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exist for the publication of theoretical and experimental investigations of all aspects of the mechanics and thermodynamics of fluid-flow with special reference to fluid-flow machines

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poświęcone są publikacjom naukowym z zakresu teorii i badań doświadczalnych w dziedzinie mechaniki i termodynamiki przepływów, ze szczególnym uwzględnieniem problematyki maszyn przepływowych

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JERZY ŚWIRYDCZUK[1]

On the calculation of vorticity from velocity measurements[2]

The method proposed in the paper is a modification of the conventional technique for vorticity calculations based on velocity measurements. During the calculations, time variations of velocity components are recalculated into spatial derivatives of the velocity. The results obtained by means of the modified method are compared with those of the conventional technique.

1. Introduction

It has been known that the measurements of vorticity distribution in flow are amongst the most difficult measurements in fluid mechanics. In order to determine the vorticity field, it is necessary to know the partial derivatives of the three components of velocity with respect to the three coordinates of an orthogonal reference frame located at the measuring point. This requirement has set the level of difficulty in vorticity measurements very high. Consequently, no universal method of vorticity measurements has been invented yet. Instead, now and then various measuring techniques are worked out whose applications are limited to evaluating or directly recording the vorticity (most often one component only) in flows of a particular type. These methods can be generally divided into direct methods, allowing evaluation of the vorticity as some level of output signal from a measuring device, and indirect methods, where the vorticity is estimated on the basis of known distribution of another physical quantity, most often the velocity. One of the best known methods belonging to the first group is the vorticity measurement with the use of the hot-wire technique. An appropriate number and arrangement of wires in the sensing element of the probe enables direct determination of the vorticity as a voltage signal at the output from the resistance bridge. This method was first proposed by Kovasznay in 1950. According to his proposal,

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the sensing element of this probe was a square-based rectangular prism equipped with a number of wires located on the side walls along four diagonals. Originally, all wires had common power supply and worked with a Wheatstone bridge. This technique was developed further. First, each wire was given independent power supply and was regarded as an independent sensing element, which also opened up a possibility to record independently each individual component of the velocity vector. Next, the number of wires was increased up to 4, 5 or even 9 and their line-up was rearranged. These improvements enabled measurements of the three components of vorticity. One disadvantage of the method is sophisticated shape of the sensing element and complexity of the production process. All this, combined with high proneness of the sensing element to mechanical damage makes the method relatively expensive. It should also be noted that the real area of the theoretically dimensionless measuring point increases with the increasing number of wires. There are also some indications in the literature that the calibration of the probes of this type may cause certain difficulties. A comprehensive study of the hot-wire probes for vorticity measurements has been presented by Wallace [1].

In another approach to the problem, special-design vane-shaped measuring instruments were applied. The motion of the vane was to reflect the distribution of vorticity in the field under investigation [2]. The instrument was capable of measuring one component of vorticity. However, it should be said that due to high inertia and relatively long time of response of the sensing element, the technique cannot be reliable for fast-changing velocity fields.

One of the most promising methods for vorticity measurements is the PIV technique. This technique makes use of simultaneous measurement of instantaneous velocity vectors within the whole area under investigation. Its concept is based on introducing into the flow a number of marker particles reflecting light, and then illuminating the flow in some subsequent flashes, thus tracing and recording the movement of the markers. The technique is relatively new and the range of its application seems to be relatively wide. One visible disadvantage is high cost of data recording and processing.

Of all methods of vorticity evaluation, the method that uses velocity data obtained from hot-wire or laser-Doppler measurements is relatively easy in practical execution and inexpensive. In this method it is assumed that the data recorded at different instants at each point of the velocity field can be recomposed into one record that will be used for evaluating all components of the velocity derivatives in the vorticity formula. This assumption may give an impression that this technique is serviceable only for measurements in steady or oscillating flows, what would be unattractive from the practical, experimental point of view. However, if a characteristic frequency, for example the frequency of vortex shedding, and a characteristic time instant, for example the beginning of the vortex shedding cycle, can be distinguished in the flow, then this technique can also be applied to unsteady flows specified by constant average values. Examples of this type of flows can be various patterns of infinite vortex streets. This technique was developed even further at the Virginia Polytechnic Institute and State University, Blacksburg, USA, where its version called "the window method" was applied for measurements in some types of real unsteady flows, namely the flows specified by constant average values at each individual point of the flow area, but having different average values from one point to another across the flow field. Among other things, this method was used in VPI&SU to examine the vortices generated in the water downstream of a pitching airfoil and their interaction with another airfoil and a series of flat plates. In the first concept, the measuring points were evenly distributed over the flow section under investigations [3]. Then the method was constantly improved and finally evolved into a version in which measuring data are recorded along two parallel measuring columns close to each other. As a result of accounting for instantaneous and local changes of velocity in the calculation procedure, it was possible to determine vorticity distribution in a flow section much larger than that between the two measuring columns. Generally, two measuring steps can be distinguished in this method, namely the vorticity evaluation and the vorticity displacement steps (a more detailed description of the method can be found in [4, 5]). The objective of the present paper is to propose a modification of the window method, in its part concerning the vorticity evaluation, which will make the velocity data from the second column unnecessary and permit one to compute the vorticity using the data from one column only. This modification will shorten the time of data recording, and at the same time will make the requirements concerning the stability of flow parameters during the measurement less restrictive. A comparative analysis of the results of the modified version with those obtained from the two-column method will be given on the basis of measuring data recorded during the experimental investigations described in [5].

2. The process of recording velocity components.

The experimental investigations carried out in [5] aimed at determination of vorticity distribution in a flow in which large-scale vortex structures interact with short flat plates. The paper [5] gives an extensive account of the investigating stand, the course of investigations as well as of the results. However, for its importance for the present paper, a brief description of the investigating stand and the measuring technique will be presented beneath. A schematic of the investigating stand with the arrangement of measuring stations is shown in Fig. 1.

The investigations were carried out in a closed-cycle water tunnel with a free-stream velocity of 12.5 cm/s. In the test section, next to its inlet a symmetrical NACA 0012 airfoil of chord length $C = 101.6$ mm was mounted to perform pitching motion about its quarter chord. The airfoil was driven by a low-speed motor and a bar-linkage system to transfer the rotational motion of the motor to the pitching motion of the airfoil. The pitching amplitude about the position of zero-attack angle was $\Delta\alpha = \pm 10$ deg. The pitching period T was equal to 1.24 s. This selection of the free-stream velocity and the pitching frequency led to a double row of vortices forming downstream of the airfoil trailing edge with the sense

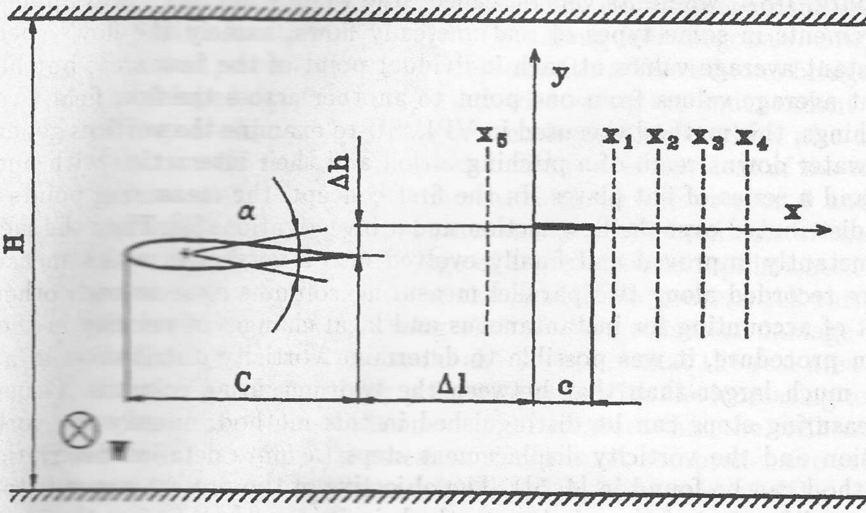

Fig. 1. Schematic of the experimental stand for investigations of vortex-plate interactions. H, W – dimensions of the test section, C – chord length of the pitching airfoil, c – chord length of the plate, $\Delta l, \Delta h$ – distances between the leading edge of the plate and the trailing edge of the airfoil in the x, y directions, x_k – location of the measuring stations.

of rotation opposite to that of the Karman vortex street. The process of recording the two components of velocity was done by means of a He-Ne Laser-Doppler anemometer in the computer-controlled data recording line. In order to eliminate the influence of accidental turbulent fluctuations on the time variation of the velocity components, the recorded data were then averaged over 20 cycles. Each time the beginning of the cycle was determined as the beginning of rotation of the driving motor. The data were stored in the computer memory for further analysis. In order to determine particular stages of development of the investigated phenomenon, the process of data recording was carried out along 5 measuring stations, $x_k, k = 1, \ldots, 5$, located at different distances from the trailing edge of the pitching airfoil.

3. The conventional method of vorticity calculations

The complete set of measuring data consists of a number of instantaneous components of velocity vector recorded at measuring points arranged along two measuring columns, separated by $\Delta x = 1.905$ mm, belonging to the same measuring station. The distance between two neighbouring points of a column was also $\Delta y = 1.905$ mm. In Fig. 2, the arrangement of the measuring points along two columns is presented. In the discussed experiment, the distance between the measuring stations Δx was 19.05 mm, which is 10 times the distance between the two columns of the same station. At each measuring point, 200 instantane-

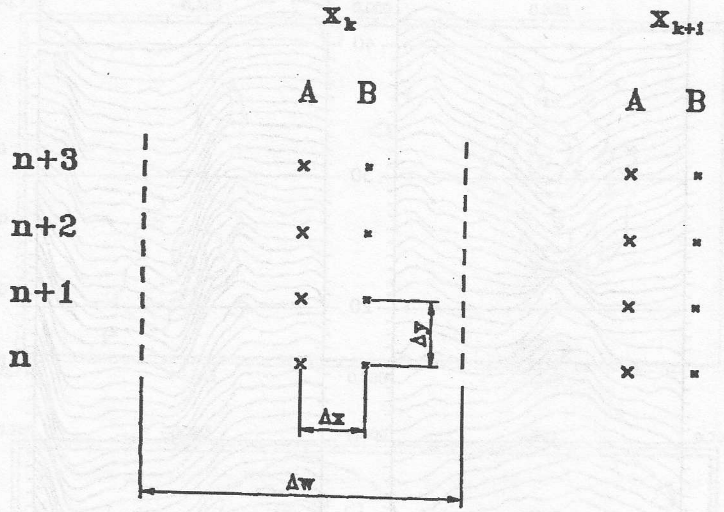

Fig. 2. Arrangement of measuring points along the measuring station: x_k, x_{k+1} – measuring stations, A, B – measuring columns, $n, n+1, \ldots$ – measuring points along one column, Δy – distance between neighbouring points of one column, Δx – distance between the columns belonging to the same measuring station, Δw – distance between measuring stations.

ous values of velocity components were recorded at regular time intervals. The total period of recording was equal to the period of oscillations of the airfoil. One complete data set was a starting point for determination of vorticity in flow in the window of the measuring station. In Fig. 3, time fluctuations of velocity components recorded along one measuring column are shown in a table.

The algorithm of calculations is based on good repeatability of the investigated phenomenon – data corresponding to the same phase of the cycle are treated as if they were measured at the same instant.

The vorticity at a measuring point (n, A) is calculated from the formula:

$$\Omega(n, A) = \frac{\partial v_y}{\partial x} - \frac{\partial v_x}{\partial y} \cong \frac{v_y(n, B) - v_y(n, A)}{\Delta x} - \frac{v_x(n+1, A) - v_x(n, A)}{\Delta y} \tag{3.1}$$

with all quantities referring to the same time t.

The investigations consisted of two stages. At the first stage, investigations of vorticity distribution in the region of undisturbed wake were carried out. The vorticity field recorded at this stage was relatively regular, with two rows of large scale vortices clearly visible. A classical example of vorticity distribution obtained at the first stage of investigations is shown in Fig. 4a,[3] where two regions of strong

[3]For technical reasons, the results are presented in the $y-t$ coordinate system in which the abscissa x is scaled so as to meet the relation $\Delta y = \Delta x = U \cdot \Delta t$. Therefore, the figures display vorticity distributions "frozen" at an instant of their crossing the measuring column.

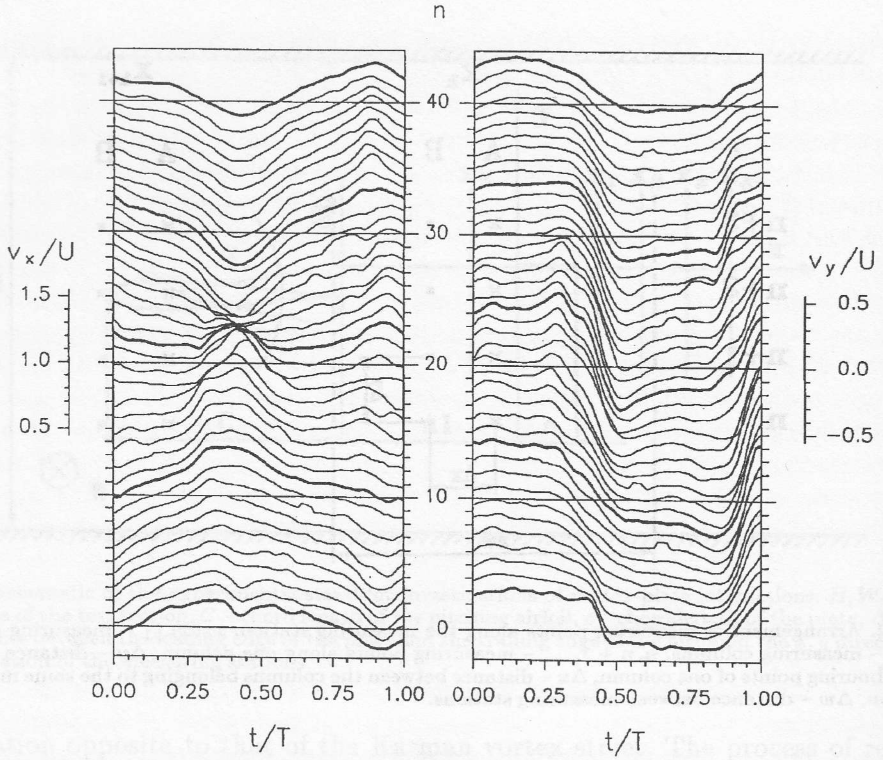

Fig. 3. Time history of the velocity component fluctuations recorded at points located along column $A, x/C = 0.0$, flow without plate. Horizontal lines that cross the curves refer to the levels of the bold curves $v_x/U = 1.0$; and $v_y/U = 0.0$, respectively.

positive and negative vorticity form vortex cores. At the second stage, an obstacle in the form of a plate was placed in the way of one row of shed vortices. The main interest of investigations during this stage was the distribution of vorticity – a measure of vortex-plate interaction. The position of the plate in the tunnel is shown in Fig. 1. The measurements were carried out for a number of plates of different chord length, c, and/or different shapes of the both the leading and the trailing edges. Data recorded at this stage gave irregular vorticity distributions with a large number of small but relatively intensive vortices. An example of vorticity field of this type is shown in Fig. 4b. These results were obtained for the plate having a rectangular cross section, with the chord length, c, equal to 25.4 mm, and thickness, g, equal to 1.0 mm.

Interpreting the velocity derivatives in the vorticity formula as physical, finite increments of distances, $\Delta x, \Delta y$, makes it possible to expect that the obtained results reflect, to a certain accuracy level, the real vorticity distribution in the flow. Therefore the results obtained using the conventional method make good reference guide for comparison with other results obtained with the help of different methods. However, a big disadvantage of this method is long recording time, and subsequent necessity of using data from column A and B, recorded at

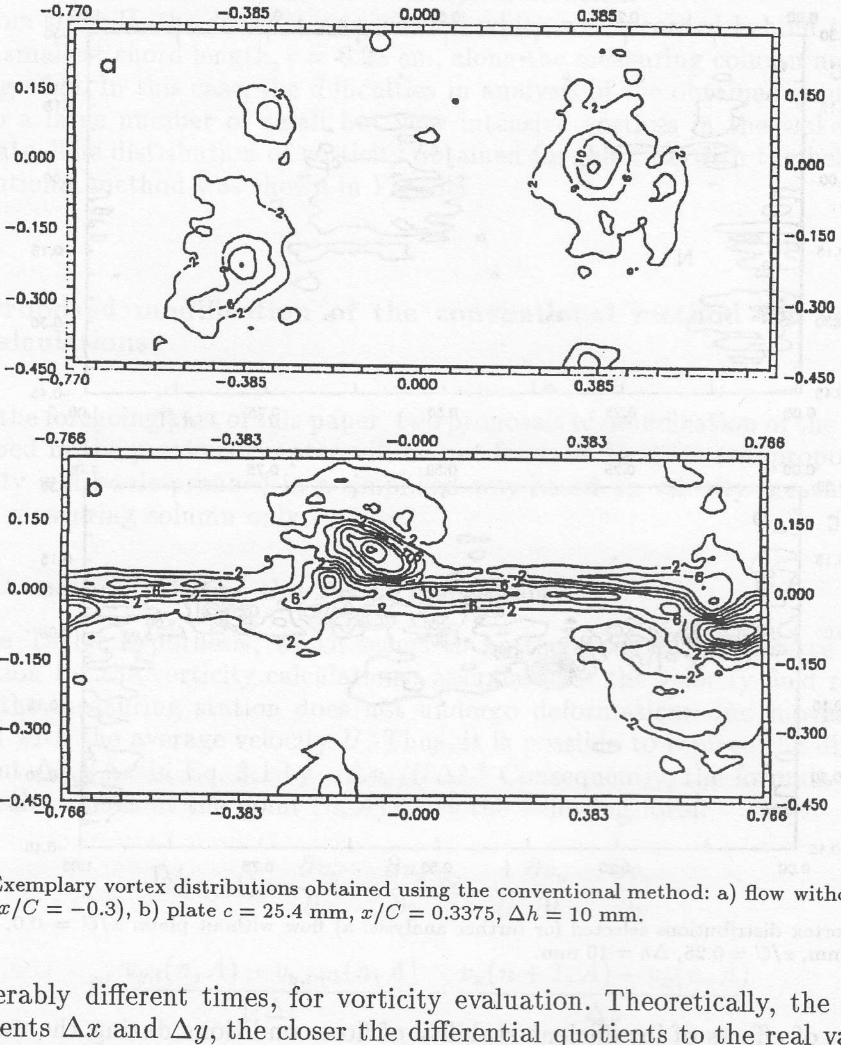

Fig. 4. Exemplary vortex distributions obtained using the conventional method: a) flow without plate: $x = x_5$ ($x/C = -0.3$), b) plate $c = 25.4$ mm, $x/C = 0.3375$, $\Delta h = 10$ mm.

considerably different times, for vorticity evaluation. Theoretically, the smaller increments Δx and Δy, the closer the differential quotients to the real values of spatial derivatives at point n, A. However, if values of $\Delta x, \Delta y$ are specified very small, then the velocity data are recorded at points close to each other and are therefore sensitive to any recording errors, accidental fluctuations and weak velocity trends. That rises the requirement for keeping the flow parameters steady during the entire course of recording, which is generally difficult to perform, and in some cases can make the measurements impossible. The need to eliminate the above discussed disadvantage made the background for the attempt to modify the conventional method used in [5]. For the purpose of this task, two sets of velocity component records, each referring to one stage of the measurements, were selected:

From stage I, the set of data recorded along the measuring station at $x = 0.0$, that is at the hypothetical location of the plate was selected. This set makes an

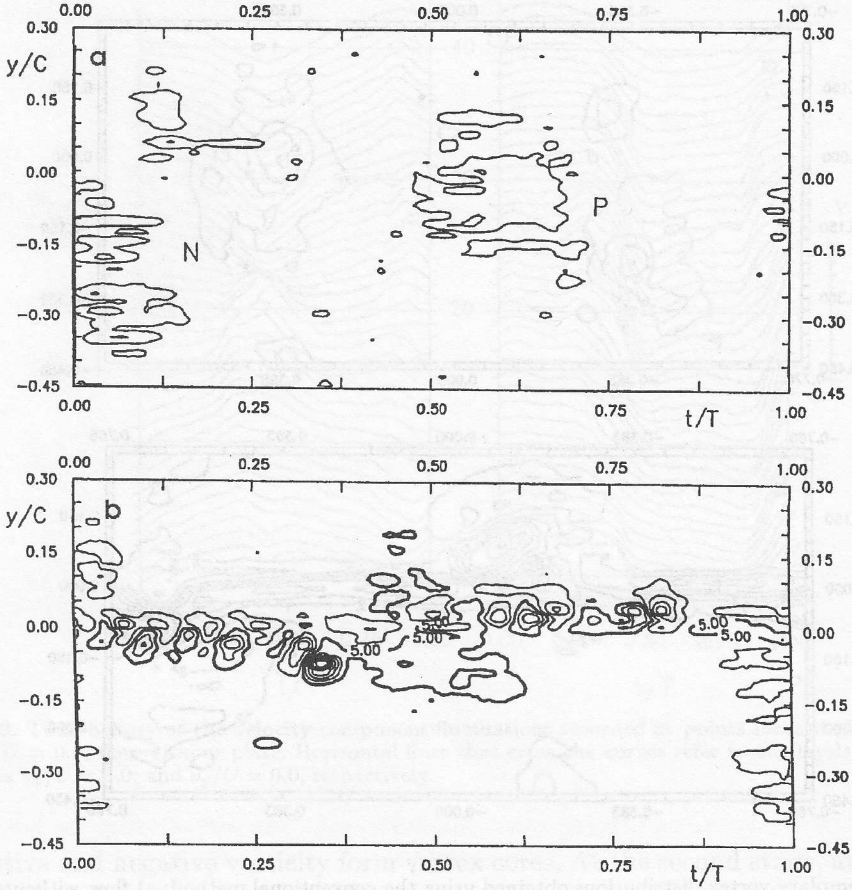

Fig. 5. Vortex distributions selected for further analysis: a) flow without plate: $x/C = 0.0$, b) plate $c = 6.35$ mm, $x/C = 0.25$, $\Delta h = 10$ mm.

example of effects of insufficient stability of flow conditions during the measurement, which, as it was shown in Fig. 5a, led to the vorticity distribution visibly different from that recorded at normal conditions. As just as in Fig. 4a, in Fig. 5a the vortex core regions are visible, with positive (vortex P) and negative (vortex N) circulations, but the vorticity distribution in both cores is very irregular. It is very likely that one reason for a bad quality of data recorded here were some irregularities in the pitching motion of the airfoil. The recording process lasted relatively long in this experiment (the duration of one recording cycle was between two and three hours) and it was very likely that some accidental changes, for example increased friction in the driving system of the airfoil made the data less repeatable. This "low-quality" data set was selected with the aim to verify whether the proposed modifications in the vorticity evaluation, limiting the requirement of stability of flow parameters to the order of 1 minute, lead to visible improvement of the pattern of the vorticity distribution.

From stage II, the data set was selected which was recorded behind the plate of the smallest chord length, $c = 6.28$ cm, along the measuring column next to its trailing edge. In this case, the difficulties in analysis of the obtained results were due to a large number of small but very intensive vortices in the wake behind the plate. The distribution of vorticity obtained for this case with the help of the conventional method was shown in Fig. 5b.

4. Proposed modification of the conventional method for vorticity calculations

In the foregoing part of this paper, two proposals of modification of the method described in the previous chapter will be put forward. In these two proposals the vorticity will be determined in a simplified way based on velocity measurements in one measuring column only.

4.1. A method utilizing the Taylor hypothesis

The Taylor hypothesis, which seems to be the most natural source of simplification for the vorticity calculations, assumes that the velocity field recorded along the measuring station does not undergo deformations and moves downstream with the average velocity U. Thus, it is possible to replace the difference quotient $\Delta v_y/\Delta x$ in Eq. 3.1 by $-\Delta v_y/U\Delta t$.[4] Consequently, the formula for vorticity calculations at the point (n, A) takes the following form:

$$\Omega(n,A) = \frac{\partial v_y}{\partial x} - \frac{\partial v_x}{\partial y} \cong -\frac{1}{U}\frac{\partial v_y}{\partial t} - \frac{\partial v_x}{\partial y} =$$

$$\cong \frac{v_{y,t}(n,A) - v_{y,t+1}(n,A)}{U\Delta t} - \frac{v_x(n+1,A) - v_x(n,A)}{\Delta y}. \tag{4.1}$$

An essential advantage of the formula (4.1) over (3.1) is that the velocity component at the point (n, B) does not appear in the former and there is no need to record it. Therefore, it is possible, at least theoretically, to approximate the vorticity distribution from measurements along one measuring column only. It is quite clear that all this could considerably simplify the preparation procedure and the measuring process itself. However, it remains debatable whether the assumed simplifications would, or would not distort considerably the authenticity of the obtained results. The problem will be resumed in Chapter 5.

[4]It should be emphasized that in this case the Taylor hypothesis is understood in a narrower sense than in stationary cases. The flow conditions are assumed here to be stable during the time interval, Δt, that is necessary to evaluate the velocity derivatives, and not during the entire recording session.

4.2. A method accounting for the local velocity of fluid particles

When applying the Taylor hypothesis for unsteady flows, one should be ready to accept that the results are charged with errors that can not be easily evaluated. Therefore, it seems reasonable to make further attempts to modify more adequately the method for vorticity calculations on the basis of a careful analysis of fluid motion. While doing this, one should keep in mind the general intention to utilize experimental data from one measuring column only. Let us remark that the only question to be resolved is how to evaluate the derivative $\partial v_y/\partial x$ as the other derivative $\partial v_x/\partial y$ can be calculated directly from the measuring data. It is suggested that $\partial v_y/\partial x$ be evaluated from the definition of substantial derivative, which after several transformations takes the following form:

$$\frac{\partial v_y}{\partial x} = \frac{1}{v_x}\left[\frac{dv_y}{dt} - \frac{\partial v_y}{\partial t} - v_y\frac{\partial v_y}{\partial y}\right]. \tag{4.2}$$

The components v_x, v_y are given directly from the measurements. The time-derivative $\partial v_y/\partial t$ can be approximated by the difference quotient $\Delta v_y/\Delta t$, calculated on the basis of instantaneous values of v_y recorded at the measuring point (n, A) at two subsequent instants t and $t + \Delta t$.[5] Similarly the partial derivative $\partial v_y/\partial y$ can be evaluated on the basis of instantaneous values of v_y recorded at the same time in two neighbouring measuring points, for example $(n, A), (n + 1, A)$.

An attempt to approximate directly the substantial derivative dv_y/dt by the difference quotient $(v_{y,t+\Delta t} - v_{y,t})/\Delta t$ falls on a difficulty in determination of the final value of the velocity component $v_{y,t+\Delta t}$. At this stage it should be reminded that the complete set of data consists of data measured in one column at n_y points for n_t instants of the whole period T of oscillations. These data can be arranged into a matrix of n_y rows and n_t columns where data recorded at the same time at different measuring points constitute one row and data recorded at the same measuring point but at different times belong to one column. A part of this matrix with nine neighbouring elements is shown in Fig. 6. One should keep in mind that the direction of the time increment, Δt, is opposite to that of the spatial increment, Δx. Therefore, it can be assumed that if a fluid particle moved in an otherwise frozen velocity field, it could be found, after a time increment Δt, at a point of the velocity field (point K in Fig. 6) determined by velocity components recorded at the measuring point in the previous time instant, $t - 1$. The only unknown would be the deviation S_y of the fluid particle from the free-stream direction v_x caused by the component v_y. However, it can be assumed that this deviation is approximately equal to v_y, at the time t, multiplied by the time increment Δt. Consequently, the final velocity $v_{y,t+\Delta t}$ of the fluid particle could be evaluated via interpolation of velocity distribution along the measuring column

[5]The technique described here should be thought the simplest way of evaluation of Δv. However, in order to increase the accuracy, one can use certain averaging techniques, for example by means of extending the time increment to $2{\cdot}\Delta t$ and performing calculations for values recorded at instants $t - -\Delta t$ and $t + \Delta$t. This method can also be applied for evaluating other difference quotients.

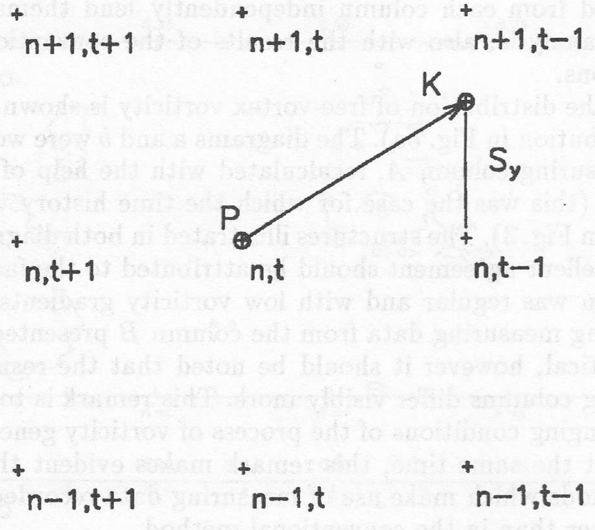

Fig. 6. The concept of evaluating the final velocity of the fluid particle (denotations explained in text).

at the time $t-1$. The interpolating point should be then determined from the relation $(v_y \cdot \Delta t)/\Delta y$[6].

As a result of the preceding considerations, the formula to calculate the vorticity at the point (n, A) takes the form:

$$\Omega(n,A) = \frac{\partial v_y}{\partial x} - \frac{\partial v_x}{\partial y} \cong \frac{1}{v_{x,t}} \Bigg[\frac{\Delta v_y}{\Delta t} - \frac{v_{y,t+1}(n,A) - v_{y,t}(n,A)}{\Delta t} \tag{4.3}$$

$$- v_{y,t} \frac{v_{y,t}(n+1,A) - v_{y,t}(n,A)}{\Delta y} \Bigg] \frac{v_{x,t}(n+1,A) - v_{x,t}(n,A)}{\Delta y}$$

where the difference quotient $\Delta v_y / \Delta t$ is evaluated as before.

In contrast to Eq. (4.1), the above formula accounts for the individual instantaneous velocity of the fluid particle, therefore giving a more accurate description of the fluid motion.

5. Results

As data from one measuring column only are used for vorticity calculations, each column, A and B, of the measuring station x_k can be considered an independent set of measuring data. Therefore, vorticity distributions recalculated

[6]It should be emphasized here that this argumentation is only valid for the cases, in which the velocity components v_y are considerably smaller than v_x. When regions of strong vorticity, or stagnation points are present in the flow, it would be necessary to work out another interpolation method for this regions which uses velocity data from all neighbouring points.

from data obtained from each column independently lend themselves perfectly to a comparative analysis, also with the results of the conventional method of vorticity calculations.

In Figs. 7a-d, the distribution of free-vortex vorticity is shown (compare with the vorticity distribution in Fig. 5a). The diagrams a and *b* were worked out based on data from measuring column *A*, recalculated with the help of Eqs. (4.1) and (4.3), respectively (this was the case for which the time history velocity components were shown in Fig. 3). The structures illustrated in both diagrams are almost identical. This excellent agreement should be attributed to the fact that the flow under investigation was regular and with low vorticity gradients. Similarly, the results of processing measuring data from the column *B* presented in Figs. *c* and *d* are almost identical, however it should be noted that the results referring to different measuring columns differ visibly more. This remark is to confirm earlier suggestions of changing conditions of the process of vorticity generation from the pitching airfoil. At the same time, this remark makes evident the advantage of the modified methods which make use of measuring data recorded in subsequent instants much closer than in the conventional method.

In Fig. 8, the distribution of vorticity referring to the vortex-plate interaction is presented for the case shown earlier in Fig. 5b. In this case, the differences between the vorticity patterns are more visible and it remains open to speculation which of these patterns gives more realistic view on vorticity distribution behind the flat plate. The distribution obtained with the help of the conventional method makes an impression of being regular. However, the vorticity contours are somehow elongated, especially between $t = 0.6 - 0.7$, which seems to be less realistic than for analogous parts of the wake in Fig. 8, where the vorticity contours are more of ovals. On the other hand, the vorticity contours obtained by means of the modified methods are more irregular, especially in Figs. *b* and *d*, that is in the cases when local changes of velocity field were incorporated in the calculations. Drawing on comparison of Figs. 3 and 6, one can make a conclusion that in oscillating flow under investigation, the conventional method produces more averaged results. This can be either positive or negative in the case of oscillating flows. Nevertheless, general view of the vorticity distribution does not change significantly with the method of vorticity calculations. This should be an argument to accept the modified methods as a reliable means of vorticity calculations.

6. Final conclusions

In the paper, two modifications of the conventional method for vorticity calculations are presented on the basis of measurements of the velocity components along two measuring columns positioned next to each other and in perpendicular to the free-stream direction. Both modifications considerably simplify the calculation process as they make use of data from one measuring column only. In the modified versions, the spatial derivative of the velocity vector in the free-stream direction is evaluated either from

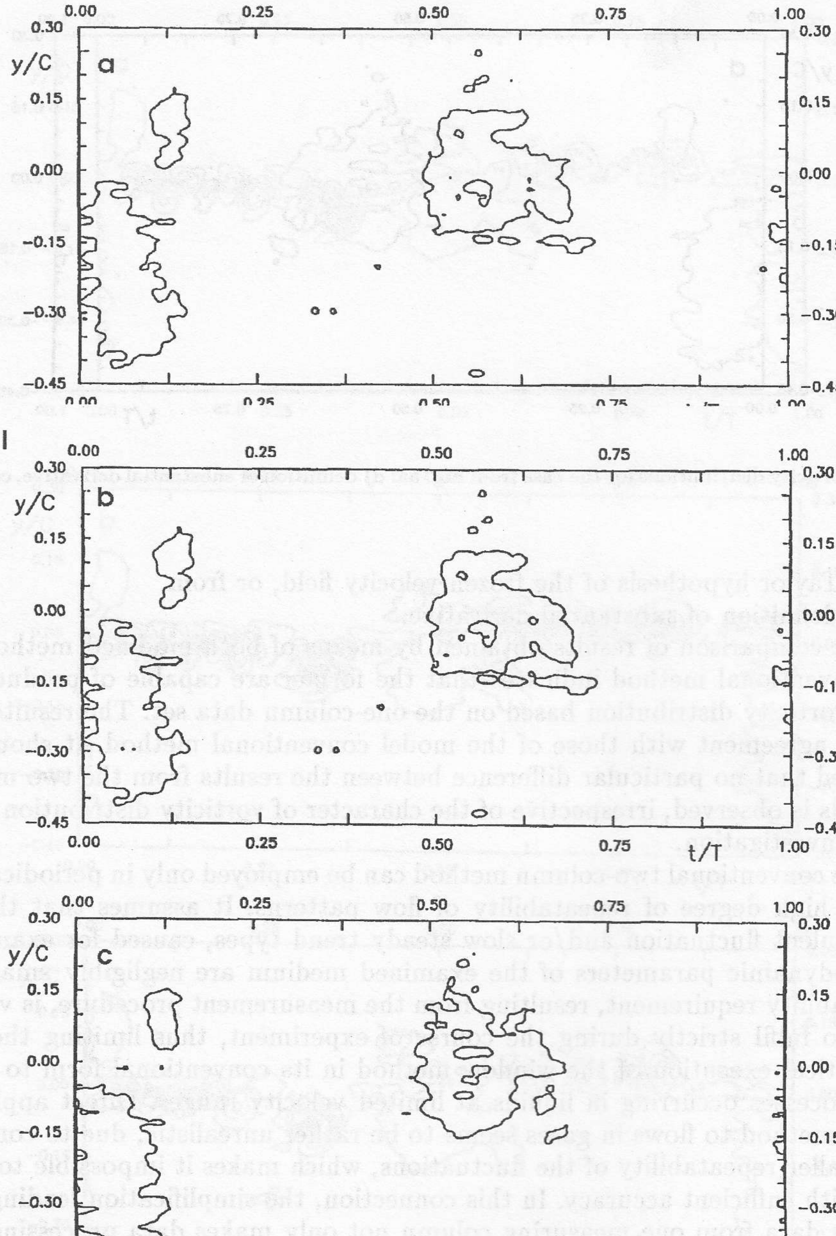

Fig. 7. Vorticity distributions for the case from Fig. 5a: a) Taylor hypothesis, column A, b) definition of substantial derivative, column A, c) Taylor hypothesis, column B

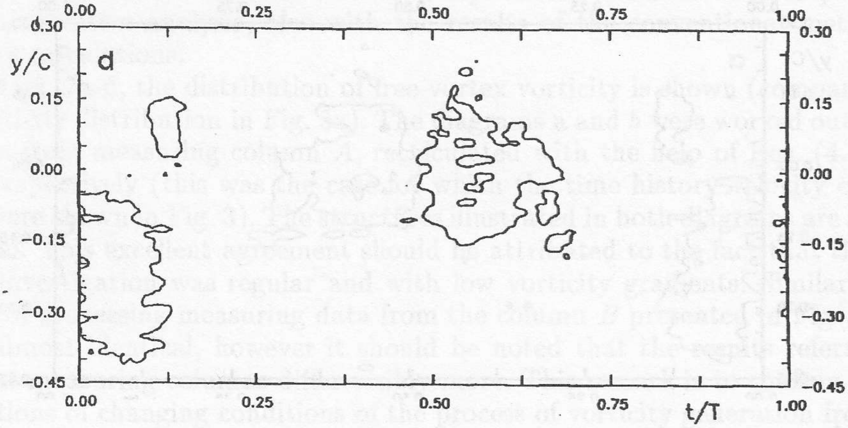

Fig. 7. Vorticity distributions for the case from Fig. 5a: d) definition of substantial derivative, column *B*.

a) the Taylor hypothesis of the frozen velocity field, or from
b) the definition of substantial derivative.

The comparison of results obtained by means of both modified methods and the conventional method indicates that the former are capable of producing reliable vorticity distribution based on the one-column data set. The results are in a good agreement with those of the model conventional method. It should also be noted that no particular difference between the results from the two modified methods is observed, irrespective of the character of vorticity distribution in flow under investigation.

The conventional two-column method can be employed only in periodical flows with a high degree of repeatability of flow patterns. It assumes that the level of turbulent fluctuation and/or slow steady trend types, caused for example by thermodynamic parameters of the examined medium are negligibly small. This repeatability requirement, resulting from the measurement procedure, is very difficult to fulfil strictly during the course of experiment, thus limiting the range of practical execution of the window method in its conventional form to oscillating processes occurring in liquids at limited velocity ranges. Direct application of this method to flows in gases seems to be rather unrealistic, due to considerably smaller repeatability of the fluctuations, which makes it impossible to collect data with sufficient accuracy. In this connection, the simplification leading to recording data from one measuring column not only makes data processing much easier but also allows one to limit the requirement of high repeatability of the flow conditions to the time between recordings at two neighbouring points along the measuring column, accepting, at the same time, for example the existence of weak slow trends during the entire recording process. This new formula of the repeatability requirement is much easier to fulfil. As a result of this, the window method in one of its modified versions can be used to investigate a much wider

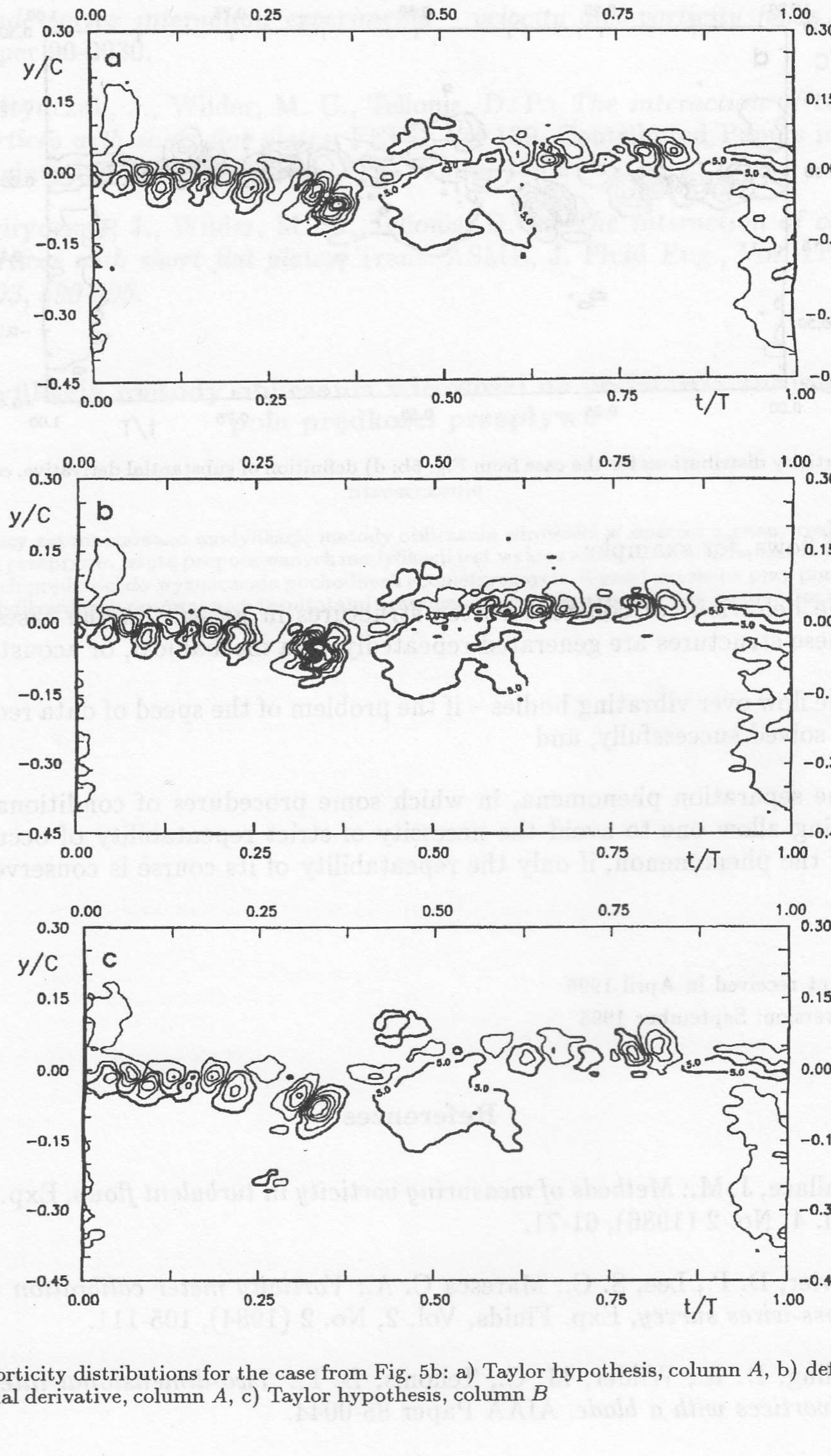

Fig. 8. Vorticity distributions for the case from Fig. 5b: a) Taylor hypothesis, column A, b) definition of substantial derivative, column A, c) Taylor hypothesis, column B

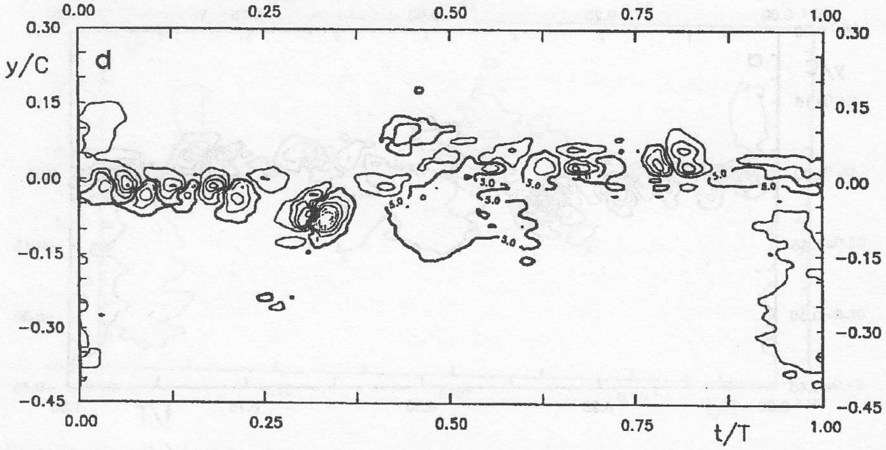

Fig. 8. Vorticity distributions for the case from Fig. 5b: d) definition of substantial derivative, column *B*

range of flows, for example:

- the behaviour of coherent vortex structures in gases – in the cases when these structures are generated repeatedly, in a mechanical, or acoustic way,
- the flow over vibrating bodies – if the problem of the speed of data recording is solved successfully, and
- the separation phenomena, in which some procedures of conditional sampling allow one to avoid the necessity of strict repeatability of occurrence of the phenomenon, if only the repeatability of its course is conserved.

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Modyfikacja metody obliczania wirowości na podstawie znajomości pola prędkości przepływu

Streszczenie

W pracy zaproponowano modyfikację metody obliczania wirowości w oparciu o znany rozkład pola prędkości przepływu. Istotą proponowanych modyfikacji jest wykorzystanie przebiegów czasowych zmian składowych prędkości do wyznaczenia pochodnych geometrycznych. Wyniki uzyskane przy pomocy metod zmodyfikowanych porównano z rezultatami otrzymanymi przy użyciu metody konwencjonalnej.