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MEASUREMENT OF WIND POWER AND ENERGY USING AN ANEMOMETER WITHOUT MOVING PARTS
MERENJE SNAGE I ENERGIJE VETRA KORIŠĆENJEM ANEMOMETRA BEZ POKRETNIH DELOVA

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ABSTRACT

The paper deals with the application of a newly developed anemometer without moving parts. It is digitized and has built-in electronics that convert the vibrations of two aluminum fixed frames into two digital signals: one, which shows the strength (speed absolute value)) of the wind, and the other, which shows its direction. Earlier works have shown that the two-bit stochastic digital measurement method overcomes (eliminates) the problem of the offset of the analog adder. The authors of this paper apply this idea to the digital output of the sensor, where the role of the offset of the analog adder is taken over by the integral nonlinearity of the digital output of the anemometer. The first step in this direction is dithering digitally the sensor output. This principle is presented in detail, as well as a rough estimate of the accuracy gain in measuring wind energy.

Keywords: *wind power, wind energy, two-bit SDMM, anemometer with fixed frames.*

REZIME

Rad se bavi primenom novorazvijenog anemometra bez pokretnih delova. On je digitalizovan i ima ugrađenu elektroniku koja vibracije dva aluminijumska nepokretna rama pretvara u dva digitalna signala: jedan, koji prikazuje jačinu (apsolutnu vrednost brzine) vetra, i drugi, koji prikazuje njegov smer. Oba signala se koriste za potrebe računanja snage i energije vetra. U ranijim radovima je pokazano da dvobitna stohastička digitalna merna metode prevazilazi (eliminiše) problem ofseta analognog sabirača. Autori ovog rada primenjuju tu ideju na digitalni izlaz senzora gde ulogu ofseta analognog sabirača preuzima integralna nelinearnost digitalnog izlaza anemometra. Prvi korak u tom pravcu jeste digitalno diterovanje izlaza senzora. Ovaj princip je detaljno prikazan, kao i gruba ocena dobitka tačnosti u merenju energije vetra. U radu je pokazano da tačnost u merenju energije vetra nije lošija od granične tačnosti u slučaju anemometra sa šoljicama koji generiše sinusoidalni napon.Anemometar se sastoji od dva nepokretna aluminijumska rama koji su pod uglom od pi/2. Vetar na njima stvara vibracije koje se digitalno mere, lokalno obrađuju i pretvaraju u dva niza digitalnih podataka:o trenutnom intenzitetu vibracija srazmerno apsolutnoj vrednosti brzine vetra i trenutnoj vrednosti ugla pod kojim vetar duva. Namenjen je upravljanju jedrećim dronovima sa morima (u prvom redu – italijanskom) na kojima nema niskih temeperatura i eventualno ledene kiše (komentar autora). Elektronika za obradu je integrisana u anemometar i on, nominalno, ima dva digitalna izlaza

Ključne reči: *snaga vetra, energija vetra, dvobitna SDMM, anemometar bez pokretnih delova.*

INTRODUCTION

In *(Vujicic V. et. al., 2020)* it was shown that an anemometer with cups can measure wind energy very accurately. This fact is especially important for analyzing many possible locations for wind farms. Measuring the average wind direction is a far simpler problem - simply a standard weather vane is mechanically coupled to an absolute encoder *(Austerlitz H., 2003)* in order to measure the angle and directly obtain digital information about the current wind direction, and averaging this information gives the average wind direction. The difficulty in the use of both sensors, anemometers with cups and weather vanes, is that important parts are movable, so their usability decreases drastically in difficult weather conditions.

As one possible solution to overcome this situation is a sensor for simultaneous measurement of wind speed and direction - anemometer with fixed frames – which was designed and made *(Pugi L. et. al., 2018)*. The topic of this paper is the application of anemometers with fixed frames in measuring energy and average wind direction at potential locations for the construction of wind farms.

MATERIAL AND METHOD

Commonly used terms “wind power” and “wind energy” have a strictly scientific definition: “wind energy” is “kinetic energy of wind” while “wind power” is first derivative in time of “kinetic energy of wind”. For more details see *(Licina B. 2020)*.

Note that very accurate measurement of wind energy using two-bit SDMM is described in *(Vujicic, V. et. al., 2020)*. Let us note, further, that in *(Sovilj P. et. al., 2020)* it is shown how using two-bit SDMM accurate measurements can be made even with the presence of significant nonlinearities of the applied sensor.

Finally, note that the output of the anemometer with fixed frames is digital (actually there are two digital outputs - one is the wind speed, and the other is wind direction). The sensor is shown in Fig. 1. and two calibration nonlinear curves in Fig. 2. and Fig. 3. *(Pugi L. et. al., 2018)*.

Problem to be solved:

a) Measure accurately (over a long period of time) the wind energy at a given location taking into account the nonlinearity of the anemometer with fixed frames. The problem is equivalent to measuring the mean wind power in the same time interval.

b) Measure accurately the average wind direction over the same time interval as under a).

RESULTS

The fact that the sensor provides two digital outputs naturally imposes the application of two-bit SDMM where hardware analog dithering is replaced by software dithering *(Vujicic V. et. al., 1998)*, and further processing is, in principle, is the same as in *(Vujicic V. et. al., 2020)* and *(Sovilj P. et. al., 2020)*. Furthermore, since software dithering is drastically simpler than hardware and, in addition, adaptable, it is possible to apply an optimal 3-bit resolution *(Urekar M., 2018)* and thus, with minimal processing complexity, get an effective acceleration of 9 times compared to the existing measurement technology. The accuracy of the measurement defined by the calibration curves is not impaired. Paper *(Sovilj P. et. al., 2020)* shows how two-bit SDMM is used in nonlinear sensor measurements. The basis for this is to have at your disposal either:

i. inverse calibration polynomial *(Sovilj P. et. al., 2020)* or
ii. error diagram of appropriate measuring quantity *(Juhász A. et al., 2020)*.

In *(Juhász A. et al., 2020)* it is shown how two mutually coupled quantities can be measured - CT ratio and phase error (angle). In our case here, mutually coupled quantities are wind strength (amplitude) and wind direction (angle). The new principle of nonlinear regression, developed in *(Juhász A. et al., 2020)*, enables the use of the output from a nonlinear sensor, current measuring transformer (CT) in *(Juhász A. et al., 2020)*, or anemometer with frames in this case, up to the accuracy limit of the calibration system shown in Fig. 2 and Fig. 3 without any need for sensor linearization.

Fig. 1. Photo of the evolution of anemometers with frames (Pugi L. et. al., 2018).

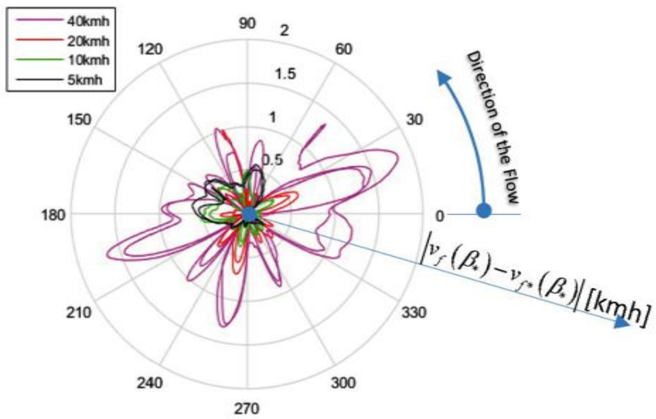

Fig. 2. Wind speed calibration curve (Pugi L. et. al., 2018).

On the other hand, the digital outputs of the anemometer with frames offer the possibility of direct processing using SSM and obtaining the required quantities - energy and average wind direction. The problem that generally occurs here is elaborated in *(Licina B. 2020)*, which boils down to a huge increase of error due to the integral nonlinearity of the applied ADC in the sensor. This error has been shown to be at least two orders of magnitude lower in the case of the application of two-bit SDMM. Therefore, without a doubt, it is necessary to apply software-dithered two-bit SDMM here as well, and not directly SSM.

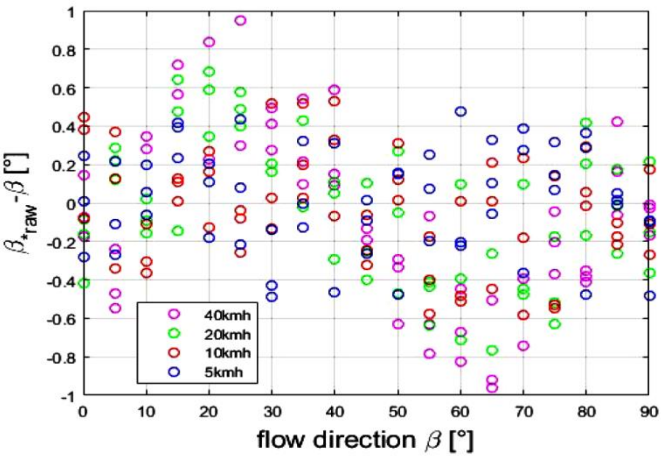

Fig. 3. Wind direction calibration curve (Pugi L. et. al., 2018).

The sensor without moving parts used in *(Pugi L. et. al., 2018)* at its output provides two digital data in a floating-point representation:

- intensity (speed) of wind |v| and
- direction of wind blowing φ

Complete processing using two-bit SDMM is performed in a microcomputer *(Beaglebone, Raspberry)*, and its general scheme is shown in Fig. 4.

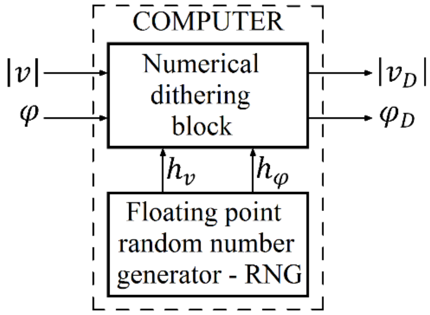

Fig. 4. General schematic of numerical dithering.

Fig. 5. shows the algorithm for calculating one-bit dithered intensity (speed) of wind |vD|, where to the input signal of wind speed |v|, obtained from the sensor without moving parts, dither signal hv is superimposed (vu = |v| + hv), where:

$$|v| \leq V_{FS} , \tag{1}$$

$$|h_v| \leq \frac{V_{FS}}{2} . \tag{2}$$

Fig. 6. shows the algorithm for calculating one-bit dithered direction (angle) of wind φD, where to the input signal of direction (angle) of wind φ, also obtained from the sensor without moving parts, dither signal hφ is superimposed (φu = φ + hφ), where:

$$|\varphi| \leq 2\pi , \tag{3}$$

$$|h_\varphi| \leq \pi . \tag{4}$$

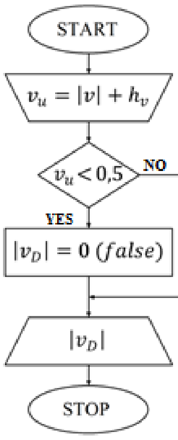

Fig. 5. One bit dithered intensity of wind |v|.

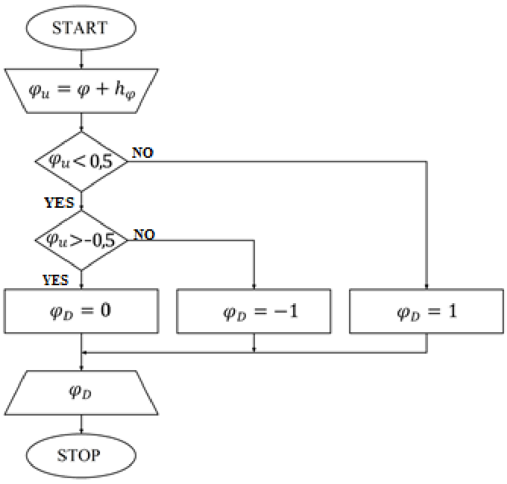

Fig. 6. The algorithm for calculating one-bit dithered direction (angle) of wind φD.

Note also that the software dithering procedure is shown only for the mantises of the input data. Operations on exponents are not shown because they are much simpler and, basically, defined by relations (1) and (2), i.e. (3) and (4), respectively.

DISCUSSION

In *(Licina B. 2020)* it was shown that the nonlinearity of a two-bit stochastic addition AD converter (SAADK), if DAC AD5791 is used, practically makes an error in order of ppm over a long time interval (say one day), and the processing error practically disappears *(Sovilj P. et. al., 2020)*. If, on the other hand, SSM and ADC are used [say 16-bit ADC LTC1605 elaborated in *(Licina B. 2020)*] whose integral nonlinearity is in the order of 16 ppm, which is a correct estimate, then the mean value of the cube output from the ADC is:

$$(A+\delta A)^3 = A^3 + 3A^2(\delta A) + 3A(\delta A)^2 + (\delta A)^3 \qquad (5)$$

where A denotes the absolute value of speed, and δA is the integral nonlinearity of applied AD converter. In first approximation, the error mean value of the cube of the output from ADC is:

$$3 \cdot \frac{(\delta A)}{A} = 3 \cdot 16\ ppm = 48\ ppm \qquad (6)$$

Therefore, it is almost two orders of magnitude higher than when using a two-bit SAADK that has an analog adder offset of 1/5000 FS (1 mV, on 5 V). If as an offset of analog adder we take δA, value within the LSB of a given AD converter, as shown in *(Sovilj P. et. al., 2020)*, then its value is even lower and is $1/2^{16} \approx 1/65000$.

Depending on the method applied in the construction of ADC in the SSM method, the influence of integral nonlinearity can be significantly reduced, if only the MSB in two-bit software-dithered SDMM is used. Or MSB and the first following lower bit in case of three-bit software-dithered SDMM which is, proven in *(Urekar M., 2018)*, the optimal resolution in the application of SDMM. Namely, if, for example, the applied method of successive approximations is applied in a specific ADC, the integral nonlinearity is not affected by all resistors in the R-2R network, but only the first two or four respectively, so the integral nonlinearity is much lower.

CONCLUSION

The paper shows that the concept of software dithering of the anemometer with fixed frames output offers the possibility of a much more accurate measurement of energy but also the mean wind direction. In cited literature, the idea of measuring with a nonlinear sensor, both with one and with two outputs, has been defined and experimentally tested. In our case, one output represents the wind (speed) intensity |*v*|, and the other output represents the wind direction *φ*.

Therefore, large nonlinearities, as can be seen on calibration diagrams in Fig. 2. and Fig. 3. practically have no influence on the accuracy of energy measurement, i.e. the average direction of wind blowing - above of all, is determined by the accuracy of equipment and procedure used for calibration. As shown in *(Pugi L. et. al., 2018)*, - wind tunnel - was used for calibration of an anemometer with fixed frames.

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