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Assessment of uncertainties in hot-wire anemometry and oil-film interferometry measurements for wall-bounded turbulent flows

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ABSTRACT

In this study, the sources of uncertainty of hot-wire anemometry (HWA) and oil-film interferometry (OFI) measurements are assessed. Both statistical and classical methods are used for the forward and inverse problems, so that the contributions to the overall uncertainty of the measured quantities can be evaluated. The correlations between the parameters are taken into account through the Bayesian inference with error-in-variable (EiV) model. In the forward problem, very small differences were found when using Monte Carlo (MC), Polynomial Chaos Expansion (PCE) and linear perturbation methods. In flow velocity measurements with HWA, the results indicate that the estimated uncertainty is lower when the correlations among parameters are considered, than when they are not taken into account. Moreover, global sensitivity analyses with Sobol indices showed that the HWA measurements are most sensitive to the wire voltage, and in the case of OFI the most sensitive factor is the calculation of fringe velocity. The relative errors in wall-shear stress, friction velocity and viscous length are 0.44%, 0.23% and0.22%, respectively. Note that these values are lower than the ones reported in other wall-bounded turbulence studies. Note that in most studies of wall-bounded turbulence the correlations among parameters are not considered, and the uncertainties from the various parameters are directly added when determining the overall uncertainty of the measured quantity. In the present analysis we account for these correlations, which may lead to a lower overall uncertainty estimate due to error cancellation Furthermore, our results also indicate that the crucial aspect when obtaining accurate inner-scaled velocity measurements is the wind-tunnel flow quality, which is more critical than the accuracy in wall-shear stress measurements.

1. Introduction

Turbulent flows are extremely complicated due to the wide range of temporal and spatial scales present in them, responsible for various energy transfer mechanisms. The case of wall-bounded turbulence is even more complex due to the fact that the presence of the wall introduces an inhomogeneity in the wall-normal direction, which significantly affects the size of the turbulent structures. As discussed by Jiménez [1], at a particular wall-normal distance the energy transfer is on average from the largest, energy-containing scales towards the smallest, dissipative ones. However, due to the presence of the wall, whether a particular turbulent structure can be considered large or small depends on its wall-normal distance, a fact that increases the complexity of these flows.

Experimental uncertainty is a relevant topic in wall-bounded turbulence, due to the fact that small measurement errors may lead to very different conclusions regarding the nature of turbulent boundary layers (TBLs), especially when data at intermediate Reynolds numbers, Re, are extrapolated to high-Re conditions. Note that the separation between the largest and smallest scales increases with Reynolds number. An example showing the relevance of accurate and independent measurement techniques is the relatively recent debate regarding the functional form of the so-called overlap region in TBLs, stirred among other factors by the different accuracies of the datasets analysed by various research groups. See for instance Refs. [2–6] for further details on this topic. In this particular example the main quantity under investigation was the inner-scaled mean velocity profile $U^+(y^+)$, where U is the streamwise mean velocity, y is the wall-normal location, and the superscript '+' denotes inner scaling as described in detail in Section 3.

Two widely used measurement techniques to experimentally determine the inner-scaled mean velocity profile are hot-wire

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anemometry (HWA) for the velocity, and oil-film interferometry (OFI) for the wall-shear stress. It is exactly these two methods that we study in this paper with reference to their measurement uncertainty. The measured quantities from combined HWA–OFI experiments can be used to estimate the von Kármán coefficient κ, a very important parameter in wall-bounded turbulence research which is the inverse of the slope of the logarithmic layer in the overlap region, assuming that this is the functional form of the latter. Experimental uncertainties have led to multiple interpretations of the measurements, a fact that is illustrated in the work by Zanoun et al. [7], where the reported value of κ is represented as a function of the year (over seven decades), with values ranging from 0.32 to 0.46. The value of κ reported by the Superpipe team in Princeton [8,9] has also suffered changes over the years, a fact that could be explained by the different Pitot-tube probes used in the various studies, combined with the uncertainty in probe location for very high-Re and pressurized pipe-flow measurements [10]. Note that in Ref. [11] a documentation of their changes in other turbulence quantities is also provided. By employing a Bayesian statistical tool, Oliver and Moser [12] studied the impact of the uncertainties in the experimental data of the flow mean and wall shear velocities on the overlap layer model parameters, including κ. The uncertainties in the data were assumed to be random and have specific distributions with presumed magnitudes close to what is expected from high-quality experiments. The conclusions of the mentioned works are complemented with the studies by Vinuesa et al. [6] and Segalini et al. [13], in which the influence of the measurement uncertainty in the determination of κ are systematically evaluated.

Other relevant studies are the assessment of temporal and spatial resolution issues in hot-wire-anemometry found in Refs. [14] and [15], respectively, the influence of temperature fluctuations in hot wires [16] and the evaluation of resolution issues in particle-image-velocimetry (PIV) measurements of turbulence quantities from Ref. [17]. In this context, the need for measurement corrections due to the underlying imperfections of the probes has been analyzed in a number of studies over the years. Some of these studies include the early work on Pitot tubes by MacMillan [18], together with the more recent assessments by McKeon et al. [19] and Bailey et al. [20]; the work on hot-wire corrections by Monkewitz et al. [21], Smits et al. [22] and Segalini et al. [23]; and the work by Vinuesa and Nagib [24], focused on Pitot tube measurements and wall-position of hot-wire probes. Note that a very important factor when establishing a canonical boundary layer is the flow development, as reported by Chauhan et al. [25] and Sanmiguel Vila et al. [26]. Moreover, other recent studies have documented a dependence of the value of κ on flow geometry [27] and the streamwise pressure under which the TBL develops [28,29]. In any case, it can be stated that there is some consensus in the wall-bounded turbulence community regarding the validity of the logarithmic law [5,30,31], with values of κ between 0.38 and around 0.40 (as already discussed by von Karman in 1934 [32]).

Given the potential impact of measurement uncertainties in the conclusions drawn for experiments in wall-bounded turbulence, the aim of the present work is to implement relevant tools provided within the field of uncertainty quantification (UQ), see *e.g.* [33,34], to analyse the uncertainties involved in the HWA–OFI measurements and characterize the sensitivity of such measurements to various factors, in order to identify the ones with the highest impact on the overall uncertainty. To this end, we consider velocity measurements obtained by means of HWA, as well as wall shear stress measurements with OFI. Although in some experimental studies these aspects have been partly addressed [20], a thorough identification of the underlying uncertainties, as well as their detailed uncertainty propagation, is lacking in the wall-bounded turbulence literature. We start from the basic quantities measured in HWA and OFI experiments, and perform a characterization of the forward propagation of uncertainties (known as forward problem [33]) in order to assess the respective contribution of all of these parameters to the final quantities, namely the flow velocity and wall-shear stress. There are various approaches in the UQ framework to perform the forward problem, ranging from the classical perturbation method to sample-based ones. A key aspect of the present study is to apply these methods to different forward problems involved in the HWA–OFI measurements. In addition, applying different approaches to tackle the inverse problems comprised of estimation of the model parameters appearing in different stages of the HWA–OFI measurements given uncertain data, is of central focus. In this context, it is shown how the parameter estimation approaches constructed to reflect a more realistic picture of the error structure of the measured data may estimate different values for the parameter uncertainties than the widely-used classical methods.

Besides employing the techniques that are less frequently used by the community of the experimentalists, it is interesting to show how the mathematical and statistical approaches developed in the UQ theoretical framework can be adopted to study a practical problem. To achieve this goal, the present article is structured to be self-contained up to some extent, providing the essence of the methods employed in different stages and citing relevant references for the interested readers.

This article is structured as follows: in Section 2 the uncertainty quantification techniques employed in the present study are described in detail; in Section 3 a general overview of the HWA and OFI measurement techniques is provided; in Section 4 the previously described techniques are applied to a HWA and an OFI experimental dataset, and the results are discussed; finally, a summary of the work and the main conclusions are provided in Section 6.

2. Overview of the uncertainty quantification techniques

Based on their nature, the uncertainties and errors can be generally categorized into two groups: first, the aleatoric uncertainties, which are also known as random errors, and cannot be reduced or removed by improving models or experiments since they are naturally inherent to the problem. The second type are epistemic or systematic uncertainties, which are usually biased and exist due to imperfections and discrepancies in models or experiments. Contrary to the aleatoric errors, the systematic uncertainties are not naturally defined in the probabilistic framework, see [33,35,36] and the references therein. More specifically, uncertainties in laboratory experiments may stem from different sources such as incomplete or limited observed data, limited accuracy of the measurement devices, human-related errors, and other uncontrollable unknown sources. Besides these, there might be errors due to mathematical models and formulas employed to describe the physical phenomena and to obtain quantities within the process of the experiment. These uncertainties may originate from model errors or discrepancies, a fact that implies that the mathematical relation is incapable of describing the true physics. This is another form of possible bias errors.

Therefore, various error sources are part of any experiment and cannot be completely eliminated due to physical constraints, technical infeasibility, and overwhelming expenses. However, there are techniques within the general framework of uncertainty quantification aiming at providing a better understanding of the relative importance of various identifiable uncertainties. For uncertainty analysis of an interconnected complex system consisting of several smaller intermediate models, the general strategy is to go down to the factors residing at the lowest level and account for their associated uncertainties. This can be done directly via observing