MEASUREMENT UNCERTAINTY EVALUATION OF THE WIND SPEED IN THE ATMOSPHERIC BOUNDARY LAYER

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Abstract. A method for measuring wind speed by the trajectory of an acoustic package under the influence of air flows in the boundary atmospheric layer is developed. Model equations for measurement components of wind speed evaluation are obtained. For each of the components, an equation for the combined standard uncertainty is written, sensitivity coefficients are calculated for input quantities, and uncertainty budgets are constructed. The last can serve as the basis for creating a software tool for measurement uncertainty evaluation.

Key words: Wind speed, boundary atmospheric layer, model equation, measurement, uncertainty budget

1. Introduction

In meteorology, one of the most commonly measured atmospheric quantities is wind speed. The latter is caused by the movement of air from high to low pressure, due to changes in temperature in different layers of the atmosphere. Increasing the safety of takeoff and landing of aircraft requires monitoring wind conditions near airfield runways in the atmospheric boundary layer, which is a transition zone from the surface to the free atmosphere and a height from tens of meters to several kilometers. The usage of air layers with contact sensors of various designs for this is quite labor-intensive poorly controlled, and also dangerous for aircraft. Therefore, to solve this problem, remote acoustic or radio-acoustic sensing systems are recommended [1-3]. The most developed acoustic methods for measuring atmospheric parameters are the method of determining wind speed and direction from the Doppler frequency shift of scattered signals and the amplitude method of determining turbulence parameters [4-6].

2. Drawbacks

The disadvantages of these methods are the measurement of only the vertical component of wind speed, short range, low accuracy, and complexity of hardware implementation. The authors proposed another measurement method based on measuring the movements of an acoustic package under the influence of wind [7-8], which has no listed disadvantages. This method requires a study of its metrological characteristics.

3. Goal

Development of procedures for measurement uncertainty evaluation of wind speed in the atmospheric boundary layer by the proposed method.

4. The essence of the method and the formation of model equations

The essence of the method, which consists of measuring the acoustic packet trajectory under the influence of air currents [7], can be described as moving the end of the radius vector $R(t)$ connecting the radiation point taken as the origin of coordinates 0 with the current location of the acoustic packet P (Fig.).

The time-varying length of the radius vector $R(t)$ can be written as

$$R(t) = \sqrt{X^2(t) + Y^2(t) + Z^2(t)} \ ,$$

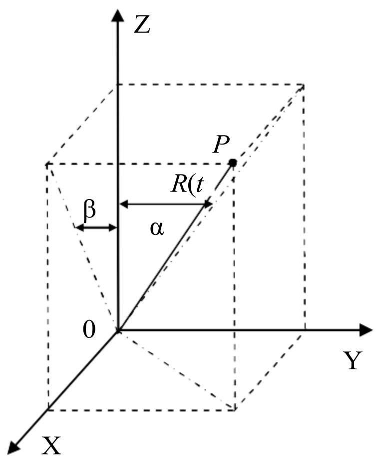
and its projections on the coordinate axes are equal to [7]:

$$Z(t) = \frac{R(t)}{\sqrt{1 + \mathrm{tg}^2[\alpha(t)] + \mathrm{g}^2[\beta(t)]}} \ ; \qquad (1)$$

$$X(t) = \frac{R(t) \cdot \mathrm{tg}[\alpha(t)]}{\sqrt{1 + \mathrm{tg}^2[\alpha(t)] + \mathrm{g}^2[\beta(t)]}} \ ; \qquad (2)$$

$$Y(t) = \frac{R(t) \cdot \mathrm{tg}[\beta(t)]}{\sqrt{1 + \mathrm{tg}^2[\alpha(t)] + \mathrm{g}^2[\beta(t)]}} \ . \qquad (3)$$

where $\mathrm{tg}[\alpha(t)] = \frac{X(t)}{Z(t)}$, $\mathrm{tg}[\beta(t)] = \frac{Y(t)}{Z(t)}$.



The essence of the wind speed measurement method

The length of the radius vector $R(t)$ can be calculated at successive times t by the formula:

$$R(t) = C \cdot \Delta t \ , \qquad (4)$$

where C is the sound speed in the air, Δt is the delay time of the sound signal from the moment of emission until it is received by receiving acoustic antennas. Therefore, model equations for estimating wind speed components can be obtained from expressions (1)-(3) [5]:

$$V_Z = \frac{C\cdot\Delta t}{\sqrt{1+\mathrm{tg}^2[\alpha(t)]+\mathrm{g}^2[\beta(t)]}}\,; \quad (5)$$

$$V_X = \frac{C\cdot\Delta t\cdot\mathrm{tg}[\alpha(t)]}{\sqrt{1+\mathrm{tg}^2[\alpha(t)]+\mathrm{g}^2[\beta(t)]}}\,; \quad (6)$$

$$V_Y = \frac{C\cdot\Delta t\cdot\mathrm{tg}[\beta(t)]}{\sqrt{1+\mathrm{tg}^2[\alpha(t)]+\mathrm{g}^2[\beta(t)]}}\,. \quad (7)$$

5. Measurement uncertainty evaluation

The standard uncertainty of wind speed measuring in the YOZ plane is evaluated by the following expression [9-10]:

$$u_c(V_X)=\sqrt{c_C^2(V_X)\cdot u^2(C)+c_{\Delta t}^2(V_X)\cdot u^2(\Delta t)}\,+$$
$$+\sqrt{c_\alpha^2(V_X)\cdot u^2(\alpha)+c_\beta^2(V_X)\cdot u^2(\beta)}\,, \quad (8)$$

where $c_C(V_X)$; $c_{\Delta t}(V_X)$; $c_\alpha(V_X)$; $c_\beta(V_X)$ are sensitivity coefficients of the measurand to the corresponding input quantities, which are calculated as partial derivatives of the velocity component V_X according to the corresponding input quantities of equation (6), given in Table. 1.

The measurement uncertainty budget for this case is given in Table 2.

The standard uncertainty of wind speed measuring in the XOZ plane is evaluated by the following expression [9-10]:

$$u_c(V_Y)=\sqrt{c_C^2(V_Y)\cdot u^2(C)+c_{\Delta t}^2(V_Y)\cdot u^2(\Delta t)}\,+$$
$$+\sqrt{c_\alpha^2(V_Y)\cdot u^2(\alpha)+c_\beta^2(V_Y)\cdot u^2(\beta)}\,, \quad (13)$$

where $c_C(V_Y)=\dfrac{\partial V_Y}{\partial C}$; $c_{\Delta t}(V_Y)=\dfrac{\partial V_Y}{\partial \Delta t}$; $c_\alpha(V_Y)=\dfrac{\partial V_Y}{\partial \alpha}$; $c_\beta(V_Y)=\dfrac{\partial V_Y}{\partial \beta}$ are sensitivity coefficients of the measurand to the corresponding input quantities, which are calculated as partial derivatives of the velocity component V_Y according to the corresponding input quantities of equation (7), given in Table. 3.

Table 1. Sensitivity coefficients of the velocity component V_X for the corresponding input quantities of equation (6)

$c_C(V_X)=\dfrac{\partial V_X}{\partial C}$	$c_{\Delta t}(V_X)=\dfrac{\partial V_X}{\partial \Delta t}$	$c_\alpha(V_X)=\dfrac{\partial V_X}{\partial \alpha}$	$c_\beta(V_X)=\dfrac{\partial V_X}{\partial \beta}$
$\dfrac{\Delta t\cdot\mathrm{tg}(\alpha)}{\sqrt{1+\mathrm{tg}^2(\alpha)+\mathrm{tg}^2(\beta)}}$ (9)	$\dfrac{C\cdot\mathrm{tg}(\alpha)}{\sqrt{1+\mathrm{tg}^2(\alpha)+\mathrm{tg}^2(\beta)}}$ (10)	$\dfrac{C\Delta t\cdot[1+\mathrm{tg}^2(\beta)]}{[1+\mathrm{tg}^2(\alpha)+\mathrm{tg}^2(\beta)]^{3/2}\cdot\cos^2(\alpha)}$ (11)	$\dfrac{-C\Delta t\cdot\mathrm{tg}(\beta)}{[1+\mathrm{tg}^2(\alpha)+\mathrm{tg}^2(\beta)]^{3/2}\cdot\cos^2(\beta)}$ (12)

Table 2. Measurement uncertainty budget of the velocity component V_X

Input quantities	Input quantity values	The standard uncertainty of the input quantities	Types of uncertainty	Sensitivity coefficients	Uncertainty contributions
C	$\hat{C}$	$u(\hat{C})$	B	(9)	$c_C(\hat{V}_X)\cdot u(\hat{C})$
Δt	$\Delta\hat{t}$	$u(\Delta\hat{t})$	B	(10)	$c_{\Delta t}(\hat{V}_X)\cdot u(\Delta\hat{t})$
α	$\hat{\alpha}$	$u(\hat{\alpha})$	B	(11)	$c_\alpha(\hat{V}_X)\cdot u(\hat{\alpha})$
β	$\hat{\beta}$	$u(\hat{\beta})$	B	(12)	$c_\beta(\hat{V}_X)\cdot u(\hat{\beta})$
Measurand	Measurand value	The standard uncertainty of the measurand	Law of distribution	Coverage factor	Expanded uncertainty
V_X	$\dfrac{\hat{C}\cdot\Delta\hat{t}\cdot\mathrm{tg}[\hat{\alpha}(t)]}{\sqrt{1+\mathrm{tg}^2[\hat{\alpha}(t)]+\mathrm{g}^2[\hat{\beta}(t)]}}$	(8)	Gaussian	2	$U(V_X)$

Table 3. Sensitivity coefficients of the velocity component V_Y for the corresponding input quantities of equation (7)

$c_C(V_Y)=\dfrac{\partial V_Y}{\partial C}$	$c_{\Delta t}(V_Y)=\dfrac{\partial V_Y}{\partial \Delta t}$	$c_\alpha(V_Y)=\dfrac{\partial V_Y}{\partial \alpha}$	$c_\beta(V_Y)=\dfrac{\partial V_Y}{\partial \beta}$
$\dfrac{\Delta t\cdot\mathrm{tg}(\alpha)}{\sqrt{1+\mathrm{tg}^2(\alpha)+\mathrm{tg}^2(\beta)}}$ (14)	$\dfrac{C\cdot\mathrm{tg}(\alpha)}{\sqrt{1+\mathrm{tg}^2(\alpha)+\mathrm{tg}^2(\beta)}}$ (15)	$\dfrac{-C\Delta t\cdot\mathrm{tg}(\alpha)}{[1+\mathrm{tg}^2(\alpha)+\mathrm{tg}^2(\beta)]^{3/2}\cdot\cos^2(\alpha)}$ 16)	$\dfrac{C\Delta t\cdot[1+\mathrm{tg}^2(\alpha)]}{[1+\mathrm{tg}^2(\alpha)+\mathrm{tg}^2(\beta)]^{3/2}\cdot\cos^2(\beta)}$ (17)

Table 4. Measurement uncertainty budget of the velocity component V_Y

Input quantities	Input quantity values	The standard uncertainty of the input quantities	Types of uncertainty	Sensitivity coefficients	Uncertainty contributions
C	$\hat{C}$	$u(\hat{C})$	B	(14)	$c_C(\hat{V}_Y)\cdot u(\hat{C})$
Δt	$\Delta\hat{t}$	$u(\Delta\hat{t})$	B	(15)	$c_{\Delta_t}(\hat{V}_Y)\cdot u(\hat{\Delta}_t)$
α	$\hat{\alpha}$	$u(\hat{\alpha})$	B	(16)	$c_\alpha(\hat{V}_Y)\cdot u(\hat{\alpha})$
β	$\hat{\beta}$	$u(\hat{\beta})$	B	(17)	$c_\beta(\hat{V}_Y)\cdot u(\hat{\beta})$
Measurand	Measurand value	The standard uncertainty of the measurand	Law of distribution	Coverage factor	Expanded uncertainty
V_Y	$\dfrac{\hat{C}\cdot\Delta\hat{t}\cdot \mathrm{tg}[\hat{\beta}(t)]}{\sqrt{1+\mathrm{tg}^2[\hat{\alpha}(t)]+\mathrm{g}^2[\hat{\beta}(t)]}}$	(13)	Gaussian	2	$U(V_Y)$

The measurement uncertainty budget for this case is given in Table 4.

The standard uncertainty of wind speed measuring in the XOY plane is evaluated by the following expression [9-10]:

$$u_c(V_Z)=\sqrt{c_C^2(V_Z)\cdot u^2(C)+c_{\Delta t}^2(V_Z)\cdot u^2(\Delta t)}+$$

$$+\sqrt{c_\alpha^2(V_Z)\cdot u^2(\alpha)+c_\beta^2(V_Z)\cdot u^2(\beta)}\,, \qquad (18)$$

here $c_C(V_Z)=\dfrac{\partial V_Z}{\partial C}$; $c_{\Delta t}(V_Z)=\dfrac{\partial V_Z}{\partial \Delta t}$; $c_\alpha(V_Z)=\dfrac{\partial V_Z}{\partial \alpha}$; $c_\beta(V_Z)=\dfrac{\partial V_Z}{\partial \beta}$ are sensitivity coefficients of the measurand to the corresponding input quantities, which are calculated as partial derivatives of the velocity component according to the corresponding input quantities of equation (8), given in Table. 5.

The measurement uncertainty budget for this case is given in Table 6.

Table 5. Sensitivity coefficients of the velocity component V_Z for the corresponding input quantities of equation (8)

$c_C(V_Z)=\dfrac{\partial V_Z}{\partial C}$	$c_{\Delta t}(V_Z)=\dfrac{\partial V_Z}{\partial \Delta t}$	$c_\alpha(V_Z)=\dfrac{\partial V_Z}{\partial \alpha}$	$c_\beta(V_Z)=\dfrac{\partial V_Z}{\partial \beta}$
$\dfrac{\Delta t\cdot \mathrm{tg}(\alpha)}{\sqrt{1+\mathrm{tg}^2(\alpha)+\mathrm{tg}^2(\beta)}}$ (19)	$\dfrac{C\cdot \mathrm{tg}(\alpha)}{\sqrt{1+\mathrm{tg}^2(\alpha)+\mathrm{tg}^2(\beta)}}$ (20)	$\dfrac{-C\Delta t\cdot \mathrm{tg}(\alpha)}{[1+\mathrm{tg}^2(\alpha)+\mathrm{tg}^2(\beta)]^{3/2}\cdot\cos^2(\alpha)}$ (21)	$\dfrac{-C\Delta t\cdot \mathrm{tg}(\beta)}{[1+\mathrm{tg}^2(\alpha)+\mathrm{tg}^2(\beta)]^{3/2}\cdot\cos^2(\beta)}$ (22)

Table 6. Measurement uncertainty budget of the velocity component V_Z

Input quantities	Input quantity values	The standard uncertainty of the input quantities	Types of uncertainty	Sensitivity coefficients	Uncertainty contributions
C	$\hat{C}$	$u(\hat{C})$	B	(19)	$c_C(\hat{V}_Z)\cdot u(\hat{C})$
Δt	$\Delta\hat{t}$	$u(\Delta\hat{t})$	B	(20)	$c_{\Delta_t}(\hat{V}_Z)\cdot u(\hat{\Delta}_t)$
α	$\hat{\alpha}$	$u(\hat{\alpha})$	B	(21)	$c_\alpha(\hat{V}_Z)\cdot u(\hat{\alpha})$
β	$\hat{\beta}$	$u(\hat{\beta})$	B	(22)	$c_\beta(\hat{V}_Z)\cdot u(\hat{\beta})$
Measurand	Measurand value	The standard uncertainty of the measurand	Law of distribution	Coverage factor	Expanded uncertainty
V_Z	$\dfrac{\hat{C}\cdot\Delta\hat{t}}{\sqrt{1+\mathrm{tg}^2[\hat{\alpha}(t)]+\mathrm{g}^2[\hat{\beta}(t)]}}$	(18)	Gaussian	2	$U(V_Z)$

The expanded uncertainty for all considered cases is calculated by multiplying the standard combined uncertainty by the coverage factor, which for a confidence level of 0.95, assuming a normal distribution of the measurand value, is 2.

5. Conclusions

The method developed by the authors for measur- ing wind speed by measuring the trajectory of an acoustic package under the influence of air flows in the boundary atmospheric layer permits getting rid of the use of air layers with contact sensors of various designs and increases safety for aircraft. Implementation of the pro- posed method contributes to overcome the shortcomings of existing methods, namely, obtain a three-dimensional velocity vector and evaluate for each of the vectors the standard and expanded measurement uncertainty, which, thanks to the developed uncertainty budgets, can be assessed in real-time.

6. Gratitude

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7. Conflict of Interest

The authors state that there are no financial or other potential conflicts regarding this work

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