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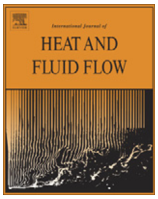

Turbulent flow dynamics caused by a truncated cylinder

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ABSTRACT

The turbulent flow field around a quite simple geometry has been analysed in detail based on a snapshot database taken from numerical simulation. Here, emphasis is placed on the dominant coherent motion and the flow dynamics in the separated wake. The method-based analysis is performed using POD, filtering and phase-averaging. The results obtained show a highly intermittent flow topology, which reveals different (at least three) recurring vortex arrangements, but with considerably stochastic character. Corresponding frequencies, the periodicity as well as correlation and interaction of predominant vortex motions are discussed. The methods employed are not limited to the configuration exemplarily chosen.

1. Introduction and motivation

Turbulence as frequently occurring and therefore important feature of flows in nature and engineering is far from being understood in all its characteristics completely. Reasons are especially the three-dimensional and stochastic nature, which complicates a detailed description and limits its validity often to the flow configuration investigated. Lumley (1970) described the symptoms associated with turbulence very aptly in his preface:

> . . ., the turbulence syndrome includes the following symptoms: The velocity field is such a complicated function of space and time that a statistical description is easier than a detailed description; it is essentially three-dimensional, in the sense that the dynamical mechanism responsible for it (the stretching of vorticity by velocity gradients) can only take place in three dimensions; it is essentially nonlinear and rotational, for the same reasons; a system of partial differential equations exists, relating the instantaneous velocity field to itself a every time and place. . . .
> (Lumley, 1970)

The analysis and understanding of turbulence covering its temporal variations are important to characterise and quantify properties like strong mixing and high drag. The importance originates from the fact that many (if not most) flows relevant for engineers are partially or completely turbulent. Since analytical solutions of the mathematical description can only be derived for a few specific, almost exclusively laminar flow types, the experimental measurement and numerical prediction methods are of utmost significance. Currently, results from experiments and numerics are the base of any turbulence analysis, where statistical evaluations are common but contribute little to our understanding in detail.

Turbulence is often closely connected to flow separation from bodies and obstacles, thereby the shape of the body in many cases plays only a minor role for the development of turbulence. Thus, a configuration to investigate complex turbulence can be quite simple and generic. A relatively short wall-mounted cylinder with a free end has been chosen here (details in Section 2). Such a geometrically simple obstacle is subjected to multiple flow separations at sufficiently high Reynolds number of the incoming flow. The flow around the finite cylinder is essentially characterised by boundary layer separation from the solid surface with subsequent instability of the shear layer leading to complex vortex formations in the wake. This type of flows, where several flow portions (from the head, the shell and the plate) interact in three dimensions, is typical for many industrial applications and has to be examined in detail in order to understand mixing processes and the phenomena leading to increased drag, noise and structural responses (e.g. vibrations). Bradshaw (1971) illustrates the flow around a wall-mounted finite cylinder as obstacle in a boundary layer and used this to exemplify a 'building in a wind'. In the accompanying figure he indicated the complexity and unsteadiness of the wake. This relationship led him to a statement being significant for turbulence and its three-dimensionality:

> Three-dimensional separated flows (. . .) are the most complicated form of turbulence, containing all the difficult features of two-dimensional separated flows plus the effects of stretching of mean flow vorticity. . . .
> (Bradshaw, 1971)

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A finite circular cylinder can be regarded as a prototype for many technical applications, e.g. buildings, cooling towers, telegraph poles, chimneys and fittings on vehicles. In general, many flows subjected to separation from smooth surfaces and highly turbulent wake flow with weak periodicity of the constituted vortices are represented. Although the geometry is quite simple the flow around (for sufficiently high Reynolds number and small aspect ratio) is substantially unsteady due to different interacting turbulent phenomena. Ayoub and Karamcheti (1982) take the aircraft landing gear as an example, which can be understood as an obstacle on a large surface during take off and landing and has itself some elements that are geometrically similar. In addition, the authors point out that the flow region on the cylinder top is a relatively intense noise generator and hence contributes to the aerodynamic noise problem. Sumner et al. (2004) name the commonly known example of the downward motion of smoke behind chimneys as an important problem, by which pollution can be transported to the ground. Furthermore, they provide a summary of various contradictions related to the flow topology in the literature. The statement of Sumner et al. (2004) that a complete understanding of such flows is still missing in the literature due to the challenges for visualisation, measurement and modelling, also motivates the present investigations.

Statistical analysis of turbulent flows gives an average description, but does not contain any dynamic features of the flow. Nevertheless the statistics often indicate that there are strong fluctuations in large areas which are of the same order as the incoming flow and/or mean flow (cf. Fig. 1). However, the analysis of the flow dynamics is difficult due to the spatial and stochastic character of turbulence. Thus the present investigations concentrate on the quantitative identification of the dominant coherent motion and their interaction in the flow field. The main objectives are to provide new insights into the dynamics of the flow around the finite cylinder and to improve the understanding of turbulent interaction. Therefore the investigations might be helpful for those being interested in temporal evolving and interacting turbulence as well as similar configurations.

An extensive literature survey of previous investigations on flows around finite cylinder has been given in Frederich (2010). Most recent workings also capturing features of the instantaneous flow field are published by Krajnović (2008) and Palau-Salvador et al. (2010). The investigations of Krajnović (2008) concentrate on the prediction and explanation of important flow mechanisms as well as instantaneous flow structures. Especially in the wake, the results documented reveal a moderate level of intermittency and are hardly comparable to those for the present configuration, since a lower Reynolds number and particularly a relatively long cylinder has been investigated. In contrast, the findings of Palau-Salvador et al. (2010) for a comparable short cylinder configuration support the fluid-dynamical features reported below, but are mostly descriptive than quantitative for the instantaneous phenomena. The present investigations document the algorithmic extraction of dominant turbulent dynamics in the wake and their quantitative relation to instantaneous wake structures.

A description of the configuration and a summary of the statistically analysed flow field are given in Section 2. The basic methods which are used to analyse the temporal evolution of the flow are presented in Section 3. Thereafter a selection of the most important (with respect to the flow dynamics) results obtained is depicted and discussed in Section 4 before conclusion and outlook are given.

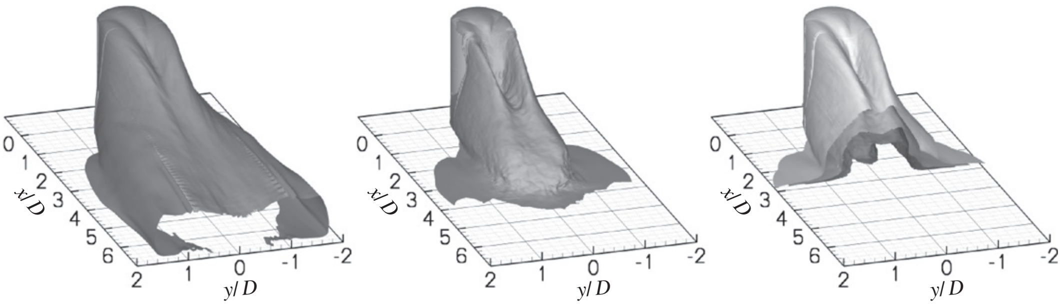
2. Flow field investigated

The cylinder configuration chosen has been defined by the project associated with these investigations. A finite cylinder of diameter D and aspect ratio $L/D = 2$ is placed on a ground plate near its leading edge in order to minimise the effect of the boundary layer on the plate. This boundary layer is additionally tripped by a wire one diameter upstream of the cylinder. The Reynolds number considered is $\mathrm{Re}_D = DU_\infty/\nu = 200000$ and based on the diameter, the inflow velocity U_∞ and kinematic viscosity ν.

For the numerical prediction of the flow field Large-Eddy simulation (LES) with the standard Smagorinsky-Model, where $C_s = 0.1$, has been employed. This is in agreement with previous LES of finite cylinders (e.g. Krajnović, 2008) and gives good results for well-resolved flow fields. For the present Reynolds number the transition of the boundary layer on the cylinder shell can be assumed to be fixed by separation.

The spatial discretisation consists of approximately 12.3 million grid points, arranged block-structured and refined locally around and behind the cylinder. All boundary layers are resolved and the cylinder is discretised with 246 cells in spanwise direction (compressed towards the ends) and with 248 cells in circumferential direction. The resolution in the wake flow has been estimated with energy dissipation spectra to be close to $0.01D$. The resulting maximum wall units are for the regions of interest within or close to the range sufficient for well resolved LES (e.g. given in Fröhlich, 2006). A detailed description of the grid and the realised resolution can be found in Frederich (2010).

The temporal discretisation is defined by the timestep $\Delta t = 0.005\ D/U_\infty$, which results in maximum CFL numbers smaller than one. At the inlet boundary a spatially variable but temporally constant inflow profile has been used. Further details of the configuration and the numerical model are published elsewhere, e.g. in Frederich et al. (2008a). For the analysis of the unsteadiness and dynamics 2750 snapshots of the whole flow field have been captured within nearly 70 convective units D/U_∞ (every fifth timestep of the LES). As the results below reveal these data cover only 12–14 shedding cycles of the predominant vortex phenomena, whose frequency is subjected to significant temporal variation.



(a) $|u_{rms,i}| = 0.25\,U$ (b) $|u_{rms,i}|/|\bar{u}_i| = 1$ (c) $|u_{rms,i}|/|\bar{u}_i| = 0.5, 1, 1.5$

Fig. 1. Regions of strong velocity fluctuations in the flow around a wall-mounted finite cylinder.