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V-type Hot Wire Probe Calibration

Sofisticated equipment with unique hot wire V-probes, with high time and spatial resolution, and computer-aided calibration method for turbulence experimental research are described. This method requires the V-probe to be pitched in the uniform jet of the unique open calibration air tunnel at several velocities. From the outcome signal, a calibration array can be generated. Corresponding experimental curves are fitted with Chebishev polynomials, which decreases computational time. This method requires fewer assumptions than one based on the King's law.

Keywords: *hotwire probe, CTA, measurements, calibration, algorithm, Chebishev polynomials.*

1. INTRODUCTION

Flow problems and their quantification arise in many different areas. Used equipment must ensure accurate and reliable flow measurements. Since nowadays, for measurements either in science or industry, hot wire anemometer probes based on constant temperature anemometer (CTA) concept are widely present. Today, CTA is a well-established technology whose advantages have been proven by numerous measurements.

The measurement chain starts with the probe of various geometries, with sensing elements. In this paper is presented a V-wire probe, manufactured by Petar Vukoslavčević (Podgorica 2001.), its geometry and characteristics. It was made for exploring a complex phenomenon of swirl turbulent flow in conduits [1]. Here is also described calibration equipment and algorithm. Calibration procedure, as a very important part of every measurement, is of crucial significance for good interpretation of every result.

2. ANEMOMETER PROBE TYPE VP-2vs

Special V-type probe named VP-2vs, which belongs to the group CTA (constant temperature anemometer), has better space and time resolution than probes of the same type. It has been manufactured in the Fluid Mechanics Laboratory, Faculty of Mechanical Engineering, Podgorica, for the experiments performed in the PhD thesis [1]. One of the main characteristics is its great vitality, demonstrated in the turbulent flow field. This characteristic is of great importance in highly swirling turbulent flows [2], [3].

This probe has an extremely small geometrical parameters, what results in very satisfying space resultion of the measurements. Time response is very small, having for the consequence very wide frequency domain, even 1 MHz.

Sensors are made of the wolfram fibres of diameter 2.5 μm and length 0.7 mm. Sensors are welded at the ends on the prongs, wire stands, made of stainless steel. Prongs are of 0.4 mm diameter, sharpened on the top to the size of 75 μm (Fig. 1.). Wolfram fibres are welded to the prongs by the special apparatus for micro welding with highly precise mechanism which provides electrode and prong precise positioning.

Each fibre has its own two prongs, having as a result their electrical independence, what makes them being possible for plugging in their own electric circuits. All four probe prongs are positioned in a cylindrical metal pipe of a small diameter, and fixed in a defined position with a special nonconductive epoxy glue, which, also, placed in two other positions, makes them being parallel to each other. This small pipe is fixed inside the probe, made of hard plastic. Each metal prong has its own connector at the end. Probe has the fifth, shorter prong with a small pin on the top, whose function is probe positioning in the wall vicinity.

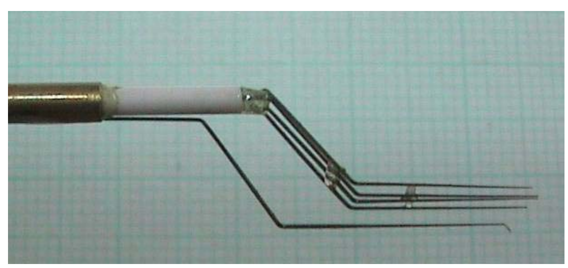

Figure 1. Anemometer probe, type VP-2vs (axonometric view). On the top of the probe prongs (right side of the picture), two invisible, for this zoom, sensors are welded in the form of the capital letter "V". Distinct fifth prong is clearly visible.

3. CALIBRATION TUNNEL

In the Fluid Mechanics Laboratory at the Faculty of Mechanical Engineering, University of Belgrade probe calibration tunnel has been made during the work on the PhD thesis [1]. This air tunnel is of opened type, has a modern concept and is similar to the tunnel constructed in the Fluid Mechanics Laboratory, Faculty of Mechanical Engineering in Podgorica [4].

Turbomachine is a blower with a power of 250 W, which sucks the air into the tunnel. Then air streams

Received: September 2007, Accepted: October 2007.
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into a diffusor, followed by a straight pipe, where three stream straighteners (nets, combs) are positioned and at the end a nozzle, which is the main part of the tunnel. The maximum speed in the jet is 38 m/s.

Figure 2. Open air tunnel for hot-wire probe calibration. Pipe and diffuser are made of hard plastic, nozzle of duralluminium.

The most important part of this tunnel is a specially profilled nozzle. Its contour is defined with the equation:

$$R(x) = R_{\mathrm{ul}} - \frac{3}{2}(R_{\mathrm{ul}} - R_{\mathrm{iz}})(x/L)^2 + (R_{\mathrm{ul}} - R_{\mathrm{iz}})(x/L)^3 \; . \quad (1)$$

As equation (1) represents the third order polynomial function, this is the cubic nozzle formed in this way, where R_{ul} represents inlet diameter, R_{iz} outlet diameter and L is the length.

Anemometer probe calibration needs a variety of speeds in the measuring section, at the nozzle outlet. Speed variation is achieved by use of frequency regulator, of resolution 0.1 Hz. Outlet speed has been measured by etalon Pitot tube, whit top positioned in the calibration tunnel axis in the plane on 10 mm from the nozzle outlet section, connected to the Betz manometer of 5 Pa resolution.

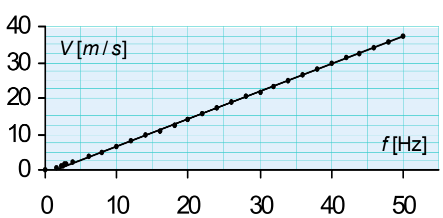

Figure 3. Speed in an uniform jet-frequency dependence

Multiple repeated measurements in the above defined positions, in the jet, are presented with functional dependency speed of frequency, by linear equation (2):

$$V = 0.7958 f - 0.8482 \; . \quad (2)$$

Speed uniformity in the calibration section is in the limit of satisfyingly 1%, which is experimentally proved. Average turbulence intensity in this section is around 0.5%. This calibration tunnel is reliable, one of the most important parts of the calibration equipment, for hotwire anemometer probes.

4. HOTWIRE CALIBRATION METHOD

Sensing elements of the VP-2vs probe, during measurements are in the tangential plane forming measuring volume. Averaged flow field of this volume is defined with the speed vector $\vec{\tilde{v}}$, which is almost in the tangential plane, changing its direction and intensity in the time. Two CTA units (each connected with its own sensor) constantly induce voltages $\tilde{e}_1$ and $\tilde{e}_2$, i.e. deliver signals which are a measure of the flow velocity changeable vector. Afterwards, it is necessary to perform hardware signal processing, i.e. A/D conversion of the continual voltage signals in the digital ones.

In the further signal analysis, the method where, for each pair of voltages collected at the same time $(\tilde{e}_{n1}, \tilde{e}_{n2})$, direction and intensity of the velocity vector $\vec{\tilde{v}}$ is estimated, i.e. an adequate pair $(\tilde{v}_n, \tilde{\varphi}_n)$ is found. To accomplish this, hotwire probe calibration must precede.

During calibration process probe VP-2vs is positioned in the jet measuring section of air tunnel under known angle φ_i and exposed to the known average velocity vector $\vec{V}_i$ (Fig. 4), which induces average voltages E_{1i} and E_{2i}.

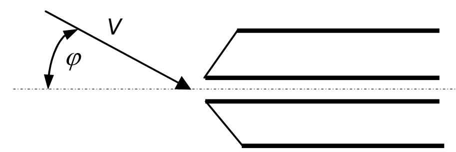

Figure 4.VP-2vs probe calibration

By varying angle φ_i, which is constituted between directions of the probe main axis and the average velocity vector, two pairs are found (V, φ) and (E_1, E_2), where only one pair (V_i, φ_i) corresponds to the pair (E_{1i}, E_{2i}), which is defined with the calibration mapping function. Pair of chosen voltages $(\tilde{e}_{n1}, \tilde{e}_{n2})$ is transformed to the correspondent pair $(\tilde{v}_n, \tilde{\varphi}_n)$ with the inverse calibration mapping function.

If all the pairs $(\tilde{e}_{n1}, \tilde{e}_{n2})$ and their correspondent ones $(\tilde{v}_n, \tilde{\varphi}_n)$ were realized during measurements, we would have an almost ideal calibration process. In this process a huge number of data are collected, and consequently ideal calibration process would take a long period of time.

On the other side, sensors, depending on the air pollution, change their own characteristics more slowly or faster, which requires calibration and measuring process in as short as possible period of time.

Balancing the need for as big as possible number of correspondent calibration pairs $(V_i, \varphi_i) \Leftrightarrow (E_{1i}, E_{2i})$ and calibration time duration, requires optimal solution. Static calibration has been performed on the calibration tunnel, described in section 3.

Considering hotwire anemometer probe calibration and measuring process as similar, but with opposite enter and exit information, the idea about realization of new signal processing algorithm for these two procedures has come into sight.

4.1. Probe calibration in a stationary field

Signal sampling frequency and acqusition time have to be determined at the beginning of the calibration process. The signal was recorded at some average speed of 5 m/s, with sampling frequency of 2 kHz lasting 60 s. Recorded analog (voltage) signal is first averaged for the maximum number of chosen data. Afterwards, an average voltage is calculated for the half and fourth of this number. This method of bisection stopped at the 0.1% difference between two successive average voltages. This procedure has been solved by dividing with two total time or sampling frequency. It was concluded that enough recording time is $T_{\mathrm{sb}} = 10$ s , and sampling frequency $f_{\mathrm{sb}} = 200$ Hz .

During calibration process VP-2vs probe is positioned under defined angle φ_i in the jet of constant fluid flow (Fig. 5.). Angle φ_i and air velocity $\vec{\mathrm{V}}_i$ (determined by appropriate frequency f_i, described in the 3. section) are defined in this calibration equipment.

Figure 5. VP-2vs probe static calibration in the tunnel air jet

Two sensor independent voltage signals are converted into digital in the form of chosen data: $\tilde{\mathrm{e}}_{\mathrm{nb}1}(V_i, \varphi_i)$ and $\tilde{\mathrm{e}}_{\mathrm{nb}2}(V_i, \varphi_i)$ and then recorded. Average values of these two sample assemblies are time averaged voltages E_{1i} and E_{2i}. In this way, for one chosen pair (V_i, φ_i) is determined correspondent pair (E_{1i}, E_{2i}). By repeating this procedure we get around a hundred of these pairs, which is satisfying exact and no time consuming comparing to the classical approach.

Preliminary calibration and measurements have been conducted using the programs with incorporated generalized algorithm [5], [6]. It was shown that maximum speed didn't exceed 15 m/s, and 98 percents of φ angle values were in the interval (-20°, 20°). This is the domain that was considered in the main calibration procedure. Probe was positioned in a defined angle φ, and ten arbitrary velocity values were varied until the value of 20 m/s. The whole procedure was repeated for other φ values, which were in the interval (-24°, 24°), with step of 6°. After the calibration for all values of angle φ and calibration speed V, average values E of selected voltage signals for both sensors are then calculated. In this way we get the third "space" coordinate - E for the calibration diagram (φ , V, E) of one sensor (Fig. 6.).

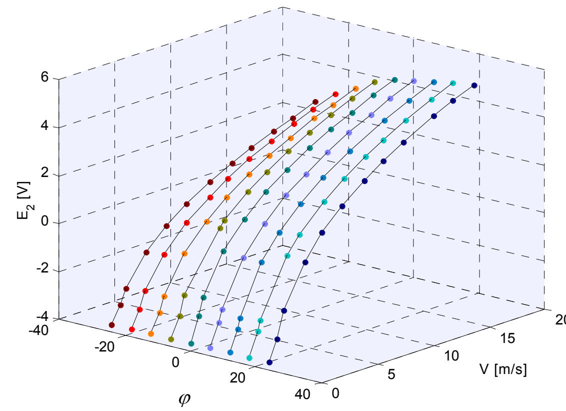

Figure 6. Second sensor calibration points in space

Calibration points of the same angle φ are all positioned around one parabola of the fifth order, with mean square error around zero, which lies in the plane parallel to the coordinate plane (V , E).

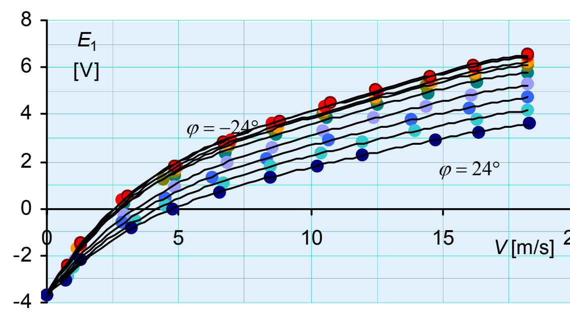

Figure 7. First sensor calibration points in the V-E plane

Result of the calibration points projection from the space (Fig. 6.) to the plane (E , V) is next the diagram.

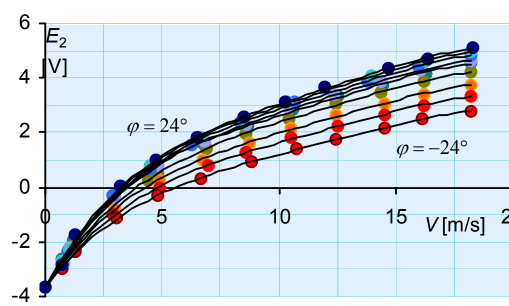

Figure 8. Second sensor calibration points in the V-E plane

What is the function relation $E(V)$, for $\varphi = \text{const}$, which approximates the curves with calibration data in the best manner? Generally, there is no universal solution for this representation. One of the best ways is to use the physical law which represents this phenomenon and its analytic expression.

It was done by King [7], where it has been considered the process of heat convection from the hot wire to the surrounding fluid flow. The following equation, named King's law, presents this phenomenon analytically:

$$E^2 = A + BV^n . \quad (2)$$

Numerous experiments have shown that exponent n has an average value 0.45. In some other approaches calibration speed is divided into few intervals, with empirical curve calculated for each with its own exponent. Jankov has proposed and tested modified (universal) King's law, defined with the following expression [8]:

$$V = \left(\frac{E^2 - E_0^2}{B} \right)^N , \quad (4)$$

where E_0 is the zero speed (V=0) voltage.

Opposite to the King's law, here B and N are not constants, but implicit functions of the argument $(E^2 - E_0^2)$:

$$\begin{aligned} B &= B_0 + B_1(E^2 - E_0^2) + B_2(E^2 - E_0^2)^2 , \\ N &= N_0 + N_1(E^2 - E_0^2) + N_2(E^2 - E_0^2)^2 . \end{aligned} \quad (5)$$

Coefficients B and N are determined with the Gauss least-squares method on the calibration point population.

This very interesting functional dependency wasn't tested here, but the dependency $E(V)$ was searched among the parabola of various degrees.

4.2. Algorithm for processing dual-sensor probe signals

There are various methodologies for probe measurements. Among these an outstanding one is Generalized algorithm for measuring turbulent velocity and swirl fields based on the papers [5], [9] and described in details in [6].

Calibration results analysis, based on the above stated method, provides four calibration coefficients. It calculates from the simultaneously chosen voltages $\tilde{e}_{n1}$ and $\tilde{e}_{n2}$, velocity components in the probe main axis direction $(\tilde{u}_{ns})$ and perpendicular to it $(\tilde{w}_{ns})$. If the coefficients are calculated on the basis of the results obtained in static calibration, the problem of numerical procedure convergence will be of importance. If the coefficients of the static calibration procedure were not calculated on the basis of the whole calibration velocity domain, but on some of its intervals, this problem would be eliminated. In this way, almost each pair of $(\tilde{e}_{n1}, \tilde{e}_{n2})$ would give $(\tilde{u}_{ns}, \tilde{w}_{ns})$.

In this paper is presented a new processing method, which is first tested on some pilot measurements, resulting in a very good agreement with results obtained by generalized method.

The main idea is in the fact that calibration and measuring process, use the same transfer function, for transforming inlet (velocity vector $\vec{\tilde{v}}$) into outlet signal (voltage pair $(\tilde{e}_1, \tilde{e}_2)$). Transfer function is physically realized by sensors with CTA bridge, and it is an anemometer characteristic. Calibration process is an experimental identification of this function on the basis of known signals. Measurements consider this function as almost known, and inlet signal as only unknown.

There are two unions of calibration points with coordinates (φ, E_k, V), $(k = 1, 2)$. Number of calibration data is the same in these two populations, for each sensor, and equal to the number of correspondent pairs $(\varphi_i, V_i) \Leftrightarrow (E_{1i}, E_{2i})$.

In this text is presented a method, which was mostly used in these researches. Graphical presentation is given in Fig. 9-11. Fig. 9. corresponds to Fig. 7., just axes switched their places.

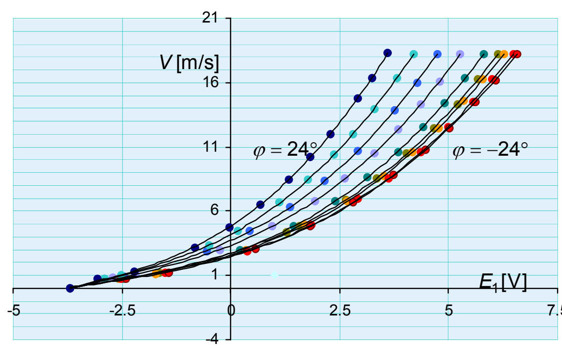

Figure 9. First sensor calibration points in the E-V plane

The same for the Fig. 10. and its correspondent Fig. 8.

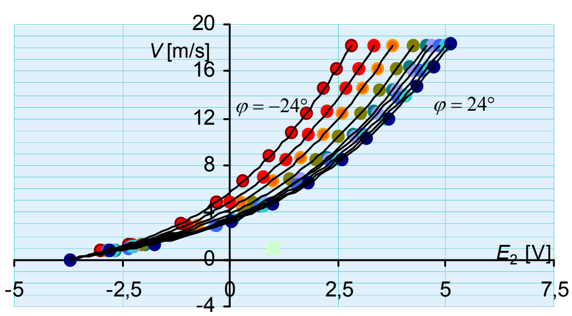

Figure 10. Second sensor calibration points in the E-V plane

What is the function relation $E(V)$, for $\varphi = \text{const}$?

Various order parabola have been tested. The test has been performed on the both sensors sample of calibration points for different φ values. These calibration points present the result of various dynamic and static calibrations. It has been shown that all functions $V = f_i(E_j)$, with $\varphi = \text{const}$, are presented with the following equation:

$$V(\varphi_i, E_j) = C_{0i} + C_{1i}E_j + C_{2i}E_j^2 + C_{3i}E_j^3 + C_{4i}E_j^4 . \quad (7)$$

Defining functional relations $V = f_i(E_j)$ for all the calibration curves of both sensors, finalizes the process of calibration.

5. MEASUREMENTS

5.1. Algorithm for defining velocity field

Benefit of the calibration process is defining velocity vector $\vec{\tilde{v}}_n(v, \varphi)$. Algorithm is the same for all voltage pairs (e_1, e_2), as explained here on one example.

Here it is known a functional relation of the calibration curves and one measured voltage pair (e_1, e_2). For the value $e_1 = E_1$ in Fig. 9. from the curves $V = F_1(\varphi, E_1)$ till $V = F_9(\varphi, E_9)$ nine points M_{1i} are derived. In the same manner, for the known voltage $e_2 = E_2$ in Fig. 10., nine other points are M_{2i} derived. These points are presented in Fig. 11.

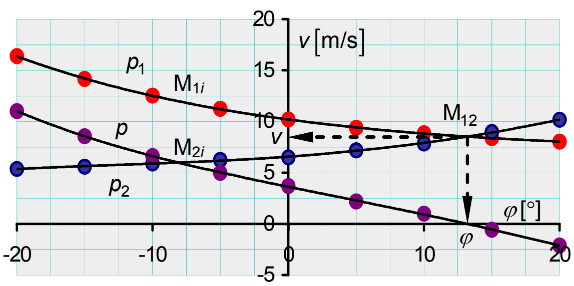

Figure 11. Final solution definition

It is obvious that all these points are situated in the vicinity of curves p_1 and p_2, whose analytical definitions should be parabolic functions. Unknown parameters, parabola coefficients, are found by the least-square fit method. It was shown that the best agreement for representative pairs (e_1, e_2) chosen by accident had coefficients of the parabola of the fifth order:

$$\begin{aligned} p_1 : v &= A_0 + A_1\varphi + A_2\varphi^2 + A_3\varphi^3 + A_4\varphi^4 + A_5\varphi^5, \\ p_2 : v &= B_0 + B_1\varphi + B_2\varphi^2 + B_3\varphi^3 + B_4\varphi^4 + B_5\varphi^5, \end{aligned} \quad (8)$$

where coefficients A_i and B_i depends on voltages e_1 and e_2, respectively. Minimizing angle φ step would increase number of points M_{1i} and M_{2i}, which would lead to more accurate estimations of the curves p_1 and p_2. Solution is the intersection point of these curves $M_{12}(\tilde{\varphi}, \tilde{v})$. Coordinate φ is the angle between the probe main axis and the instantaneous speed $\vec{\tilde{v}}$, and coordinate v is the velocity intensity.

In Fig. 11. it is also presented curve p, whose coordinates present differences of the appropriate p_1 and p_2 cordinates. It is obvious that unknown angle φ could be graphically achieved in the intersection of the p curve and abscise. Angle φ is also one of two real solutions of the fifth order polynomial function. The one with smaller absolute value is valid.

If curve p intersects abscise at angle φ which belongs to the calibration interval, good validation is achieved. If this is not the case, then there is no good estimation for the angle, and consequently for the speed. It happens when the measured flow field velocity and angle are not appropriately predefined, and not taken into consideration during measurements. Another reason could be positioning of the probe in the average velocity direction.

Time consumption could be minimized by using the same method as in calibration, forming array of correspondent pairs. There is a number of pairs (e_1, e_2), which is a processor time consuming. This could be diminished by calculating corresponding values (φ, v) for each pair (e_1, e_2) in advance, forming data base in such manner, and during the analysis to choose, the closest, appropriate one. This has been programmed for, the number defined with resolution of the data acquisition system, 512 × 512 different values, selected in the whole domain with equal steps.

Error estimation was done on the population of 100 measured values, i.e. angle/velocity combinations. Angle was varied in the segment $\varphi \in [-24^\circ, 24^\circ]$ and speed in $v \in [1\,\text{m/s}, 19\,\text{m/s}]$. Maximum error with respect to v was 2.5%, for both velocity components. Above 2 m/s these errors drop to maximum 0.5% .

5.2. Software for the new algorithm

This algorithm incorporates the number of calculations of empirical curves using pairs of measured values (x_i, y_i) $(i = 1, 2 \ldots n)$. Usually, this curve is presented like linear combination of ordinary functions:

$$\hat{y} = \sum_{j=0}^{m} \beta_j \psi_j(x), \quad (9)$$

where m should be smaller than n, $\psi_j(x)$ are known functions, while parameters β_j $(j = 1, 2 \ldots m)$ are unknown and should be determined on the population of n times measured y for various x. It is accepted that all x_i values are accurately determined, while y_i values are measured with some error $\sigma_i^2 = \sigma^2$, for the chosen empirical curve, sum of squares of standard deviation value y_i of $\hat{y}_i$ is:

$$E^2(\hat{y}) = \sum_{i=1}^{n} (y_i - \hat{y}_i)^2 . \quad (10)$$

Condition of minimum value of this sum gives a system of linear equations, which is called a system of normal Gauss equations [10]:

$$\begin{bmatrix} \sum\psi_0^2 & .... & \sum\psi_m\psi_0 \\ ...... & .... & .... \\ \sum\psi_0\psi_m & .... & \sum\psi_m^2 \end{bmatrix} \begin{bmatrix} \beta_0 \\ .... \\ \beta_m \end{bmatrix} = \begin{bmatrix} \sum y_i\psi_0 \\ .... \\ \sum y_i\psi_m \end{bmatrix}, \quad (11)$$

or in short:

$$\sum\psi_m\psi_0 = \sum_{i=1}^{n}\psi_m(x_i)\psi_0(x_i), \\ \sum y_i\psi_0 = \sum_{i=1}^{n} y_i\psi_0(x_i) . \quad (12)$$

Unknown coefficients of the empirical curve $\hat{y} = f(x)$ are calculated from this system of equations.

Approximation of the real curve produces an additional error, which influences the final solution. The first information obtained in this case is given by the standard regression error, whose square $\varepsilon^2(\hat{y})$ is calculated as an average value of the square deviation:

$$\varepsilon^2(\hat{y}) = \frac{1}{n}\sum_{i=1}^{n}(y_i - \hat{y}_i)^2.$$

named square average deviation.

The smaller the value of the square average deviation, the better approximation. This could be achieved by increasing the number of estimated points. Here are chosen polynomial functions of various exponents for empirical functions. With increasing of the polynomial degree, residuum sum decreases. Starting with one polynomial degree, the sum increases. Adopted value is the one with minimum residuum sum.

Polynomial degree identification can be performed by appropriate dispersion analysis, which leads to the Fisher's F-criterion, a general criterion of regression quality [11].

Processing of the measured results with the above stated method has been programmed. All empirical functions were of the fifth order, which was first determined on the representative population. Unknown parameters of the empirical curve are very sensitive to small mistakes in coefficients of the system of equations. This results in a significant numerical instability that increases with increment of functions in a sum, i.e. polynomial degree.

This instability can be eliminated if orthogonal Chebishev (Pafnuty Lvovich Chebyshev, 1821-1894.) polynomial functions are used [10-13].

Using these orthogonal basic functions system, the matrix of the normal Gauss equations becomes diagonal, where each unknown coefficients β_i are calculated independent of each other.

The system of basis functions $\psi_0(x)$, $\psi_1(x)$, …, $\psi_m(x)$, in series (9), is called orthogonal on the population x_1, x_2, …, x_m, if two random functions of this system are orthogonal, i.e. if satisfied for various k, j values in interval $(0, m)$:

$$\sum_{i=1}^{n}\psi_k(x_i)_j(x_i) \text{ is } \begin{cases} \neq 0 & \text{for } j = k, \\ = 0 & \text{for } j \neq k. \end{cases} \quad (13)$$

Chebishev polynomial functions are here orthogonal basis functions, where first two members and a recursive formula for polynomial functions of greater degree [13]:

$$P_0(x) = 1, P_1(x) = x, \\ P_{m+2}(x) = 2x\,P_{m+1}(x) - P_m(x) . \quad (14)$$

If experimental results are equally distributed on the interval of the independent value x, i.e. if it is satisfied $x_{i+1} - x_i = h$, introducing shift: $z = (x - \bar{x})/h$ Chebishev polynomials are:

$$P_0(z) = 1, P_1(z) = z, \\ P_{m+1}(z) = zP_m(z) - \frac{m^2(n^2 - m^2)}{4(4m^2 - 1)}P_{m-1}(z). \quad (15)$$

Empirical curve $\hat{y} = f(z)$ is now:

$$\hat{y} = \sum_{i=0}^{m} C_i P_i(z). \quad (16)$$

Coefficients C_i are calculated independently of each other:

$$C_0 = \frac{\sum_{i=1}^{n} y_i}{n} = \bar{y}, \quad C_j = \frac{\sum_{i=1}^{n} y_i P_j(z_i)}{\sum_{i=1}^{n} P_j^2(z_i)}, \quad i = 1,2,...,m. \quad (17)$$

Orthogonal polynomial functions also have a few more advantages. Determined polynomial function of degree k provides all equal coefficients, except one new C_{k+1}, for defining polynomial function of k+1 degree.

Chebishev polynomials, contrary to the ordinary polynomials, have significantly simpler residuum sum calculation, where for the k-th degree function states:

$$n\varepsilon_k^2 = \sum_{i=1}^{n} Y_i^2 - n\sum_{j=0}^{k}\hat{C}_j^2\,\overline{P_j^2(z)}, \quad (18)$$

while residuum sum of the polynomial function of the k+1-th order represents the following difference, much simpler for calculation: :

$$n\varepsilon_{k+1}^2 = n\varepsilon_k^2 - n\hat{C}_{k+1}^2\,\overline{P_{k+1}^2(z)} . \quad (19)$$

This shows that increment of the function degree results in residuum sum value decrement. Reaching the best approximate curve, residuum sum reaches minimum value equal to the average dispersion of error σ_i^2, with deviations smaller than this dispersion [10].

Use of Chebishev polynomials, instead of ordinary for estimation of empirical curve, avoids possible numerical instabilities and significantly decreases total time consuming for calculation of unknown parameters.

This new procedure for signal analysis has been also programmed. Various empirical functions have been presented in the form of Chebishev polynomials, contrary to the previous procedures where ordinary polynomials had been used. Identification of a degree of polynomial has been previously done on a representative population, and afterwards processed.

Calibration curves in Fig. 10., present random function. Besides this, these voltages, in various calibration points, have been calculated with various accuracies, i.e. error dispersions σ_i^2. It is the most complicated case of evaluation of the approximation curve parameters and confidence interval. In a statistical meaning these estimations belong to the group where dependent and independent variables are random quantities. Besides this, error dispersion depends on random variable [10-12].

For the experiment the most important facts are small square deviation and ratio of mean square deviation and random quantity along the major part of empirical curve to be almost equal. It is desirable to form a new population of calibration points with almost equal statistical weight, i.e. error dispersion. Statistical weight of unevenly correct measurements has been adopted here as inverse value of appropriate dispersion.

6. CONCLUSION

Quality of the measuring results depends on calibration quality. Measuring error, besides other, depends on calibration and measuring procedure and obtained data analysis. Measuring-calibration procedure presented in this paper is almost identical with the one presented in papers [14] and [15]. However, in this paper calibration curves are fitted with the use of Chebishev polynomials. By use of them presented numerical analysis procedure instability is avoided and calculation time consumption reduced.

Acknowledgment

This work was supported by the Ministry of Science, Republic of Serbia, Project Number TR 6381, which is gratefully acknowledged.

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МЕТОДА БАЖДАРЕЊА СОНДЕ V-ТИПА СА ЗАГРЕЈАНОМ ЖИЦОМ

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Приказана су веома прецизне, оригиналне сонде са загрејаним влакнима високе просторне и временске резолуције и калибрациони метод за турбулентна експериментална истраживања. Овај метод захтева позиционирање V-сонде под одређеним углом у односу на униформну брзину млаза отвореног аеротунела. Из добијеног сигнала формира се калибрациона матрица. Оцене одговарајућих експерименталних кривих су облика Чебишевљевих полинома, чиме се време прорачуна мерних тачака значајно смањује. Овај калибрационо-мерни поступак захтева мање претпоставки него у случају стандардних метода заснованих на Кинговом закону.