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SHORT COMMUNICATION

# Wind speed time series characterization by Hilbert transform

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SUMMARY

Predictions of wind energy potential in a given region are based on on-location observations. The time series of these observations would later be analysed and modelled either by a probability density function (pdf) such as a Weibull curve to represent the data or recently by soft computing techniques, such as neural networks (NNs). In this paper, discrete Hilbert transform has been applied to characterize the wind sample data measured on İzmir Institute of Technology campus area which is located in Urla, İzmir, Turkey, in March 2001 and 2002. By applying discrete Hilbert transform filter, the instantaneous amplitude, phase and frequency are found, and characterization of wind speed is accomplished. Authors have also tried to estimate the hourly wind data using daily sequence by Hilbert transform technique. Results are varying.
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KEY WORDS: discrete Hilbert transform; wind speed estimation; wind speed characterization; wind speed time series

## 1. INTRODUCTION

The energy literature is abundant in modelling methods to estimate the wind energy potential of a region. They range from statistical to soft computing techniques. For example, some applications in meteorology by Fuzzy Logic (Murtha, 1995), wind speed estimation by neural networks (NNs) (Mohandes *et al.*, 1998), or turbine power estimation by NNs in connection with Kalman filters (Li *et al.*, 1998). Signal processing is just another tool to handle time series analyses in renewable-energy-related studies. Of these, Hilbert transform is rather a less known yet quite powerful way to use in wind speed prediction of the wind energy potential of a region for reasons characteristic to Hilbert transform.

In the last decade, the Hilbert transform and its properties are applied to analyse time variant applications in signal processing. The application of this transform to signal theory is first introduced by Denis Gabor (Hahn, 1996). The theory of Hilbert transformation is closely

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related to the theory of Fourier transformation. Time series analysis has long been performed by Fourier transform which gives better results for both steady and periodic signals. However, whenever analysis of transient signals is needed this transform is inadequate to represent these series. Hilbert transform technique is useful for transient signals. For example, in the case of random data, the information of Fourier analysis will be periodic, which is in fact not. This is, of course, caused by the nature of Fourier transform which is trigonometric and periodic.

In terms of sampling frequency and its effects on the parameters of Weibull wind speed probability density distribution and the standard errors, Ramirez and Carta (2005) might be an interesting reference. Since there is no set standard for wind speed measurements, and since sampling rates range from a minute to as large as a day, these rates do have an impact on the model precision. It seems, as it is applied in this paper, an hourly basis can be a good trade-off between the computational cost and precision.

Finally, in another relevant paper by Zhu and Yang (2002), authors used the discrete Hilbert transform technique to estimate the wind speed in Hong Kong by using the data sequence obtained in June 1989. It was found that the variance of the output and input signals are the same for zero mean input sequence and energy spectra are also identical.

In this study, Hilbert transform is used to analyse a set of wind data that can be referred to as random and non-stationary. The purpose of this paper is not to contend that Hilbert transform is an alternative accurate method to existing ones, but rather inform the renewal energy circles of the possible uses of this less-known technique.

## 2. HILBERT TRANSFORM

Hilbert transform is defined as

$$v(t) = \frac{1}{\pi} \int_{-\infty}^{\infty} \frac{u(\eta)}{\eta - t} \mathrm{d}\eta \tag{1}$$

$v(t)$ can also be written in terms of convolution notation as

$$v(t) = \frac{1}{\pi t} * u(t) \tag{2}$$

The time-varying characteristics of wind speed data could be identified in various aspects by HT. The instantaneous frequency, phase and amplitude of the wind speed of the local weather system have been analysed through HT. The details will not be given here but more may be found in Hahn (1996).

### 2.1. Discrete Hilbert transform

Real world signals are not continuous, they cannot be expressed by a continuous function $u(t)$. They are usually experimentally observed signals and time limited. They can be expressed as discrete-time signals. So, in order to evaluate these types of signals, discrete Hilbert transform technique is used.

Let $u(i)$ be a sequence of samples. If the sampling time intervals are the same for all $u(i)$, the continuous time variable $t$ is replaced by the time variable $i = 0,1,2,\ldots, n-1$. The discrete Hilbert transform of these samples in the interval $0 \leqslant i \leqslant n-1$ can be taken by using two different methods: by circular convolution or by calculating the discrete Fourier transform of the samples, which is used in this study, with the following steps:

Firstly, the discrete Fourier transform of this sequence is calculated as

$$U(k) = \sum_{i=0}^{n-1} u(i)\,\mathrm{e}^{-\mathrm{j}w} \tag{3}$$

$$w = \frac{2\pi ik}{n}; \quad (0 \leqslant k \leqslant n-1) \tag{4}$$

After the Fourier image of the Hilbert transform $v(i)$ is obtained, the Hilbert sequence $V(k)$ is calculated by taking the inverse discrete Fourier transform (DFT). This procedure can also be summarized as follows:

$$u(i) \overset{\mathrm{DFT}}{\Rightarrow} U(k) \Rightarrow V(k) = -\mathrm{j}\,\mathrm{sgn}\left(\frac{n}{2} - k\right)\mathrm{sgn}(k)U(k) \overset{\mathrm{DFT}^{-1}}{\Rightarrow} v(i) \tag{5}$$

An important feature of the Hilbert transform is that it only affects the phase and has no effect on the amplitude of the signal, so the signal and its Hilbert transform have the same energy. A caveat is, however, to avoid a possible misinterpretation. The term energy in association with the wind represents the actual energy to be transferred to the turbines to harness the wind power. In this paper, energy is often referred to as the integrated signal power over a period, and has no direct relation to the physical wind power. The power in Hilbert transform terminology covers the amplitudes of both the original and the transformed signal, and should not be confused with the wind power containing various terms as well as wind velocity, which happens to fall beyond the scope of this work.

## 3. WIND SPEED CHARACTERIZATION

The wind data used in this paper are collected from a mast located on İzmir Institute of Technology campus area at a hill of 460 m height from the sea level for a period of 16 months. The wind data were collected at 10 and 30 m mast heights. Mean wind speeds were 7.03 and 8.14 $\mathrm{m\,s^{-1}}$ at 10 and 30 m heights, respectively. During the measurement period, there were occasional speeds of up to 30 $\mathrm{m\,s^{-1}}$ for stormy days.

The wind speed measurement was realized at 46 56 84 E, 42 43 843 N in UTM co-ordinate. Wind speed estimations were done for 30 m height which approximates the minimum height reached by the blade tip portion of a rotating turbine rotor for below MW class, and will help define the wind regime encountered by a typical rotor over its swept area.

The mast was a 30 m tall tubular tower. An additional wind wane was mounted at 30 m height of the mast. Temperature, relative humidity and atmospheric pressure data were obtained through probes for temperature and humidity, and a gauge for pressure, all having been installed on the mast (Ozerdem and Türkeli, 2003).

A data logger was connected with all the sensors on the mast to collect data in time series. A microprocessor was used to sample the speed, and the direction of wind at around 1 Hz. Power was supplied from an external battery charged by solar panels. Geography of the region was also carefully chosen so that no natural or artificial obstacles would be around to interfere

 

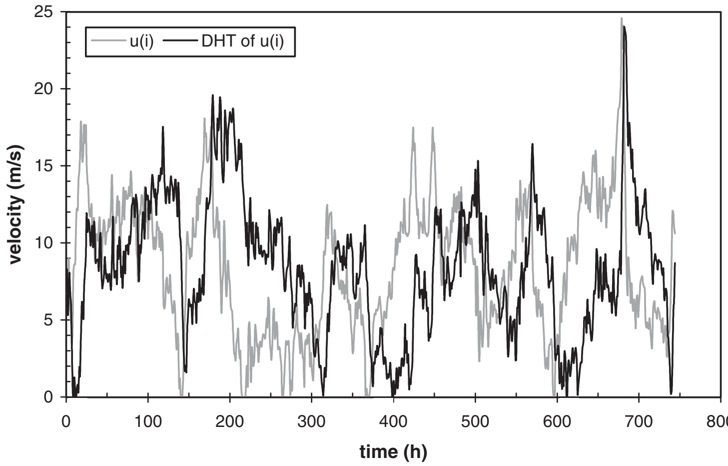


Figure 1. The sample wind speed and its discrete Hilbert transform, March 2001.

with the wind. Surface roughness was low due to low plant heights, which is an important factor in wind shear. The site is directly open to the Aegean Sea, and lies south of it.

Wind speed samples are evaluated using Hilbert transform technique. The instantaneous amplitude, phase and frequency of the data are found. The results found for March 2001 and 2002 are compared. The only reason that the data of March are used is that March has consistent and complete record end to end. Occasional data logger failures have left, however minor, gaps in the records of the remaining months. To compare and preserve the congruity, also for 2002, the month of March is chosen.

The hourly data sequence $u(i)$ for March 2001 and its Hilbert sequence calculated with the algorithm explained in Section 2 are illustrated in Figure 1. There is a 90° phase delay between the data and its Hilbert transform which comes with the definition of the Hilbert transformation.

The instantaneous phase, frequency and amplitude of the analytical signal are the local properties of the analytical signal and makes it possible to characterize the wind speed data used in this study.

For example, it has been observed that local frequency values can be negative which are not meaningful, but the reason of this is the definition of the frequency. By definition, the frequency is the time derivation of the phase. The average frequency of the data sample is about $0.09\,h^{-1}$ for March 2001 and 2002. This value can be useful to predict the change rate of wind velocity for the future.

## 4. WIND SPEED ESTIMATION

Discrete Hilbert transform technique is employed to forecast the hourly wind speed by using the daily data. This method may be useful if more frequent data interval is needed. Wind speed measurements are very important for wind resource assessment, performance, determination and prediction of the energy yield so more frequent data enables more accurate evaluation. Also the representation of wind speed can be made via Hilbert transform.

In this study, the wind data taken with an interval of one hour are used. Daily wind data are obtained by using the averages of hourly data and it is investigated whether the actual hourly data can be estimated with the daily data via the Hilbert transform technique.

Firstly, the Hilbert transform of the daily wind data samples are taken by using Equation (5) which represents the discrete Hilbert values for the days in March. Then in order to find the interval values, which represent the discrete Hilbert values for the hours in a day, the $i$ values are taken as $i = 1/24,\ 2/24, \ldots, 1,\ 1 + (1/24),\ 1 + (2/24), \ldots$ . These $i$ values are the interval values corresponding to the hours. The results obtained with this procedure are compared with the Hilbert values of the hourly wind data. The comparison has showed a good agreement. However, the estimation of hourly Hilbert transform values are not sufficient to have an idea about the wind speed data, because there is a phase shift between the actual and Hilbert transform values as the definition. So, it is necessary to represent the unshifted, real values. For this purpose, the inverse transform of the Hilbert values of daily data is taken by applying the reverse of the procedure

$$v(i) \overset{\mathrm{DFT}}{\Rightarrow} V(k) = -\mathrm{j}\,\mathrm{sgn}\left(\frac{n}{2} - k\right)\mathrm{sgn}(k)U(k) \Rightarrow U(k) \overset{\mathrm{DFT}^{-1}}{\Rightarrow} u(i) \tag{6}$$

The hourly wind data estimation is accomplished similar to the Hilbert transform values estimation, by taking the interval values for $i$. As a result of this procedure, it is found that the actual hourly wind data and estimated values are also coincident as shown in Figure 2, for March 2001. March 2002 results are also computed but not shown here. This procedure shows that the hourly wind data samples can be estimated with daily data using the local properties of Hilbert transform technique. However, low $R^2$-values for the estimation through Hilbert transform (0.3 for March 2001) demand an improvement.

Hilbert transform allows a qualitative look on general wind characteristics in a given region. For the location where the measurements were recorded, the following observations could be made. The energy concentration of the wind is located very close to zero frequency ($h^{-1}$), and

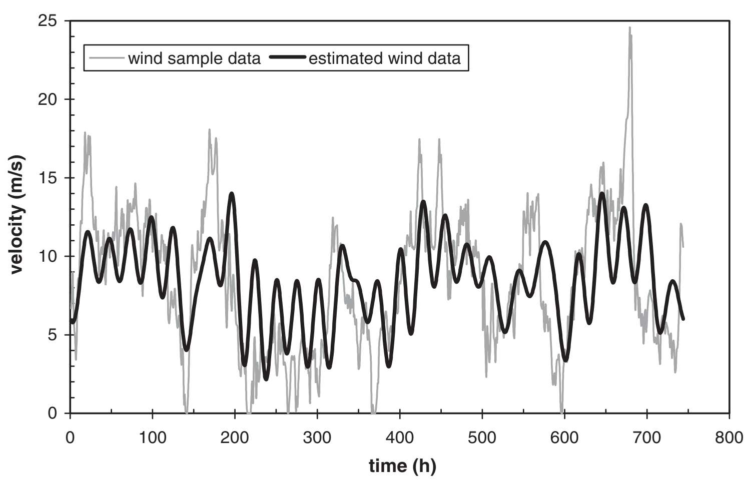


Figure 2. Estimation of wind speed values for hourly interval, March 2001.

 

low energy concentrations take place at high frequency values at either sides. Frequency plot is just another proof that the dominant wind has low frequency values for the case given here. For the data values of frequency in the range of 0.01–0.03 $h^{-1}$, wind speeds oscillate in between 8 and 12 $m\,s^{-1}$, which roughly coincides with the earlier study by Ozerdem and Türkeli (2003).

## 5. CONCLUSION

Hilbert transforms do not provide a point-to-point accurate wind speed estimation *per se*, as it can easily be seen from the study. Rather Hilbert transform was used to find the predominant wind speed throughout the month of March in 2001 and 2002, as realistically as possible, to estimate the wind energy potential of the given region. This is facilitated by the fact that the transformed time series was not altered in energy content, since both the original and the transformed data have the same energy.

The characterization of wind data in Urla, in March 2001 and 2002 is realized by the discrete Hilbert transform which was employed to carry out the analysis in time domain. For this purpose, the instantaneous amplitude and frequency of the signal were determined. Localized frequency and energy values were used together to pinpoint the localization of the energy concentration. Also Hilbert transform technique may be used to estimate the smaller interval values for nonlinearly changing systems, as applied in this study in which the hourly wind data are estimated by using daily sequence.

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