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THE RESEARCH OF UNCERTAINTY OF THE AIRFLOW VELOCITY UNIT TRANSFER IN THE RANGE FROM 0.05 TO 60 M/S

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Abstract: In this paper, we consider the main sources of uncertainty in the transfer of an airflow velocity unit using the pneumometric method in the range of more than 3 m/s. Considering the uncertainty that appears in the thermo-anemometer sensor calibration using a pneumometric measurement system for applying in a range of less than 3 m / s. Experimental data were obtained during the tests to confirm the type of aerodynamic wind tunnel "EMS 0,05/60-240".

Keywords: air flow velocity, wind tunnel, pneumometric principle, measurement uncertainty.

Introduction

In recent years, a number of aerodynamic wind tunnels have been created in TsAGI for applying as airflow velocity unit standards [1, 2]. The main method of measurement, traditionally using in TsAGI [3, 4], is the pneumometric method. The task of this paper is to estimate the uncertainty in measuring the airflow velocity in the range from 0.05 m/s to 60 m/s, including the transfer of a unit of this value, according to the results of testing a new type of aerodynamic wind tunnel "EMS 0,05/60-240".

1. The pneumometric measurement principle

The pneumometric principle of measuring the airflow velocity in the wind tunnel [5] is determined by the following equation:

$$V = \sqrt{\mu \frac{2}{\rho} \Delta P (1 - \varepsilon)}, \qquad (1)$$

μ – the dynamic pressure field factor of the wind tunnel; ρ – the air density, kg/m^3; ΔP is the dynamic pressure of the flow, Pa; ε is the correction to the compressibility.

The air density ρ is given by

$$\rho = \rho_{\text{ст}} \frac{P' T_{\text{с}}}{B_{\text{с}} T} \left(1 - 0.378 \frac{P_{\text{нп}}}{P'} \psi \right), \qquad (2)$$

$\rho_{\text{ст}}$ is the standard air density, $\rho_{\text{ст}} = 1.225$ kg/m^3; P' is the static pressure, Pa; T_c is the standard air temperature, $T_{\text{с}} = 288.15$ K; $B_{\text{с}}$ is the standard barometric pressure, $B_{\text{с}} = 101325$ Pa; T is the static temperature of flow, K; $P_{\text{нп}}$ is the pressure of saturated water vapor at t °C, Па; ψ is the relative humidity.

The correction to the compressibility is given by

$$\varepsilon = \frac{1}{2\kappa} \frac{\Delta P}{P'}, \qquad (3)$$

κ is the adiabatic index, $\kappa = 1.4$.

2. The measuring system

The block diagram of "EMS 0,05/60-240" aerodynamic wind tunnel is shown in Fig. 1.

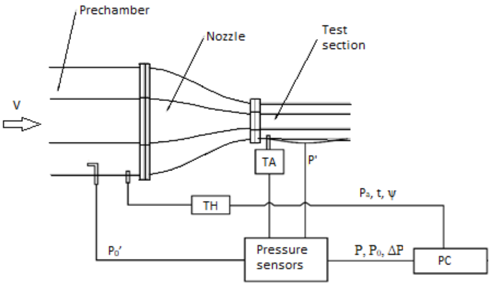

Fig. 1. The block diagram of "EMS 0,05/60-240" aerodynamic wind tunnel

The flow parameters measuring system (FPMS) used in the "EMC 0.05/60-240" is based on precision differential pressure sensors with ranges of 0.63 kPa and 6.3 kPa. The errors of these sensors were determined during individual calibration and are 0.03 Pa in the range of 0...100 Pa, 0.95 Pa in the range of 0.1 ... 0.63 kPa, 0.79 Pa in the range of 0.63...2.5 kPa. Also, the FPMS includes a temperature, air humidity and atmospheric pressure meter (TH), whose errors are 0.2°C, 2% and 3 hPa, in the respective measuring channels.

The airflow velocity in the range from 3 m/s to 60 m/s is measured using the pneumometric method. To measure the flow velocity below 3 m/s, a thermoanemometric sensor (TA) is provided, calibrated by a pneumatic system at a speed of about 3 m/s.

The design of the FPMS provides the measurement of the differential P between the atmospheric pressure P_a and the static flow pressure P': $P = P_a - P'$. Similarly, the differential P_0 between the atmospheric pressure P_a and the full flow pressure P_0' is measured. Also, the differential ΔP between the full pressure P_0' and the static pressure P' is measured. These indicated values, as well as the parameters of the atmosphere t, ψ, P_a (temperature, air humidity, atmospheric pressure) are measured simultaneously and independently.

3. The uncertainty of airflow velocity measurement

Simultaneous and independent measurements of P, P_0, ΔP in the presence of the quantity equation

$$P - P_0 - \Delta P = 0 \qquad (4)$$

allow to obtain effective estimates $\tilde{P}$ and $\Delta\tilde{P}$ of the measurement results of P and ΔP as well as to estimate the standard deviations of these estimates, as shown in [6]:

$$\tilde{P} = \frac{2P + P_0 + \Delta P}{3}; \quad \Delta\tilde{P} = \frac{2\Delta P + P - P_0}{3}; \qquad (5)$$

$$S(\Delta\tilde{P}) = S(\tilde{P}) = \begin{cases} \dfrac{P - P_0 - \Delta P}{3}, \Delta P < 630\,\text{Pa} \\ \dfrac{P - P_0 - \Delta P}{2}, \Delta P > 630\,\text{Pa} \end{cases} \qquad (6)$$

Taking into account the above, we rewrite the equations (1) – (3) in a form convenient for calculations:

$$V = \sqrt{\mu \frac{2}{\rho} \Delta\tilde{P}(1 - \varepsilon)};$$

$$\rho = 0{,}00348\,\frac{P_a - \tilde{P} - 0{,}378\,\psi P_{нп}}{t + 273{,}15}; \qquad (7)$$

$$\varepsilon = \frac{5}{14}\,\frac{\Delta\tilde{P}}{P_a - \tilde{P}};$$

$$P_{нп} = 0{,}05995\,t^3 + 0{,}3872\,t^2 + 57{,}62\,t + 555{,}6.$$

Then consider relations (7) to the form of an explicit dependence $V = V(\mu, \Delta\tilde{P}, \tilde{P}, P_a, t, \psi)$ taking into account (5), and estimate the type B standard uncertainties of the input quantities [7].

For input quantities P_a, t, ψ the corresponding standard uncertainties $u(P_a)$, $u(t)$, $u(\psi)$ are estimated by passport errors.

The standard uncertainties $u(\tilde{P})$ and $u(\Delta\tilde{P})$ are estimated based on the following considerations: $\tilde{P}$ and $\Delta\tilde{P}$ are calculated according to the equations (5) based on the direct measurements of P, P_0, ΔP, which contain instrumental uncertainties $u(P)$, $u(P_0)$, $u(\Delta P)$. These instrumental uncertainties are estimated by the results of pressure sensors calibration. At the same time, equation (6) evaluates the standard deviation of $\tilde{P}$ and $\Delta\tilde{P}$. Then

$$S^2(\tilde{P}) = S^2(\Delta\tilde{P}); u(P) = u(\Delta P);$$

$$u(\tilde{P}) = \sqrt{S^2(\tilde{P}) + \frac{5}{9}\left(\frac{u(P)}{1.96}\right)^2 + \frac{1}{9}\left(\frac{u(P_0)}{1.96}\right)^2}; \qquad (8)$$

$$u(\Delta\tilde{P}) = u(\tilde{P}).$$

The input value μ (the dynamic pressure field factor) is determined during the verification of the aerodynamic wind tunnel according to the equation

$$\mu = \mu_{ref}\,\frac{\Delta P_{ref}}{\Delta P}, \qquad (9)$$

μ_{ref} is the coefficient of the reference Pitot tube, which is part of the higher standard; ΔP_{ref} is the pressure differential, measured by this reference Pitot tube, Pa; ΔP is the pressure differential, perceived by receivers of the aerodynamic wind tunnel, Pa. The uncertainties $u(\Delta P_{ref})$ and $u(\Delta P)$ are evaluated. The standard uncertainty $u(\mu)$ is determined in accordance with the law of uncertainty transformation [7].

The combined standard uncertainty $u_c(V)$ of the airflow velocity measurement result is determined by the uncertainties of the input values also in accordance with this law.

During the thermal anemometer channel calibration, the coefficient K is determined:

$$K = \frac{V_P}{V_{TA}}, \qquad (10)$$

V_P is the velocity value measured by pneumometric method, V_{TA} is the velocity value measured by the thermal anemometer. The uncertainties $u(V_P)$ and $u(V_{TA})$ are estimated, and the standard uncertainty $u(K)$ is determined in accordance with the law of uncertainty transformation [7].

4. The results of research

The described technique was used in the processing of test results for the approval of the type of aerodynamic wind tunnel "EMC 0.05/60-240". The tests were carried out in three stages.

First, multiple measurements of ΔP_{et} and ΔP at different flow velocities in the range from 3 m/s to 60 m/s were performed and the uncertainties of u (ΔP_{et}) and u (ΔP) were estimated:

$$\begin{aligned} u^2(\Delta P_{\text{ref}}) &= s^2(\Delta \bar{P}_{\text{ref}}) + u^2(\Delta P); \\ u^2(\Delta P) &= s^2(\Delta \bar{P}) + u^2(\Delta P); \end{aligned} \tag{11}$$

$s^2(\Delta \bar{P}_{\text{ref}})$ and $s^2(\Delta \bar{P})$ are the sample variances of the average values $\Delta \bar{P}_{\text{ref}}$ and $\Delta \bar{P}$, $u(\Delta P)$ is the instrumental measurement uncertainty due to the pressure sensor. The field factor μ was determined by the equation (9) and then standard uncertainty $u(\mu)$ was evaluated.

In the second stage, the combined standard uncertainty $u_c(V)$ of the airflow velocity measurement in the range from 3 m/s to 60 m/s was estimated. To do this, n=280 samples of measured values P, P_0, ΔP, t, ψ, P_a in 11 modes were taken. For the i-th observation, the value of the airflow velocity $V_i = V(\mu, \Delta\tilde{P}_i, \tilde{P}_i, P_{a,i}, t_i, \psi_i)$ was calculated by equations (7) taking into account (5) and the combined standard uncertainty $u_c(V_i)$ was estimated. The results are shown in Fig. 2.

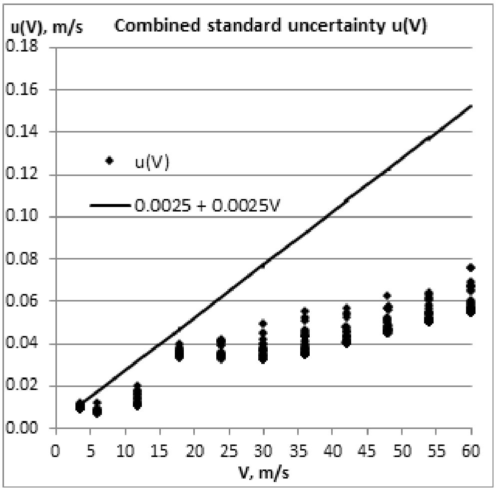

Fig.2. The combined standard uncertainty of the airflow velocity measurement

At the final stage, the uncertainty $u(K)$ of the thermal anemometer calibration factor K was evaluated. During the calibration n= 12 measurements of the airflow velocity using thermoanemometer $V_{TA,i}$ and one pneumometric measure V_P were performed. Further, the uncertainty $u(V_{TA})$ of the average value of $\bar{V}_{TA}$ was estimated by type A. The uncertainty $u(V_P)$ was estimated at the previous stage. The factor K was determined by the equation (10) and its standard

Table 1. The budget of the ai flow velocity measurement uncertainty for different modes

V, m/s	c(μ)	c(ΔP)	c(P$_a$)	c(P)	c(t)	c(ψ)	u(V)
3.4652	0.0076	0.0055	0.0030	3.84E-07	0.0007	0.0002	0.0099
5.8666	0.0047	0.0040	0.0050	8.06E-07	0.0012	0.0003	0.0080
11.7551	0.0030	0.0084	0.0100	6.93E-06	0.0025	0.0006	0.0136
17.7891	0.0260	0.0186	0.0151	3.52E-05	0.0037	0.0010	0.0356
23.8448	0.0228	0.0197	0.0203	6.64E-05	0.0050	0.0013	0.0367
29.8574	0.0163	0.0198	0.0255	1.04E-04	0.0063	0.0016	0.0367
35.9301	0.0130	0.0184	0.0307	1.40E-04	0.0076	0.0019	0.0389
41.9444	0.0150	0.0177	0.0359	1.83E-04	0.0088	0.0023	0.0437
47.9443	0.0152	0.0184	0.0411	2.48E-04	0.0101	0.0026	0.0487
53.9371	0.0148	0.0175	0.0464	2.97E-04	0.0114	0.0029	0.0531
59.8809	0.0128	0.0218	0.0516	4.58E-04	0.0126	0.0033	0.0590

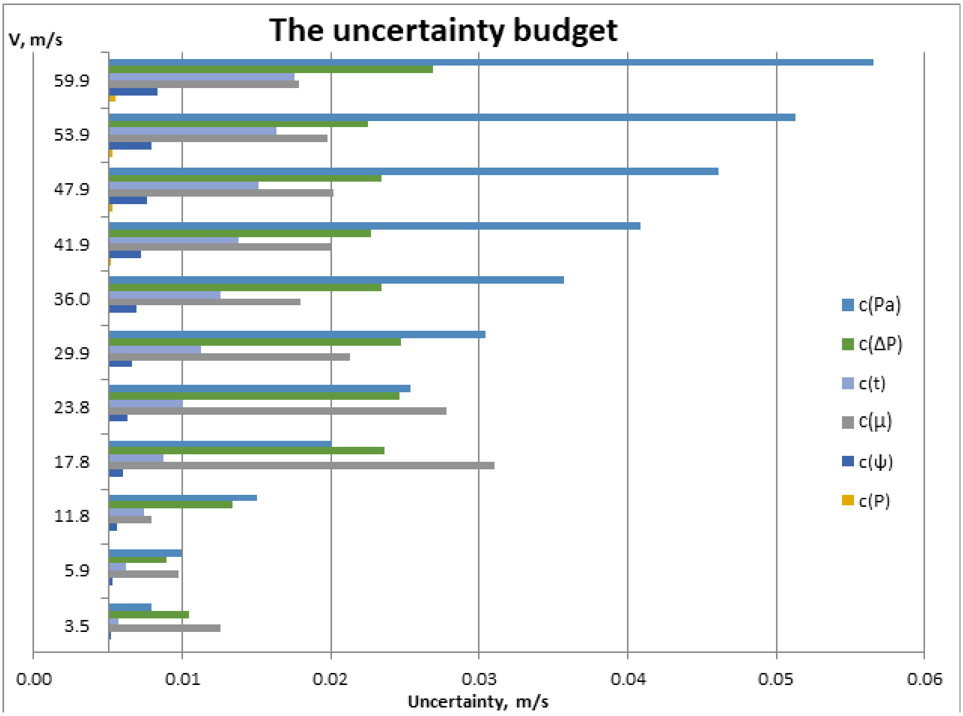

Fig. 3. The budget of the airflow velocity measurement uncertainty for different modes

uncertainty $u(K)$ was estimated.

The uncertainty budget when using the pneumatic principle of the airflow velocity measurement (including sensitivity coefficients c_i) is shown in Fig. 3 and in table 1.

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