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Indicators for the evaluation of test section flow quality

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ABSTRACT: The flow in a wind tunnel test section must meet high standards to obtain accurate and reliable measurement data. Good flow quality demands a certain degree of spatial uniformity and temporal steadiness of velocity and pressure. In this paper, a set of six new indices is developed and presented that relate spatial aspects of the mean velocity field to flow quality. One index quantifies the degree of uniformity of the velocity field and can be used directly as a flow quality indicator. The five other indices are related to different types of deviations from spatially uniform flow; skewed flow and angularity (up-flow and down-flow, swirl, cross-flow, diverging and converging flow). The indices can be used to evaluate the flow quality in existing tunnels and to assess the impact of design modifications. They can also be used in the CFD-based design of new wind tunnels.

KEYWORDS: Wind tunnel testing; Flow quality; Skewness; Angularity; Uniformity.

1 INTRODUCTION

Wind tunnel test section flow quality relates to temporal and spatial aspects of the flow. In this paper, only spatial aspects of the flow will be addressed. Strictly speaking, spatial uniformity is required in the entire empty test section of the wind tunnel. Deviations from spatial uniformity can have negative repercussions on the test results (Rae and Pope, 1984; Barlow and Rae, 1999). A skewed flow for example (i.e. with a streamwise velocity that is not symmetrically distributed over the width of the test section) will cause the static pressure over the front face of an object placed in the test section and the position of the stagnation point to be shifted. This can have a significant influence on all measured quantities around the object.

Spatial flow uniformity is often documented by contour plots of velocity magnitude or static pressure that are shown in one or more cross-sectional planes of the wind tunnel (e.g. Selig and McGranahan, 2004). Other authors provide only numerical information in the form of a single mean value and spatial standard deviation for the quantity for the entire cross-sectional plane. The first method allows determining the presence or absence of skewness and angularity. However, multiple sections are required to obtain a complete view of the flow quality in the entire test section. Mean values and spatial standard deviations have the advantage that the flow in a specific (part of the) cross-section can be characterised numerically, although the interpretation of these characteristic values is not always clear. The existing techniques do not allow for a complete and straightforward evaluation of test section flow quality. However, it is important to be able to quantify wind tunnel test section flow quality and to assess and compare the impact of features such as honeycombs, corner or guide vanes, screens, etc. for wind tunnel and flow quality optimization. To this extent, a set of six new complementary indices describing spatial uniformity and the different types of spatial non-uniformity is developed in this paper.

2 DEFINITIONS

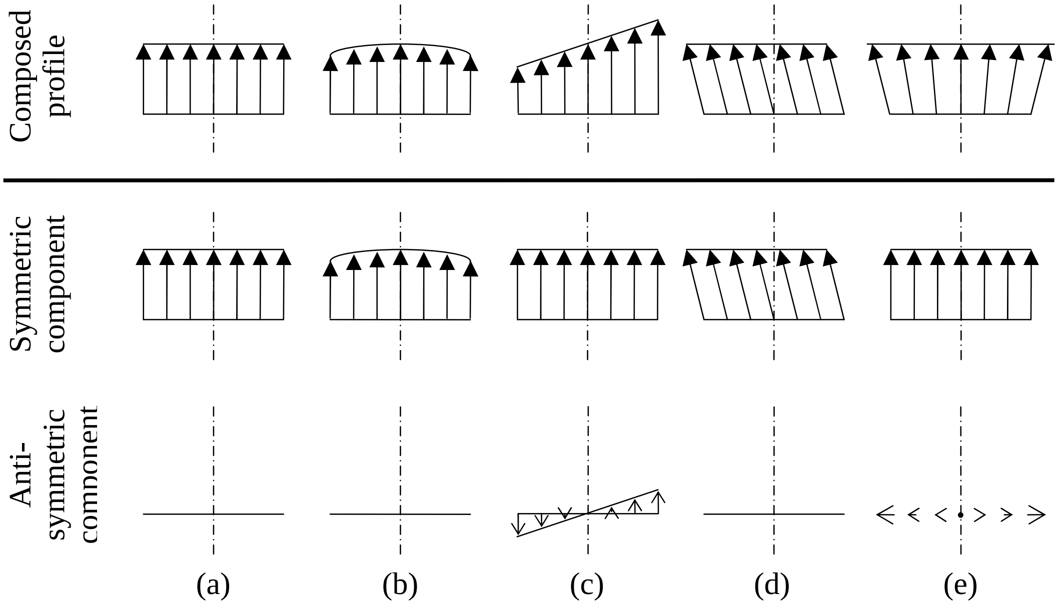


Figure 1. Top row: Definition of different types of flow: (a) ideal uniform flow; (b) symmetric flow resulting from wall friction; (c) skewed flow; (d) angularity (cross-flow or up-flow); (e) angularity (diverging or converging flow. Situations (c), (d) and (e) are to be avoided. Second and third row: decomposition of the original flow field into a symmetric and an anti-symmetric component.

The definition of the indices is based on the fact that every function a(x) can be uniquely decomposed into a symmetric and an anti-symmetric function:

$$a(x)=b(x)+c(x) \tag{1}$$

where b(x) = b(-x) is the symmetric part and c(x) = -c(-x) is the anti-symmetric part. The differences between the ideal, uniform flow pattern (Fig. 1a) and the actual flow pattern can be described in terms of symmetric and non-symmetric deviations. E.g. wall friction causes a symmetric deviation (Fig. 1b), whereas skewness is non-symmetric (Fig. 1c); cross-flow is symmetric (the flow angle is the same at both sides of the axis of the wind tunnel, Fig. 1d), whereas converging or diverging flows are non-symmetric (the flow angle is mirrored with respect to vertical centre plane of the wind tunnel, Fig. 1e). There are several ways to obtain the unique symmetric and anti-symmetric component of the mean velocity data. In this paper, the measurements at measurement points that are positioned symmetrically with respect to the vertical centre plane of the wind tunnel are compared. The average of the two data values yields the symmetric component. The difference between the average and the individual data values yields the anti-symmetric component.

Based on this knowledge, we can introduce 6 complementary indices, one of which describes lateral flow uniformity (2a) and fives others that describe different causes of lateral non-uniformity (2b-f):

$$I_{sym}^{U}(x,y)=\frac{\int U_{sym}^{2}(x,y,z)\,dz}{\int R^{2}(x,y,z)\,dz} \tag{2a}$$

$$I_{antisym}^{U}\left(x,y\right)=\frac{\int U_{antisym}^{2}\left(x,y,z\right)dz}{\int R^{2}\left(x,y,z\right)dz} \tag{2b}$$

$$I_{sym}^{V}\left(x,y\right)=\frac{\int V_{sym}^{2}\left(x,y,z\right)dz}{\int R^{2}\left(x,y,z\right)dz} \tag{2c}$$

$$I_{antisym}^{V}\left(x,y\right)=\frac{\int V_{antisym}^{2}\left(x,y,z\right)dz}{\int R^{2}\left(x,y,z\right)dz} \tag{2d}$$

$$I_{sym}^{W}\left(x,y\right)=\frac{\int W_{sym}^{2}\left(x,y,z\right)dz}{\int R^{2}\left(x,y,z\right)dz} \tag{2e}$$

$$I_{antisym}^{W}\left(x,y\right)=\frac{\int W_{antisym}^{2}\left(x,y,z\right)dz}{\int R^{2}\left(x,y,z\right)dz} \tag{2f}$$

where the integral is taken along a line across the width of the test section; x, y and z are the streamwise, vertical and lateral coordinates; U, V and W are the streamwise, vertical and lateral components of the mean velocity vector in x, y and z-direction; and R is the velocity magnitude. The subscripts “sym” and “antisym” denote the symmetric and the anti-symmetric component respectively. By taking the square of each velocity component, the occurrence of imperfections like skewness or angularity is penalized and at the same time it is avoided that several anti-symmetric contributions cancel each other. The denominator normalizes the result to a value between zero and one.

I_{sym}^{U} is the index describing lateral flow uniformity. The definition is as such that the index equals one for uniform flow, even in the presence of symmetric deviations of the streamwise wind speed component (e.g. resulting from wall effects) since these imperfections can generally not be avoided. Imperfections in the flow field, like skewness and angularity, will lead to a lower value of the index of uniformity. The five other indices quantify these flow imperfections. Lower values correspond to better flow quality. $I_{antisym}^{U}$ is a measure for the skewness of the streamwise component of the flow. I_{sym}^{W} is related to cross-flow, $I_{antisym}^{W}$ to flow that is laterally converging or diverging. I_{sym}^{V} acts as a measure of up-flow or down-flow. $I_{antisym}^{V}$ indicates skewness in the vertical component of the flow. This quantity can to a certain extent be related to swirl.

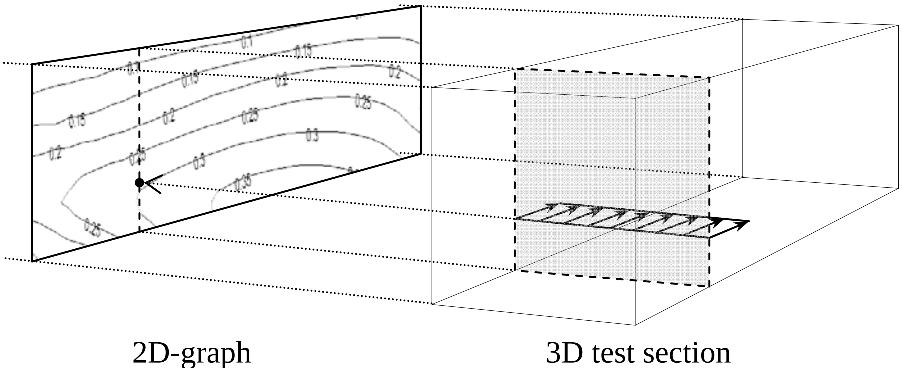
It can be shown that the following relation holds (Eq. 3).

$$I_{sym}^{U}=1-I_{antisym}^{U}-I_{sym}^{V}-I_{antisym}^{V}-I_{sym}^{W}-I_{antisym}^{W} \tag{3}$$

This relationship states that the index of uniformity I_{sym}^{U} acts as an indicator of flow quality. Good flow quality requires I_{sym}^{U} to be close to unity. Eq. (3) indicates that this can only be obtained if all other indices - related to imperfections in the flow field - are close to zero.

3 PRINCIPLE

A component of the lateral velocity profile is squared, integrated along a line across the width of the test section and normalized (Eq. 2). This yields one single value of the corresponding index at a point in a vertical plane parallel with the centre plane of the test section (Fig. 2). Pursuing this approach for all lateral profiles yields a map for the index under study. The combination of all 6 maps offers insight in the actual flow pattern and allows judging the flow quality in the entire wind tunnel test section. The performance of the indices to assess the impact of some geometrical features on the flow quality in the closed-circuit Jules Verne wind tunnel facility is described in detail in Moonen and co-authors (submitted, invited paper).



2D-graph 3D test section

Figure 2. A component of the mean velocity vector is integrated along a horizontal line across the width of the test section to obtain a value for the corresponding index. In this way, the quality of the three dimensional flow in the test section can be shown on a two-dimensional graph.

4 CONCLUSIONS

A set of six new complementary indices for the evaluation of the spatial flow quality in wind tunnel test sections has been presented. The first index quantifies spatial uniformity, while the other five indices are related to spatial imperfections in the flow field: skewness (one index) and flow angularity (indices for: up-flow/down-flow, swirl, cross-flow and converging/diverging flow). They can be visualized for the entire test section on a single graph and can provide useful information that can not directly be obtained from traditional velocity contour and vector plots or from numerical mean values and spatial standard deviations.

The indices developed in this paper are applied in the design and optimization of the boundary layer wind tunnel of the Laboratory of Building Physics, K.U.Leuven. The authors hope that the indices will also be found useful in the evaluation and optimization of test-section flow quality in other wind tunnels.

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