Uncertainty Estimation Methods in Particle Image Velocimetry

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Abstract. The aim of present work is focused on determining accuracy of the measurement using the Particle Image Velocimetry based on an analysis of synthetic Uniform flow test and Couette flow test. We focused on testing the Standard Cross Correlation algorithm and interdependence between the several metrics based on the ratio signal and noise peak and the measurement accuracy at each point. This work is describing the influence of the new corrected metric that is corrected by a displacement measured in the last iteration, detected mean density of the particles and the velocity gradient. Newly proposed method of calculating the metric, Lost of Particle Ratio, is based on the determination of the magnitudes of two correlation peaks. In this work there is defined and compared another metric based on the result of synthetics data test which is based on determination of main parameters as number of particles, gradient in interrogation area and displacement of particles calculated in the last step of correlation. For all presented metrics the relationship is between the metrics and the accuracy.

1 Introduction

The influence of individual recorded data on the result of the measurement error is monitored from the very beginning of the PIV measurement method development. At the turn of the 1980s and 1990s, Keane and Adrian looked at this issue, discovering the effects of the displacement and gradient of the outer investigated plane [1], followed by the other authors and detailing the effects of the displacement and magnitude from planar motion to the measurement [2], [3], [4]. Another parameter that significantly affects the resulting measurement accuracy is the average value and other parameters related to data such as the number of particles in the interrogation area and camera noise [5], [6], [7]. In addition to these two main groups, measurement accuracy affects a number of other parameters such as the size of the interrogation area and the weighting functions [8], [9] or the interpolation algorithm [10], [11]. The measurement accuracy of the PIV method has received considerable attention in recent years. Among the first who defined the correlation between the quality of the recorded data and the resulting measurement error was Timmins et al. who defined the uncertainty surface [12] to determine the resulting measurement error for each measurement. Another possibility to determine the resulting measurement error was defined by Charonko and Vlachos, who determined the influence of the correlation plane metrics and their work was subsequently developed by other authors [13], [14], [15], [16], [17]. Charonko and Vlachos followed by Xue et al. defined the influence of the metrics designated as Primary Peak Ratio PPR and Mutual Information MI and established the theoretical correlations between the metric value and the measurement error. In this work, we want to describe the work of these two authors and describe how to correct these two metrics and improve the resulting correlation between the metric value and the measurement error. Both the PPR and the MI have a direct effect on the number of particles in the interrogation area. Since the number of particles is one of the main parameters influencing the resulting measurement accuracy, the effort to use these metrics to determine the correlation between their value and the measurement error is very important. However, the effect of the number of the particles is not the only parameter that affects the shape and size of the correlation and noise peak and hence the size of the two metrics. Other parameters that significantly affect the overall measurement error include, in addition to the number of the particles, the number of lost pairs, the size of the velocity gradient and the particle diameter. The influence of these parameters on the shape of the correlation plane can be seen in Figure 1 and Figure 2. It can be seen from these images that the signal peak decreases and the PPR ratio decreases as the gradient increases. The number of the lost pairs and the amount of noise have the same effect. These parameters have a similar effect on MI as defined by [14]. Based on

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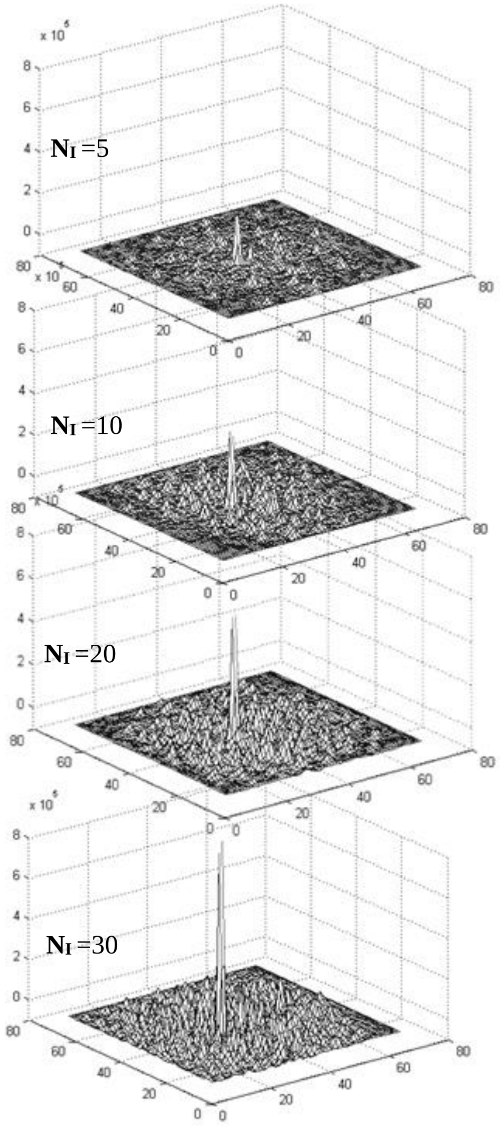

Fig.1. Correlation between seeding particle density (MI) and signal peak ratio.

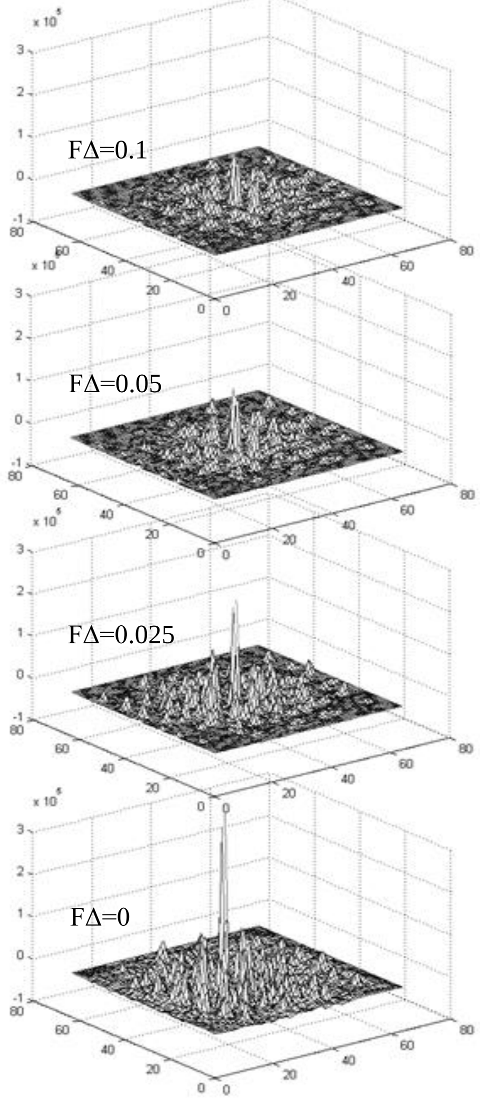

Fig. 2. Correlation between velocity gradient and signal peak ratio.

the effect of the gradient, the displacement and other parameters on the resulting size of these two metrics, we decided to find appropriate corrections that will include the effect of these parameters on the resulting measurement error and thus find a more accurate correlation between the metric value and the overall measurement error. As part of this work and based on the knowledge we have gained when searching for suitable metrics corrections, we have also defined a new metric called Lost of Pair Ratio LPR, which is based on the MI definition and corrects it by shifting the gradient and particle size.

2 Correlation plane metrics

Several metrics can be used to determine the correlation between the metric and the measurement error. In addition to the aforementioned PPR and MI, it is also possible to define the metrics defined as the Peak to Root Mean Square Ratio PRMSR and the Peak Correlation Energy PCE. In our work, we focused on finding the appropriate correction of PPR and MI. We defined the correction of these metrics based on the assumption of the knowledge of the main parameters such as particle number, velocity gradient, particle diameter size and number of lost pairs in the interrogation area. The reason why we need to look for the necessary corrections for PPR and MI is shown in Figure 3 and Figure 4. From these synthetic test results (Uniform Flow Test), a clear sensitivity of the size of the metric to both the number of particles within the interrogation area and the edge size of the interrogation area is evident.

Based on the results of synthetic tests (Uniform Flow Test UFT and Couette Flow Test -CFT), we designed the following corrected PPR and MI metrics:

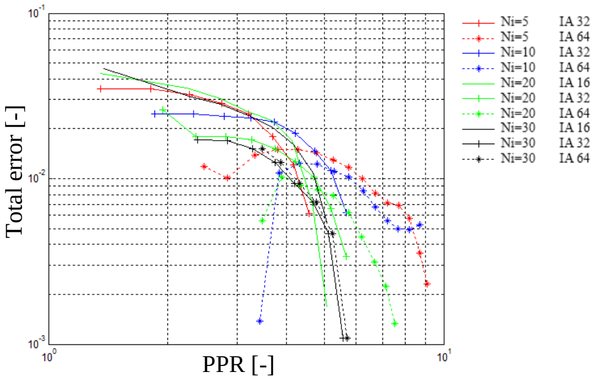

Fig. 3. Influence of seeding density and interrogation area size for PPR.

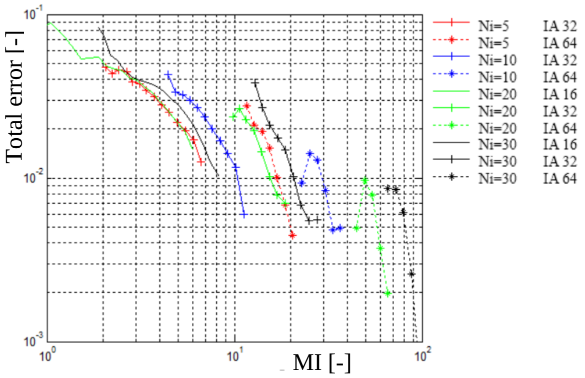

Fig. 4. Influence of seeding density and interrogation area size for MI.

PPR corrected by the size of the displacement measured in the last iteration.

$$PPR_{\Delta} = \frac{PPR - 1}{2 * (\Delta x^2 + \Delta y^2) + 0.0001} + 1 \quad (1)$$

PPR corrected by the size of displacement measured in the last iteration and the number of particles in the interrogation area.

$$PPR_{\Delta,MI} = \frac{PPR - 1}{16\sqrt{(\Delta x^2 + \Delta y^2)} * MI^{(-0.42)} + \frac{0.08}{MI}} + 1 \quad (2)$$

PPR corrected by the size of the displacement measured in the last iteration, the number of particles in the interrogation area and the gradient size in the interrogation area.

$$PPR_{\Delta,MI,GR} = \frac{PPR - 1}{\left(\begin{array}{c} 0.01 + \sqrt{\Delta x^2 + \Delta y^2} * MI^{-0.42} + \\ sgn(GR) * 4 * exp(\frac{MI}{20})\sqrt{\Delta x^2 + \Delta y^2} \bullet exp(GR) \end{array}\right)} + 1 \quad (3)$$

MI corrected by the size of the displacement measured in the last iteration.

$$MI_{\Delta} = \frac{MI}{2 * (\Delta x^2 + \Delta y^2) + 0.001} \quad (4)$$

MI corrected by the size of the displacement measured in the last iteration, and the size of the gradient in the interrogation area.

$$MI_{\Delta,GR,D} = \frac{MI}{[0.5 * (0.02 + \sqrt{\Delta x^2 + \Delta y^2} + \text{sgn}(GR) * MI * \sqrt{\Delta x^2 + \Delta y^2 e^{GR}})]} \quad (5)$$

Based on the corrections made and the results of the synthetic tests, we then proposed a new metric defined as the MI and NI ratio [16] as the ratio of velocity gradient to particle diameter. LPR is defined as:

$$LPR = (MI \cdot (1 - 0.4 \cdot Gr)) \cdot (0.01 + 2 \cdot \Delta_x \cdot N_i)^{-1} \quad (6)$$

As can be seen in Figure 5 and Figure 6, correction of PPR and MI by the displacement and particle number shows a significantly better correlation between the metric value and the overall measurement error compared to uncorrected metrics.

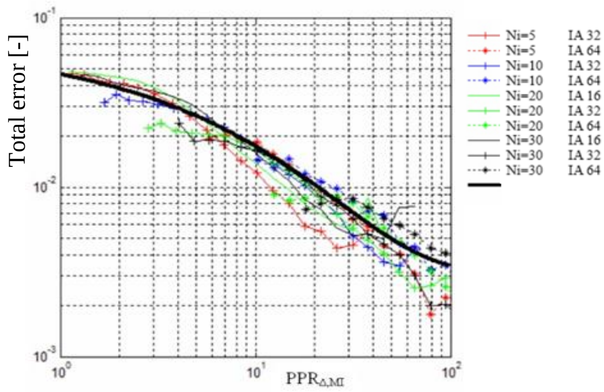

Fig. 5. Influence of seeding density and interrogation area size for PPRΔ.MI.

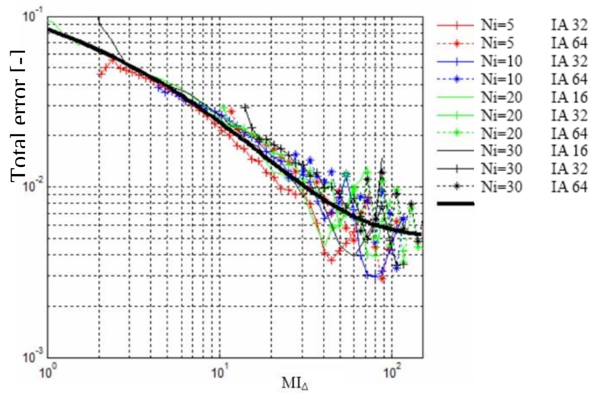

Fig. 6. Influence of seeding density and interrogation area size for MIΔ

Although the UFT results for both corrected metrics show a very good correlation between the metric value and the overall error, using the CFT test, the results for each metric already show different metric values for the metric values close to the minimum values as shown in Figure 7. For this reason, we have proposed a new metric called LPR, which does not show these shortcomings as shown in Figure 8.

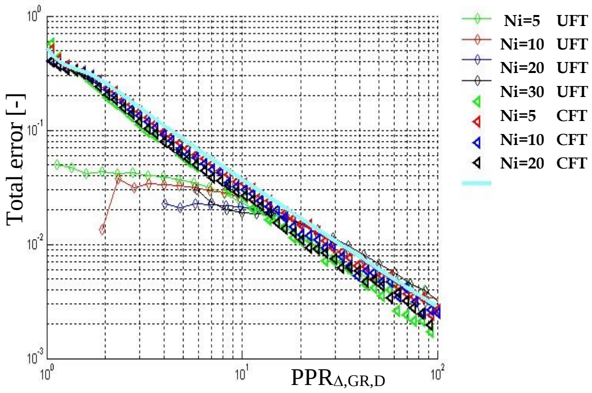

Fig. 7. Influence of seeding density and interrogation area size for PPRΔ.

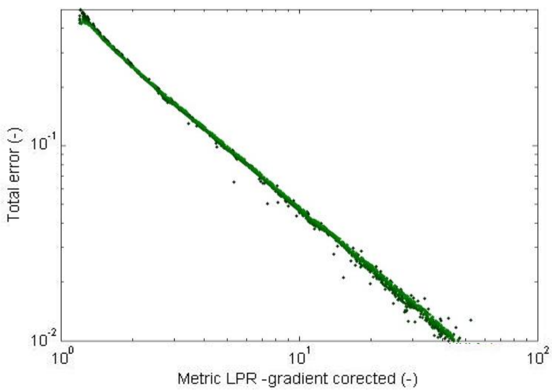

Fig. 8. Influence of seeding density and interrogation area size for fully corrected LPR metric.

3 Conclusions

The aim of this work was to compare the basic metrics used to determine the accuracy of measurements. Our goal was to describe and compare the individual corrections of metrics and on the basis of performed tests to evaluate the most advantageous metrics and then to propose further improvement of used metrics and algorithms for their determination. It is clear from the presented results that corrections of individual metrics significantly improve the resulting accuracy of the PIV measurement error determination. Using basic metrics without these corrections appears to be inaccurate and unusable for metric values near their minimum values. In contrast, corrected metrics, particularly fully corrected MIΔ, GR, D, and LPR, show a very good correlation between the metric value and the overall measurement error across the range of values. One disadvantage of the proposed procedure is the impossibility to determine the measurement error in each direction separately. This shortcoming will need to be addressed in the future work to verify the impact of the individual parameters on the measurement accuracy in each direction. Furthermore, it will be necessary to design a sufficiently robust algorithm to determine the individual parameters necessary for the calculation of corrected metrics and to verify these procedures not only on synthetic data but also on real experiments.

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