind turbulence increases errors and signal loss risks. The presented short horizon wind modeling can also be used in other fields : wind turbines (blades, mechanical forces, ...), wind response of solar panels, kites for traction, sailing, etc.

The short-term wind speed component, which corresponds to the turbulence, is a non-stationary stochastic process and thus is difficult to model in time domain. Therefore, the simulator design method presented in this paper is based on wind spectral characteristics. These characteristics will be described by models based on the well known von Kármán approximation [8] and on the [3] and [2] fractional functions. The spectral models are then used to design fractional order shaping filters capable of randomly generating wind speeds.

A first study was proposed in [4] where the approximation of PSD is proposed by using simple fractional functions. Neither synthesis of shaping filters nor any time domain simulations are provided. This article presents a complete study with more complex and realistic approximations that takes into account fractional transfer models which can be implemented in an antenna simulator that includes wind turbulence disturbances. Moreover physical meaning is also provided to the proposed model parameters in order to easily tune them for realistic wind turbulence scenarios.

2 Experimental protocol

Wind spectral characteristics, on which the models will be based, will be used as a reference for the identification. For this purpose, one-day wind speed datasets recorded next to the city of Montpellier, France are used as a reference to validate the models. The sensor used to make the measurements is an ultrasonic anemometer integrated into a Vaisala WXT520 weather transmitter that measures wind speed and direction, temperature, air pressure, precipitation,

and relative humidity. The sensor has three identical transducers that generate ultrasonic signals. The wind speed is calculated by measuring the time it takes for the ultrasonic signal to travel from one transducer to the others. The anemometer has a measurement range of 0 to 60 m/s and an accuracy of $\pm 3\%$. Figure 1 represents spectral distributions of the signal power.

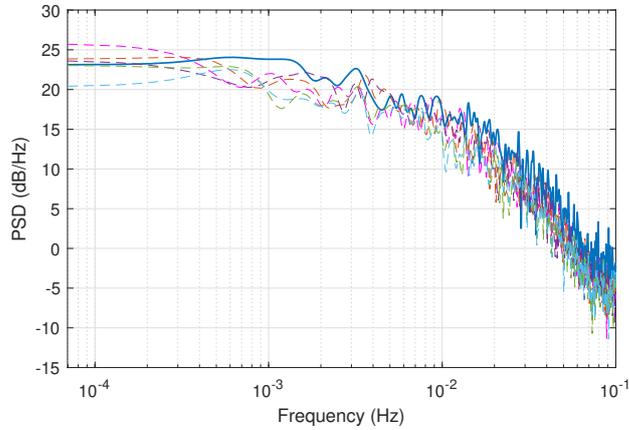


FIG. 1 – PSD of different wind speed measurements using Welch's method

3 State of the art

3.1 Wind speed components

The wind energy is distributed over a wide frequency band near the ground [1]. Van Der Hoven proposed in 1957 wind spectral analyses (Figure 2). The spectrum shows that the power spectral density can be divided into two components each with a maximum : one part corresponding to turbulence with short period variations, and the other part corresponding to long seasonal variations. The peak of interest is the turbulence peak which has a period of about 76s and it is caused by gusts and surface effects.

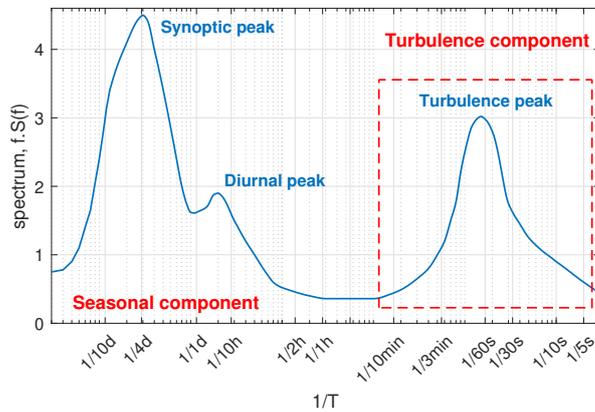


FIG. 2 – Van der Hoven's wind spectrum [7]

Wind speed can be considered as a stationary process in the energy gap ($15\text{min} < T < 3\text{h}$), contrary to turbulence ($T < 10\text{min}$) where the speed follows a random and non-stationary process. Based on Reynolds' fluid decomposition, the turbulence wind speed can be expressed as a sum of a steady component representing mean speed and a fluctuating component :

$$V(t) = \bar{V}(t) + V_{turb}(t) \quad (1)$$

where $\bar{V}(t)$ is the long-term component and $V_{turb}(t)$ the turbulence component.

3.2 von Kármán model

The von Kármán model [8] is a mathematical model of the power spectral densities of the linear and angular wind speed components. It approximates the PSD by a non-integer order

function. It was developed by the United States Department of Defense, for aircraft design and simulation applications. The model can be used to design shaping filters which take white noise as input and return a stochastic signal with the spectral characteristics of the wind turbulence as output. The von Kármán model expresses the spectrum of the longitudinal, lateral and vertical components of the wind speed. Considering von Kármán’s longitudinal model, the wind speed PSD is expressed as :

$$S(f) = \frac{4\sigma^2 \frac{L}{\bar{V}}}{\left(1 + 70.8\left(\frac{L}{\bar{V}}f\right)^2\right)^{5/6}}, \quad (2)$$

where f is the frequency, σ is the turbulence standard deviation, L is the length scale and \bar{V} is the mean speed.

4 Fractional model approximations

Fractional calculus has extended the possibilities of time and frequency identification by going beyond the limits of rational systems. Two elementary fractional functions, the Cole-Cole [2, 6] and Davidson-Cole [3, 6] functions, are generally used to model complex systems with a reduced number of parameters. In fact, the von Kármán model which uses a non-integer order, produces a filter whose transfer function has the form of a Davidson-Cole function, with a differentiation order equal to 5/6. Therefore, these two types of fractional functions, Cole-Cole and Davidson-Cole, will be relied on to improve the accuracy of the von Kármán model over the frequency band of interest range of wind turbulence.

Figure 3 presents a comparison of different model approximations of the wind turbulence PSD and Table 1 summarizes the comparison results.

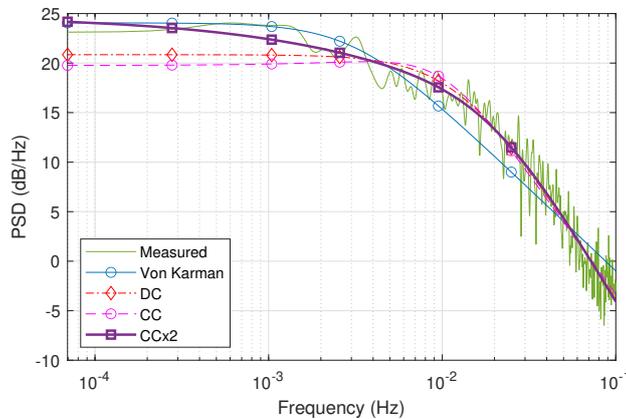


FIG. 3 – Comparison between the von Kármán model (blue), DC model (red dash-dotted), CC model (pink dashed), CCx2 model (purple) and the measured wind PSD (green)

Model	Number of parameters	Mean nAIC
von Kármán	2	2.027
Davidson-Cole	3	1.200
Cole-Cole	3	1.283
Cole-Cole×2	4	1.162

TAB. 1 – Comparison between the mean nAIC of the different models

The CC×2 model fits the wind measurements well over the entire turbulence frequency range. Even if it is a little more complex than the other models, it is the one chosen for the time simulation and to be integrated into the dynamic model of our system.

5 Wind speed generator

The real-time wind speed simulator is built from the shaping filter, stemmed from the wind model, and from the different equations to tune its parameters. The scheme in Figure 4 illustrates the functioning of the wind speed generator. The model parameters K , τ_1 and τ_2 are calculated from the mean speed \bar{V} , the length scale L and the turbulence intensity I_{ref} which are constants and chosen by the user. The order ν is also fixed. The generator input is a white noise with a standard deviation $\sigma_{noise} = 1$. The filter output is the short-term component of the wind speed $V_{turb}(t)$ representing the turbulence speed.

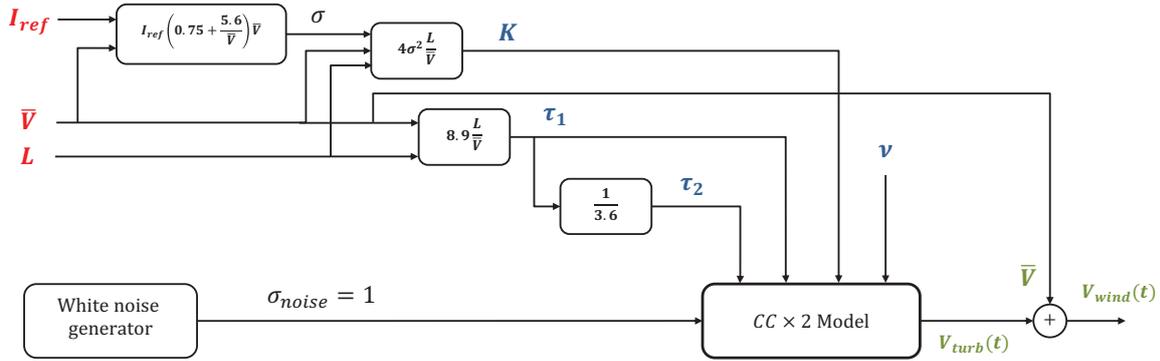


FIG. 4 – Scheme of the wind speed generator

6 Conclusion

The reference von Kármán model is only accurate in low frequency. Therefore, improved models based on the von Kármán model structure have been developed and tested such as Davidson-Cole and Cole-Cole forms of fractional functions. They allow a better fit in high frequency, because they have no constraint on the differentiation order. An improved fractional model has been proposed from a Cole-Cole two-cell fractional function, thus enabling the PSD to have a second slope. The model parameters are tuned from known constants : the mean speed, the length scale and the turbulence intensity. The generator takes as an input a random white noise and returns a signal with the same spectral characteristics as wind turbulence. The real-time wind simulator will be integrated into dynamical models of tracking parabolic antennas, in order to effectively design control laws that counters wind effects, thus rendering antennas more precise.

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