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EFFECT OF THE FLOW FIELD DEFORMATION IN A WIND TUNNEL ON AERODYNAMIC COEFFICIENTS

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Abstract. The quality of the flow field is highly significant wind tunnel measurements are bing made. When an air flow field is formed by a fan, the entire flow field rotates. Moreover, the flow field is deformed at the bends of a wind tunnel with close circulation. Although wind tunnels are equipped with devices that eliminate these non-uniformities, in most cases the air flow field does not have ideal parameters in the test section. In order to evaluate the measured results of the model in the wind tunnel, it is necessary to characterize the deformation of the flow field. The following text describes the possible general forms of the flow field non-uniformity, and their effect on the calculation of the aerodynamic coefficients.

Keywords: Flow field, speed profile, rotation, vortex, specific speed, deformation of the flow field, wind tunnel, aerodynamic coefficient.

1. Introduction

The requirement for keeping a uniform air flow field uniformity in the wind tunnel is the state when the axial speed component has an identical value in each point of the test section that influences the measured model. The radial speed component, which is perpendicular to the axial axis of the wind tunnel, should be zero.

The level of the flow field non-uniformity in the wind tunnel is screened, for example, by a measuring probe, at defined points in the test section. For this, the measuring space should be divided into four sectors in the chosen radial plane (i.e. the plane perpendicular to the axial axis of the wind tunnel). The marking and numbering of these points is presented in Fig. 1. The constant vertical and horizontal distance among these points is suitable for other analyses. Checking measurements in the defined points can be performed in other planes.

The described flow field non-uniformity analysis is justified in the core of the flow field, which is intended for wind tunnel tests one air and ground applications at a sufficient distance from the tunnel wall, where there is no influence of the boundary layer. If the method described here is repeated in the other radial planes of the test section, the character of the development of the turbulence in the axial direction can be analyzed. The turbulent pulsation level can be assessed when measuring the parameters at one point in the sector over in longer periods of time and recording the changes in these parameters. The following text focuses on the general flow field deformation in one radial plane and without time-sensitive effects.

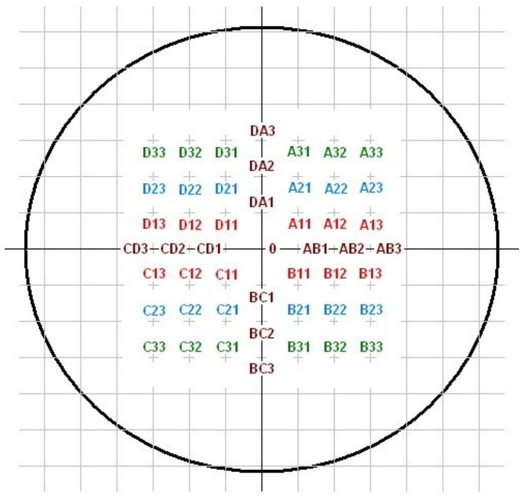

Figure 1. Definition of the probe positions

2. Description of the flow field

The air flow speed in a wind tunnel is considered as the average value of the speed distribution in a defined cross-section of the test section. The speed value then expediently meets the real conditions for the measured model. For a better description, the non-uniformity of the flow field will be classified into speed relations in the longitudinal direction of the wind tunnel (axial speed) and speed relations in the lateral direction of the wind tunnel (radial speeds).

3. Speed profile

The speeds of the air flow distributed in the longitudinal direction of the wind tunnel form the speed profile. For simplicity, the speed profile in one plane parallel

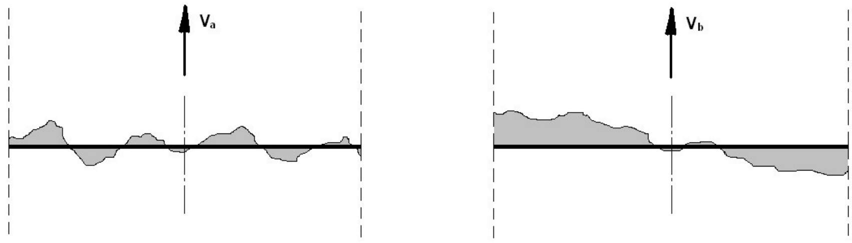

Figure 2. Two speed profile in the wind tunnel.

with the axis of the wind tunnel will be considered in the text that follows. Generally, there are two kinds of the speed profile: (1) the mirror speed profile; and (2) the diagonal speed profile. The dissimilarity between these profiles is presented in Fig. 2, where the curve illustrates the oscillations of the local speeds compared with the defined speed of the air flow.

The mirror speed profile is characterized by the V_a speed, and the local speeds in the flow field scarcely influence the results of measurements on the model, so the influence of the non-uniformity of the speed profile is insignificant. The diagonal speed profile is characterized by the V_b speed, and a no similar statement can be claimed, since the sum of the local speeds on left and right parts of the speed profile from the center still rises, and the expressive imbalance of the aerodynamic forces acts on the measured model. In connection with this schedule, if the difference among the corresponding local speeds in defined sectors is lower than a specific value, then the non-uniformity of the flow field has no effect on the measured parameters.

The definition of the non-uniformity of the speed profile is based on the fact that speed VS represents the real air flow speed in the wind tunnel. The consideration of the opposite sectors according to Fig. 1 (i.e. sectors A and D) and their local speeds leads to the expression of the difference between the speeds in the two sectors

$$\overline{V}_{SYM(DA)} = \frac{\sum_{i=1}^{k} |V_{Di} - V_{Ai}|}{kV_S}. \quad (1)$$

The speed difference $(V_{Di} - V_{Ai})$ is valid for the corresponded suffixes according to Fig. 1, where the speed field asymmetry can be presented. The specific speed $\overline{V}_{SYM(DA)}$ between these opposite sectors then expresses the level of deformation of the speed profile.

Based on the character of the definition of the speed profile, the specific speed $\overline{V}_{\mathrm{SYM}}$ between the sectors expresses the rate of the speed profile asymmetry. Despite the symmetry of the flow field between the opposite sectors, however, marked changes in one sector take place without the $\overline{V}_{\mathrm{SYM}}$ specific speed indication. These changes in the speed of the flow field should be represented by expressive differences of the local speeds against the average speed or the real speed of the flow field VS, and this character of the flow field can be expressed by the specific speed

$$\overline{V}_{AVR(DA)} = \frac{\sum_{i=1}^{k} \big(|V_{Ai} - V_S| + |V_{Di} - V_S|\big)}{2kV_S}, \quad (2)$$

which presents the rate of the speed non-uniformity in each sector. Although the speed distribution in profile is symmetrical, the speed profile does not have to be suitable for measuring.

A similar case is the asymmetry of the speed profile according to following relation:

$$\overline{V}_{\mathrm{ASM}} = \frac{\sum_{i=2}^{k} |V_i - V_{i-1}|_A + |V_i - V_{i-1}|_D}{(k-1)V_S}. \quad (3)$$

These asymmetric speed profiles, however, form the slope of the air flow accompanied by the radial speed. This case can be described by the characteristics of the flow field in the radial plane.

4. Rotation of the flow field

In the radial plane, the non-uniformity of the flow field depends on the radial speed component. This speed component acts in a plane which is perpendicular to the axis of the wind tunnel, and it causes flow field to rotate or vortices in the flow field (there is not consider here the case when one component of the radial speed is zero and the motion of the flow field is only a translation). The local radial speed could correspond to character of other local speeds in considered plane, and then it creates overall rotation of the air flow. The second case when characters of the local radial speeds differ, and then the local non-uniformities of the air flow rotation are created, or local vortices are produced.

A similar process can be used for evaluating the radial speed effect. The rotation of the flow field will be defined by analogy with the speed profile (Fig. 2). The rotation of the flow field also has two profiles: (1) the rotary flow field, with radial speed V_r; and (2) the vortex flow field, with local radial speed V_q (Fig. 3). For the following analyses, it is more useful to translate the measured radial speed components in tunnel coordinates into the tangential speed component and the normal speed component relative to the axis of the wind tunnel.

A required condition for the rotary flow field is that the normal speed component is insignificant in each point of the flow field $V_{n(i)} \to 0$. In a flow field that

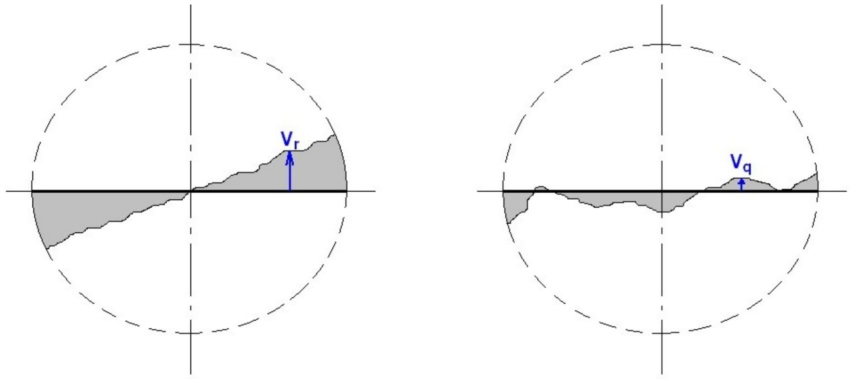

Figure 3. Character of the rotary flow field.

is rotating uniformly, the local tangential speeds rise evenly from the axis of the wind tunnel. In accordance with the speed profile, the requirement for the rotary flow field can be defined by non-uniformity of the rotation of the flow field

$$\overline{V}_{\mathrm{ROT}} = \frac{r}{V_S} \sum_{i=2}^{k} \left| \frac{\Delta V_{t(i,i-1)} \Delta y_{k,1} - \Delta V_{t(k,1)} \Delta y_{i,i-1}}{\Delta y_{i,i-1} \Delta y_{k,1}} \right|, \tag{4}$$

where $\Delta V_{t(\ell,m)} = V_{t(\ell)} - V_{t(m)}$, $\Delta y_{\ell,m} = y_\ell - y_m$ and r is the diameter of the wind tunnel. In this relation, parameter y represents the perpendicular distance from the axis of the wind tunnel to the point of tangential speed V_t. Of course, the flow field must have the same character in all sectors (Fig. 1).

Another factor in the rotations of the flow field, i.e. the rotary flow field and the vortex flow field, is not only value but also the orientation of the normal speed component V_n. In principle, there are three cases:

(1.) outer rotation, when $V_n > 0$;

(2.) inner rotation, when $V_n < 0$;

(3.) steady rotation, when $V_n = 0$;

In the last case $V_n = 0$, if it is on whole cross-section, a rotary flow field is formed. However, there are situations in the vortex flow field when the local normal speed is zero.

The angle υ_2 between radial speed V_r and normal speed V_n is the characteristic parameter of the vortex flow field. The intensity of the local vortex then will be defined by the cosine of this angle in the range from −1 to +1. The intensity of the vortex flow field is now defined by the following relation:

$$\overline{V}_{\mathrm{VOR}} = \frac{\sqrt{(\Delta y)^2 + (\Delta z)^2}}{r} \left(\frac{|V_{r(i)} - V_{r(i-1)}|}{V_S} + \frac{|\upsilon_{2(i)} - \upsilon_{2(i-1)}|}{2\pi} \right), \tag{5}$$

where a constant distance between measured positions Δy and Δz is expected.

5. Deformation Character of the Flow Field

The deformation of the flow field in the wind tunnel described above is based on the change of the speed profile in the axial direction and the rotation or the vortex flow field in the radial direction.

For the speed profile, there are the mirror speed profile, with the flow symmetry, and the diagonal speed profile, with some unsymmetrical level. The specific speed $\overline{V}_{\mathrm{SYM}}$ indicates the level of symmetry or asymmetry. However, disproportion of the local speed can occur in the symmetry speed profile. The specific speed $\overline{V}_{\mathrm{AVR}}$ indicates these local speed disproportions in the air flow.

There are the rotation of the flow field, and the vortex flow field in the radial direction. The normal speed component value determines the range of each case. For the rotation of the flow field, the specific speed $\overline{V}_{\mathrm{ROT}}$ indicates the non-uniformity of the rotation of the flow field. This specific speed depends on the diameter of the wind tunnel, and is related to the defined speed of the flow field in the tunnel, or the average speed of the flow field. If the flow field has a vortex character, then the specific speed $\overline{V}_{\mathrm{VOR}}$ indicates the intensity of the vortex and this specific speed depends on the diameter of the wind tunnel, and is also related to the defined speed of the flow field.

6. Asymmetry of the speed profile

The specific speed $\overline{V}_{\mathrm{SYM}}$ indicates the size of the corresponding difference between the local speeds and defined flow field speed in the wind tunnel. In comparison with value for the specific speed $\overline{V}_{\mathrm{SYM}}$, the local speed non-uniformity in the flow field can be considered as insignificant. However, the same value of this specific speed could represent various kinds of flow field non-uniformities. In the following text, the difference between the local speed and the defined speed of the wind tunnel V_S will be considered. The size or the shape of the model also has a sense.

For most basic measurements, the longitudinal axis of the model is consistent with the axis of the wind

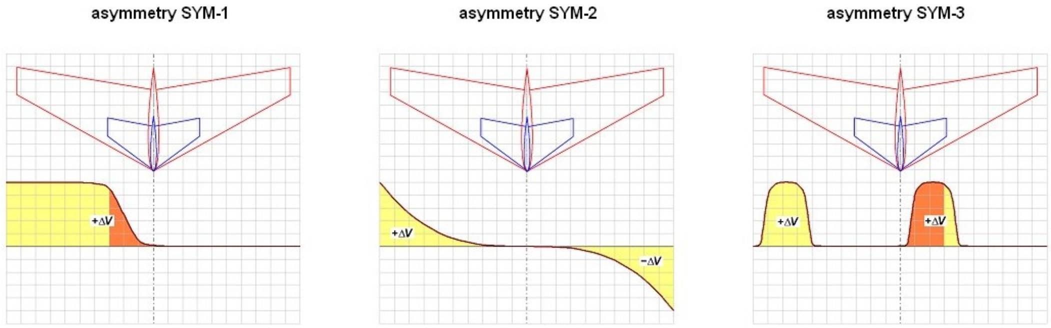

Figure 4. Basic kinds of speed profile asymmetry.

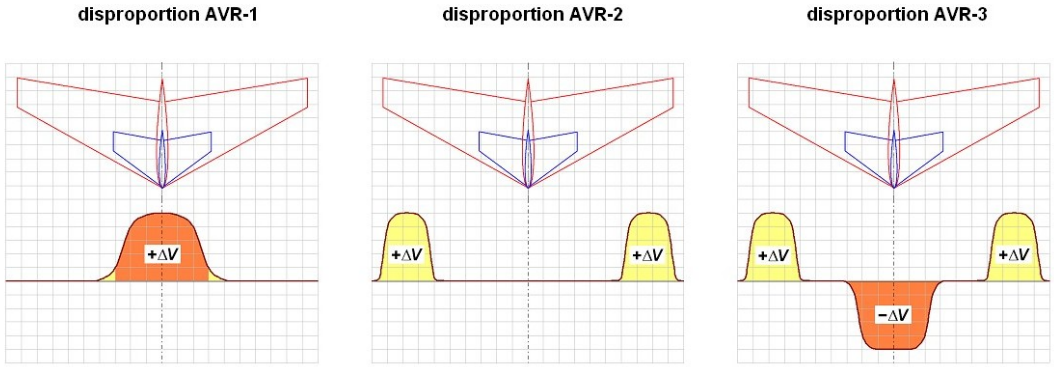

Figure 5. Basic kinds of speed profile disproportion.

tunnel, so the type of flow field non-uniformity and the size of the model are important for the error analysis. Fig. 4, shows the three basic types of speed profile asymmetry:

- SYM-1 speed asymmetry refers to the case when the change in speed occurs only in one part of the speed profile, or only in one sector (Fig. 1). If two model sizes are considered, the asymmetry is more marked in the bigger model.
- SYM-2 speed asymmetry refers to the case when the direction of the local speed differs between the opposite parts of the speed profile. However, the speed profile asymmetry does not affect the smaller model in this case.
- SYM-3 speed asymmetry describes the case when the non-symmetrical distribution of the local speed changes in the opposite parts of the speed profile can have an entire different effect for big models and for small models.

The dark color in Fig. 4 depicts the local speed differences affecting the measurement accuracy for both models. The light color depicts the local speed differences for the bigger model only.

According to this schedule, the size of the model and the position of the most extensive local speed differences should be included with the flow filed non-uniformity for measurements in the wind tunnel. In this connection, positions of the speed differences related to characteristic parts of the model are very important for the error measurement analyses.

7. Speed Profile Disproportion

It was mentioned that the symmetric speed profile can include significant discrepancies among the local speeds, which can have an influence on the results. As in the case of speed profile asymmetry, there are three basic kinds of the symmetric speed profile disproportion (Fig. 5):

- The AVR-1 speed disproportion refers to the case when the speed differences are extensive only on the smaller model, since the deformed air flows around the whole small model whereas the speed differences affect only the region near to the axis of the bigger model.
- The AVR-2 speed disproportion refers to the case when the smaller model is scarcely OK affected by the speed differences. However, the effect of the differences in speed acting on the bigger model can be great enough to affect the usefulness of the measured data.
- The AVR-3 speed disproportion describes the case when the differences in speed have different orientations on smaller models and on bigger models. According to Fig. 5, the smaller model has a flow speed that is lower than the defined speed in the wind tunnel, whereas the bigger model has a flow speed that is higher than defined speed in the wind tunnel.

The definition of the smaller model and bigger model has been mentioned as an example of the difference between the train model, where the height almost

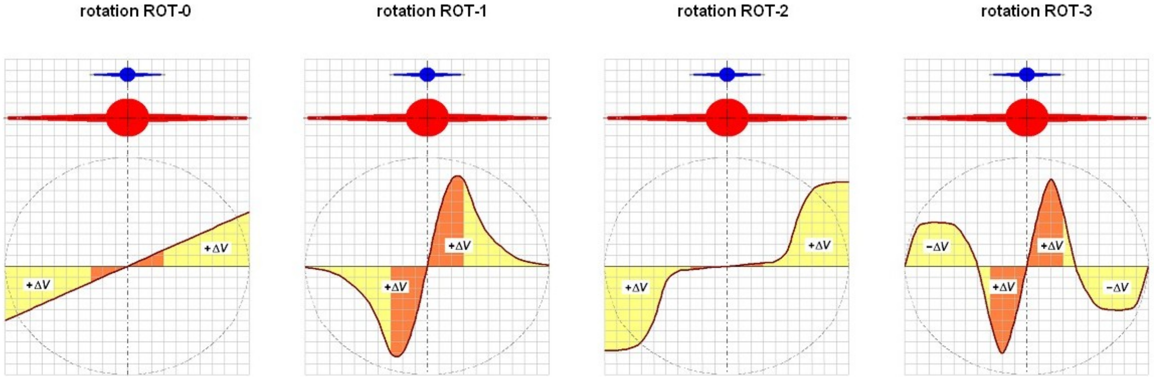

Figure 6. Basic kinds of disproportion of the rotation of the flow field.

corresponds with the width of the model, and the airplane model, where the span has a significantly greater value than the height and a significantly greater value than the diameter of the fuselage.

8. Disproportion of the flow field rotation

The requirement for the rotation of the flow field is condition defined above when the normal speed component in the radial plane is zero or has a value near to zero. Then, there is a way similar to the speed profile solution.

According tothe value for the specific speed $\overline{V}_{\mathrm{ROT}}$, the rotation of the flow field can be considered as a steady or unsteady rotation. However, the value of this specific speed does not indicate the particular rotation non-uniformities, so the rotation effects on the measured model data are essential.

The characteristic attribute of a rotating flow field is that the local radial speeds (i.e. the tangential speeds only, because the normal speeds are insignificant) at the same distance from the axis of the wind tunnel and in opposite sectors have the same value but opposite orientations. This can be called an antisymmetrical speed profile. In this case, the model is also located in center of the the wind tunnel, and there are two model sizes — the small model and the big model. four basic kinds of the flow filed rotation can therefore be defined (Fig. 6):

- The ROT-0 rotation disproportion describes the case when the tangential speeds rise steadily from the axis of the wind tunnel. This kind of rotation creates a similar force and moment for all model sizes, and is mentioned because the rotation is considered as the deformation of the flow field.
- The ROT-1 rotation disproportion describes the case when the positive augmentation of the tangential speed component effect is different on small models and on big models. The measurements on the small model can incorrect while the inaccuracy of the measurements on the big model can be acceptable, and the edge surfaces of the big model are not affected by the differences in speed.
- The ROT-2 rotation disproportion describes the case when the small model is almost unaffected by the rotation of the flow field, whereas the rotation character of the flow field could make the measurement results on the big model totally unsuitable.
- The ROT-3 rotation disproportion describes the case when the deformation of the flow field has different effects on the small model and on the. Again, this case is characterized by the positive and negative differences of the tangential speed.

Disproportionate speeds when the flow field is rotating (i.e. the ROT-1 to ROT-3 kinds) in fact create separate rotations with a joint axis, which is the axis of the wind tunnel. The radial speed of the rotation therefore has only the tangential speed component, which does not rise proportionally s from the axis, as it does typical case for ROT-0 type The flow field rotates in its layers and even for the ROT-3 type, there are the tangential speeds with the opposite orientation between some layers.

9. Vorticity of the flow field rotation

The vortex flow field represents a certain generalization of the rotating flow field, where the axis of rotation is not located in the center of the wind tunnel center, but it is in the random position on the radial speed plane. Radial speeds therefore have.a random direction in relation to the axis of the wind tunnel. The complexity of the description of the flow field was indicated in the definition of the specific speed $\overline{V}_{\mathrm{VOR}}$, where the directions of these speeds are considered. Simultaneously, the direction of the local speeds defined by angle υ_2 is important for the assessment, if the calculated difference between the local speeds is related to the same vortex.

The vortex flow field is in principle unsymmetrical, unlike the rotary flow field, where the speeds in opposite sectors (Fig. 1) are antisymmetric. However, a particular case can also be a symmetrical vortex flow field with the same vortex pattern in the opposite sectors. Since this case is highly improbable it will not be considered below. Unlike in previous cases, the situation will be described on the whole sector designated as the vortex field.

For a description of the vortex field, it is necessary to define the characteristics of the vortex. The vortex can be of high intensity, with a high (tangential) speed on the margin of the vortex, or of low intensity to the commotion vortex (i.e. the time between the creation and the collapse of the vortex is negligibly small. In addition, the region affected by the vortex must be distinct, and there are large-range vortices and small-range vortices. A vortex of immeasurable range can occur in the situation when the chosen measured distance between neighboring positions of the probe is greater than the diameter of the vortex, and the location of the whole area of the vortex with its margin is unmeasurable. The situation can have a negative effect on the results of the measured model, especially if there are critical parts of the model design. The vortex flow fields are therefore distinguished according to the characteristics individual local vortices and their dominant parameters:

- a flow field with low-intensity vortices;
- a flow field with high-intensity vortices;
- a flow field with vortices of the limited range;
- a flow field with vortices beyond the limited range.

If the flow field is described in the defined sectors (Fig. 1), the vortex distribution in the flow field is important, together with the individual vortex characteristics. Generally, the following cases are observed:

- a flow field with a random vortex; this represents the case when the isolated vortex occurs in the flow field, eventually there may be some vortices of low-intensity and with a limited range.
- a flow field with a random fixed vortex; this represents the case when the center of the vortex is exactly known, for example from repeated measurements, or the vortex is considered as stationary.a flow field with a random free vortex; this represents the case when the vortex was found on the basis of the radial speeds, and the center of the vortex was calculated or the axis of the vortex moves in relation to the axis of the wind tunnel.
- a flow field with independent vortices; there are several vortices which do not affect each other.
- a flow field with dependent vortices; there are several vortices which affect each other.

The line between individual cases is dependent on the parameters of the individual vortices related to the defined data, i.e. the vortex intensity related to the speed of the flow field in the wind tunnel, or the vortex range related to the area of the flow field, etc. These cases are taken into consideration in the description of the flow field for the radial plane. However, this description can be extended to the three-dimensional situation and then, for example, the vortex space with the free axis of the vortex is defined as the case when the axis of the vortex changes its position (or slope) in relation to the axis of the wind tunnel. These situations ensue when measures are made in more than one radial plane.

On the basis of the definition of the vortex field, the flow field is characterized into several kinds, unlike the other cases mentioned in the previous paragraphs. Unlike the previous paragraphs, where only the tangential speed component was considered, the normal speed component has a fundamental meaning in the vortex flow field. Remarks were made about the value and the orientation of the normal speed in paragraph 2.2, in the description of the rotation of the flow field rotation.

The value and the orientation of the normal speed do not need to represent unequivocally the concept of the vortex orientation, so it is necessary to explore whether the neighboring normal speeds are parts of the same vortex. The effect of the vortex flow field on the measured model therefore cannot be created according to the separated local radial speeds. This situation is illustrated in Fig. 7, where the pair of radial speeds is able to create a random vortex image. These two speeds can be included in a joint vortex - they can be included in two separate vortices with different circulations or with the same circulations, or they can be included into two vortices with different ranges and intensities. However, the measured speeds do not have to be located on the margin of the vortices and are probably not located on the margin.

The vortex flow field is a characteristic situation where the model is influenced by flow field non-uniformity only on parts of its surface. This situation can be considered as the unsymmetrical case. The random number and possibilities vortices in the flow field then exclude any definition of types of vorticity,in similar cases to above mentioned. The unique requirement for vorticity and for an analysis of its effect on the measured model is knowledge of the value and the position of the radial speed components in the flow field related to critical parts of the model. For the analyses below, the complex mechanism of the vortex flow field needs to be taken into consideration, but an explanation is beyond the scope of this paper [1].

10. A summary of Flow Field Characteristics

Non-uniformity of the flow field was described above on the basis of the speed profile and the flow field rotation. These characteristics were essential for defining the deformation effect of the flow field on the accuracy of the measurements in the wind tunnel. There are two specific speed deformations for the speed profile: speed non-uniformity, which is divided into three types, whereby the position and the model size related to this non-uniformity can be taken into consideration; and the speed disproportion, which is also divided into three types with similar characters. For rotation of the flow field, disproportions of three kinds are defined.

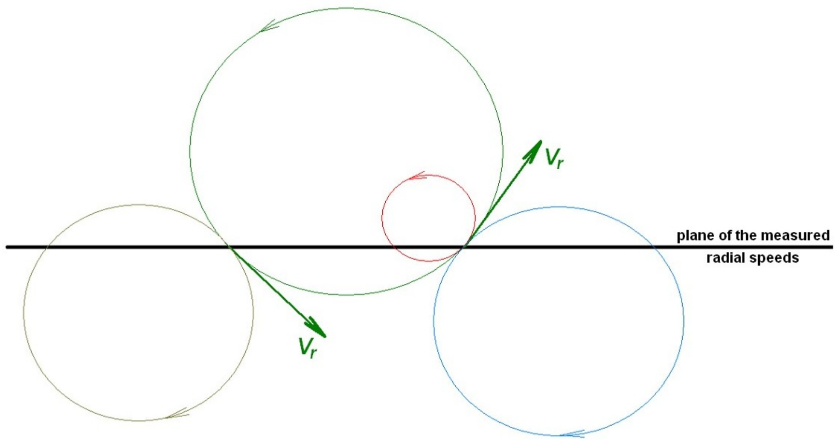

Figure 7. An example of the potential vortices for two measured radial speeds.

The ROT-0 disproportion represents the rotation of the whole flow field, where the local speeds rise proportionally from the center of the rotation (i.e. the axis of the wind tunnel).

In principle, the deformations of the flow field can generally be classified into three types:

- Type 1 — The deformation of the flow field is demonstrated on the model without the scale effect. This effect can be estimated according to acertain character, and the measurement results can be corrected (represented by the SYM-1, AVR-1, ROT-1 types).
- Type 2 — The deformation of the flow field is demonstrated only.only in the measured space. There is also a possible case where the small model is not affected by the change in the flow field, but the large model is affected (represented by the SYM-2, AVR-2, ROT-2 types).
- Type 3 — The deformation of the flow field affects similar models (differing in scale only) differently, and the standard corrections cannot be used (represented by the SYM-3, AVR-3, ROT-3 types).

In this connection, the described effects of non-uniformities of the flow field are valid for steady speeds. The change of the speed in time was not taken into consideration, since this character of the flow field is not in accordance with classical conditions for measurements on the models in the wind tunnel.

The vortex flow field refers to the unsymmetrical situation, where the radial speeds of more than one vortex create a non-uniform speed profile without a unique relation to the size of the model. The vortex flow field was defined for analyses where the range, the intensity and the number of vortices are monitored via the local radial speeds. The center of the vortex can be identified on the basis of two local radial speeds, but these two speeds do not provide any idea about the characters of the local vortices (Fig. 7). The vortex flow field is thus acceptable for the measurements when there are a limited number of low-intensity vortices. The character of the vortex flow field cannot affect the space where the critical parameters of the model are evaluated.

For a comparison of the types and kinds of speed profiles characteristics, the three basic profiles were considered. These profiles are distinguished from each other by the area in which the speeds are different from the defined speed V_S. For simplicity, the speed profiles were designed with a square differential area, as illustrated in the corresponding graphs (Fig. 8). The speed difference b and position a determine this area. The a parameter expresses the range of the deformation of the speed profile as a percentage ($a = 80\,\%$ means that the deformation extends over 80 % of the speed profile. It is drawn in the Fig. 8, where the deformations are designed as symmetrical according to the axis of the speed profile). The b parameter expresses the size of the speed difference as a percentage of the defined speed ($b = 20\,\%$ means that the difference of the speed in the region of the deformation described by the a parameter is 20 % in comparison with the defined speed of the flow field).

Generally, an increase in the specific speed value means a higher stage of non-uniformity of the flow field. For the SYM-1, SYM-2, AVR-1, and AVR-2 profiles, the specific speed grows linearly with parameters a and b. For the rotating ROT-1 and ROT-2 profiles, the specific speed increases in the range of the a parameter to 20 % for ROT-1 and 40 % for ROT-2, and the specific speed decreases in the range of the a parameter from 60 % for ROT-1 and 80 % for ROT-2. A similar case is shown for the SYM-3 profile in Fig. 8, where the specific speed increases up to 50 % of the a parameter, and then the specific speed decreases. The decreased specific speed for higher value of the a parameter indicates a more uniform flow field, but the real speed of the flow field differs in relation to the defined speed V_S. This difference between the real speed of the flow field and the defined speed creates therefore the AVR profiles.

The AVR-3 and ROT-3 profiles create two different areas in one sector, with positive and negative differential speeds. If position a_1 or a_2 is greater than 50 %,

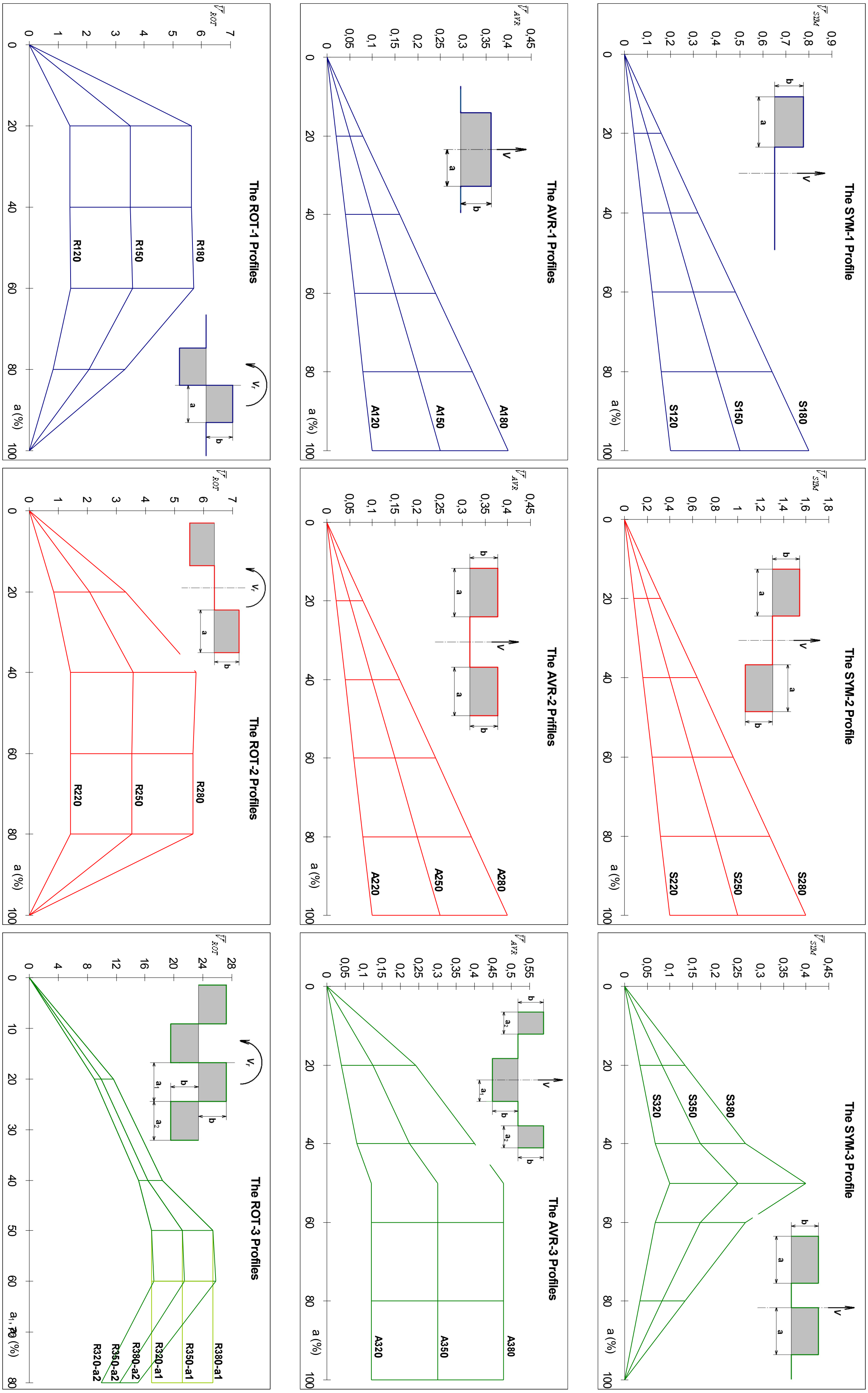

FIGURE 8. The comparison of the basic speed profiles.

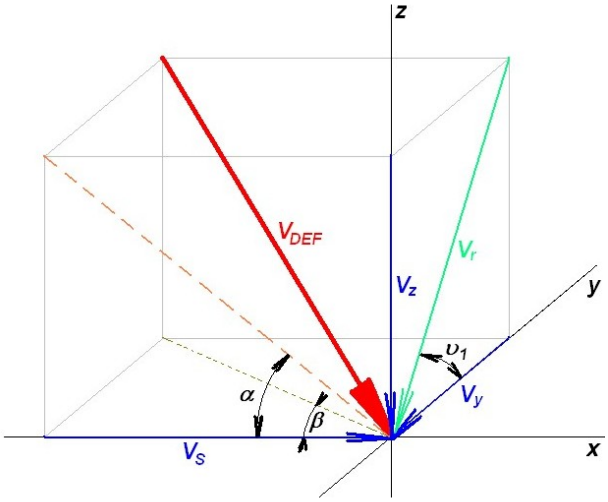

Figure 9. Deformed speed of the flow field.

the results are the same for the AVR-3 profiles (hence the corresponding graph in Fig. 8 does not distinguish parameters a_1 or a_2), but the results are different for the ROT-3 profiles. The complex characteristics of the non-uniformity of the flow field are based on all specific speeds described here, which represent the types of deformation.

These profiles are marked on the basis of their parameters. The first letter refers to the type of profile (SYM, AVR, ROT), the second number refers to the type of profile (SYM-1, SYM-2, SYM-3, etc.), and the last two numbers refer to the difference in speed, as a percentage (parameter b). The ROT marking is followed by an index tagging the position of the speed difference. For example, profile **R380-a1** indicates that there is a ROT-3 type analysis with 80 % of the speed difference in both directions (positive and negative speed differences), and the variable parameter for the position of the speed difference is the length range of a_1.

11. Consequences for the Aerodynamic Coefficients

The classification of the flow fields presented above defines the applicability of the results from the measurements due to the flow field deformation. The character of the flow field produces reactions of the force and moments of the measured model which are recorded by the tensometric balance. The values of the force or moments depend on the parameters of the flow field included in the well-known formula

$$X = C_x \frac{\varrho V_x^2}{2} l^x, \tag{6}$$

where the X is the drag, lift or side force component with the parameter $x = 2$ and is the component of pitching, yawing or rolling moment component with the parameter $x = 3$. The aerodynamic coefficients C_x are calculated on the basis of the measured forces or moments X and the flow field characteristics ϱ and V_x on model l^x. In connection with this, the speed of the flow field is the most important parameter for the accuracy of the calculation of the aerodynamic coefficients.

12. Deformed Speed of the Flow Field in the Model

The ideal flow field in the wind tunnel has the axial speed component V_S only. The deformation of the flow field produces the radial speed component, which influences the results of the measured model with additional forces and moments. In this case, the real speed of the flow field is the deformed speed V_{DEF} (Fig. 9). Matrix notation is used to express the deformed speed:

$$\begin{bmatrix} V_S \\ V_y \\ V_z \end{bmatrix} = V_{\mathrm{DEF}} \begin{bmatrix} \cos\beta\cos\alpha \\ \sin\beta\cos\upsilon_1 \\ \sin\alpha\sin\upsilon_1 \end{bmatrix}. \tag{7}$$

And after transformation to the tangential and normal speed components, the relation is as follows:

$$\begin{bmatrix} V_S \\ V_t \\ V_n \end{bmatrix} = V_{\mathrm{DEF}} \begin{bmatrix} \cos\beta\cos\alpha \\ \sin\beta\sin\upsilon_2 \\ \sin\alpha\cos\upsilon_2 \end{bmatrix}. \tag{8}$$

Angles α and β are stated on the basis of the measured speed components:

$$\tan\alpha = \frac{V_z}{V_S} \quad \text{and} \quad \tan\beta = \frac{V_y}{V_S}. \tag{9}$$

Speeds V_S, V_y and V_z are registered when the measurements of the flow field are checked, and their expression is suitable for connecting with the deformed speed via the specific speeds:

$$\overline{V}_i = \frac{V_i}{V_{\mathrm{DEF}}}, \quad \text{where } i = S, y, z. \tag{10}$$

These specific speeds present only the changes in the angles of the total speed of the flow field, according to the relation (7) or (8).

13. Aerodynamic Coefficients

The ideal situation is a flow field with no deformation. In this case, the flow field has one speed component in the direction of the axis of the wind tunnel axe, which creates the drag force only for the symmetric model. If the drag force is registered by the tensometric balance, relation (6) can be modified:

$$(C_D)_{\mathrm{VYP}} = \frac{C_D \frac{1}{2}\varrho V_{\mathrm{DEF}}^2 l^2}{\frac{1}{2}\varrho V_S^2 l^2} = \frac{C_D}{\overline{V}_S^2}. \tag{11}$$

The inaccuracy of the drag coefficient calculation is defined as $\delta C_D = C_D - (C_D)_{\mathrm{VYP}}$ and it means

$$\delta C_D = (C_D)_{\mathrm{VYP}}(\cos^2\beta\cos^2\alpha - 1). \tag{12}$$

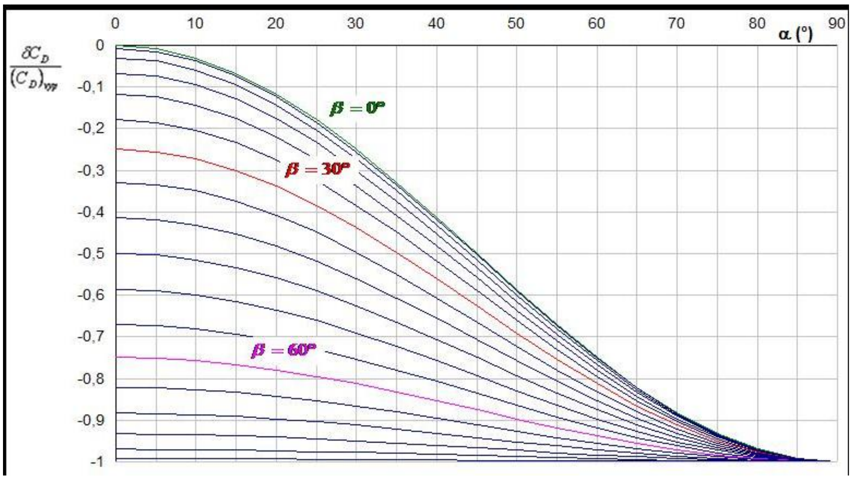

Figure 10. The inaccuracy of the drag coefficient for the deformation of the flow field.

The same process can be used for the lift and side-force coefficients, and the relation is as follows:

$$\delta C_i = (C_D)_{\mathrm{VYP}}\left(1 - \frac{1}{\overline{V}_i^2}\right), \quad \text{where } i = y, z. \tag{13}$$

Relation (13) can be used for the moment coefficients, whereby the appreciated speed produces a force acting in the real length. If the characteristic length is equal to the real length, the relations for the aerodynamic moment coefficients correspond to relations (13). If the symmetric model is measured, only the drag coefficient is non-zero for the ideal flow field. The graph in Fig. 10 presents the increasing the inaccuracy of the drag coefficient with the deformation of the flow field through angles α and β.

14. Conclusion

This paper has presented a study of flow field non-uniformity in connection with the measurements in a wind tunnel. Because the study of the flow field deformation was described on a general level, the paper mentioned all cases, including events that are improbable for the conditions in a wind tunnel. However, these situations provide a complete survey of flow field deformation. Due to the complications for the vortex flow field mentioned here, a general description of this problem requires deeper analysis.

The effect of the flow field deformation on the aerodynamic coefficients was analyzed on the basis of a classification of the non-uniformity of the flow field. This effect was designated as the inaccuracy of the calculation of the aerodynamic coefficients, and is presented in a graph for the drag coefficient.

List of symbols

- a length of the speed difference area [%]
- b value of the speed difference area [%]
- C_x aerodynamic coefficient [–]
- l characteristic length [m]
- r diameter of the wind tunnel [m]
- V speed of the flow field in the wind tunnel [$\mathrm{m\,s^{-1}}$]
- $\overline{V}$ specific speed of the speed profile [–]
- y, z distance between positions of the probe at the check measuring [m]
- δC_x inaccuracy of the aerodynamic coefficient [–]
- ϱ air density [$\mathrm{kg\,m^{-3}}$]

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