TOMOGRAPHIC PARTICLE-IMAGE VELOCIMETRY MEASUREMENTS IN A TURBULENT WAVY CHANNEL FLOW

Alexander Rubbert[1], Michael Klaas[1] & Wolfgang Schröder[1]
[1]*Chair of Fluid Mechanics and Institute of Aerodynamics, RWTH Aachen University, Aachen, Germany*

Abstract To investigate small scale turbulent structures and their statistical properties in non-isotropic turbulent flow subjected to favorable and adverse pressure gradients, a novel method to divide the instantaneous flow field into strictly monotonic elements is applied to tomographic particle-image velocimetry data. Especially the scaling regimes of velocity differences within each element with respect to their lengths are considered.

Introduction

Turbulence remains a largely unsolved problem in fluid mechanics. While direct numerical simulations can resolve even the smallest motions, they are computationally too expensive to be applied to engineering scale problems. Therefore, such problems are analyzed by resolving larger scale structures only and applying a sub-grid model which compensates for the lacking small scale resolution. Such models are mostly statistical in nature and often make use of a wide range of assumptions such as isotropy for the small scale fluctuations. Scaling laws help to approximate the magnitude of the modelled effects.
An approach to analyze turbulent structures was proposed by Peters & Wang in 2006 [5]. Instead of considering turbulent behavior as a superposition of modes, the flow field is decomposed into so-called dissipation elements based on gradient trajectories of any chosen scalar that represents the flow field. Common choices for the base scalar are velocity components, turbulent kinetic energy, or scalar dissipation rate. Each element consists of all possible gradient trajectories connecting a particular pair of local maximum and minimum points. Since the local gradient is unambiguously defined for each point, the resulting gradient trajectories cannot overlap. Consequently, the dissipation-element method can be considered as a partitioning scheme applied to an instantaneous flow field yielding a space filling ensemble of monotonic structures. Because of their strictly monotonic topology, there is no smaller scale spatial fluctuation within a single element. All turbulent behavior is captured within the element ensemble statistics. Especially geometric aspects such as orientation and topology as well as scaling laws of the underlying flow can be investigated by employing this method.
Currently, the ongoing investigation is focused on the turbulent behavior and element property scaling in flows that undergo periodical favorable and adverse pressure gradients.

Previous Work

Various investigations ranging from analytical, numerical to experimental research have previously been performed. Peters & Wang predicted a largely Reynolds number independent element length distribution which could be confirmed by direct numerical simulations [5]. Aldudak & Oberlack's analytical considerations yielded an element length scaling law related to the closest boundary of the flow domain. They also proposed a log-normal element length distribution [1]. Schäfer et al. performed measurements in the core region of a flat channel flow. The detected dissipation elements presented a good agreement with direct numerical simulations [3]. A modified channel flow with one sinusoidal wavy wall with an amplitude of 2.5 mm to impose a pressure gradient was consequently investigated. It was found that conditional mean scalar differences within elements scale linearly with element length for sufficiently large Reynolds numbers. The pressure gradient impacts this scaling law in the form of a variable offset [4]. At lower Reynolds numbers, the same behavior was found for large elements. Small elements do not obey the linear scaling law and therefore present a separate regime.

Facility & Setup

All experiments were performed in the Eiffel-type wind tunnel at the Institute of Aerodynamics at RWTH Aachen University. Its cross section measures 100 mm x 2000 mm (height x width). Transition is forced by two strips of sandpaper on the channel walls directly downstream of the wind tunnel nozzle. After passing a 9 m long inlet section, the flow reaches the test section. Upon entering the test section, a steady and fully turbulent velocity profile matching direct numerical simulation (DNS) results by Niederschulte [2] has developed.
The test section itself measures 2.5 m in length. One wall possesses a sinusoidal wall contour. Its wavelength measures 100 mm with an amplitude of 5 mm. While the contour crests reach 10 mm into the channel, the trough maintains the original flat wall position. The sinusoidal wall contour covers 1.5 m of the test section with 15 individual crests. The

final part of the test section maintains the flat walls on both sides.
Based on the 2D reference data, four measurement volumes spanning 15 x 15 x 8 mm^3 representative for the crest (C), expansion slope (ES), trough (T), and tapering slope (TS) of the wave were selected and recorded at Reynolds numbers of 3200, 6400, and 9600. The flow was seeded with DEHS-droplets with a mean diameter of ~1μm.

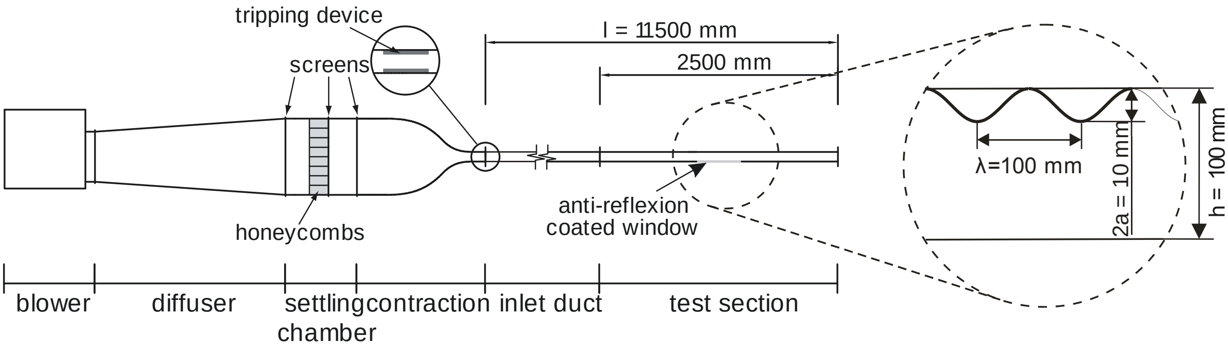

Figure 1. Schematic of the experimental facility.

Current Investigation

The current investigation is focused on the element length at which the scaling behavior of the dissipation elements' scalar differences changes from the non-linear small element scaling to the previously observed linear scaling regime for large elements [5]. The regime crossover length for lower amplitude wave profiles has been observed at approximately 2 mm varying with the bulk Reynolds number as shown in figure 2. Due to the pressure gradients, offsets for the linear regime are found. The small element regime must show a similar scaling of the conditional scalar mean making it more feasible to detect the exact crossover element length. A possible shift of the previously found approximate crossover element length due to the changed ratio between Reynolds number and pressure gradient is also of interest.
A complete analysis will be available in the final paper.

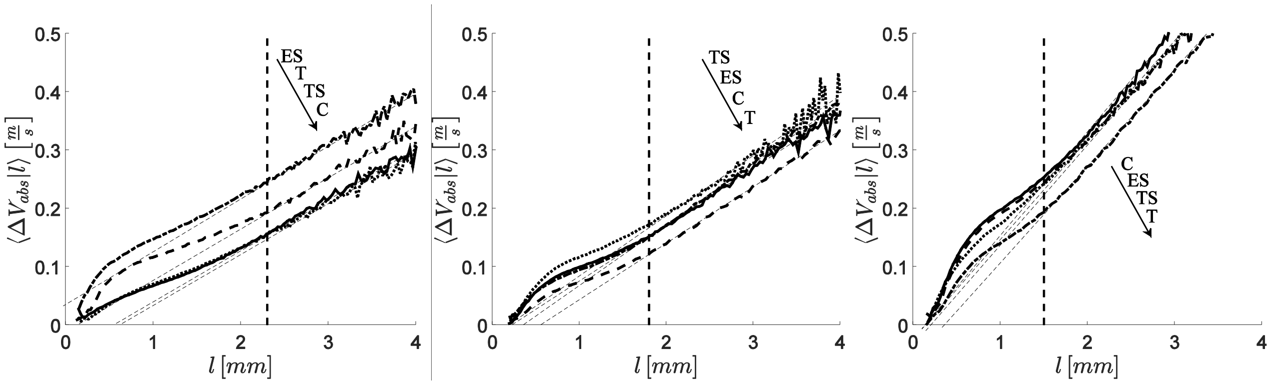

Figure 2. Conditional mean scalar difference in four volumes at Re = 3200, 6400, 9600. The vertical line indicates the approximate regime crossover length.

References

[1] Aldudak F. & Oberlack M., Dissipation element analysis in turbulent channel flow. *J Fluid Mech* **694**, 332-351, 2010
[2] Niederschulte M.A., Turbulent Flow through a Rectangular Channel. *PhD Thesis*, University of Illinois, 2011
[3] Schäfer L., Göbbert J. H., Schröder W., Dissipation element analysis in experimental and numerical shear flow. *EJM B/Fluids* **38**, 85-92, 2012
[4] Rubbert, A., Klaas, M., Schröder W., Tomographic Particle-Image Velocimetry Measurement in a Turbulent Wavy Channel Flow. *Conference Proceedings Lisbon Symposia*, 2014
[5] Wang L. & Peters N., The length-scale distribution function of the distance between extremal points in passive scalar turbulence. *J Fluid Mech* **554**, 457-475, 2006