2009 American WJTA Conference and Expo
August 18-20, 2009 • Houston, Texas

Paper

UNCERTAINTY COMPONENTS INTERACTION ON THE WATER JET VELOCITY MEASUREMENT BY LASER VELOCIMETRY

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ABSTRACT

The present study deals with a laser Doppler dual-incident-beam velocimeter in reference-beam configuration developed at the Water Jet Lab of the Dipartimento di Meccanica of the Politecnico di Milano and especially designed for water jet applications. The applied experimental procedure makes it possible, once identified the contributors to the uncertainty of the measurand, to apply an analysis of variance in order to point out if the contributors and their interaction effects are statistically effective on the measurand variability.
This work makes it possible to obtain an objective evaluation of the uncertainty sources which influence the fringe spacing in the measurement volume and the water jet velocity. This way it is possible to point out how to obtain the improvement of the measurement system acting on them.

Keywords: laser Doppler, uncertainty, velocity measurement, water jet, Anova.

1. INTRODUCTION

The water jet material removal mechanism is based on the amount of kinetic energy available for the jet at the impact with the workpiece. This fact implies that one of the main characteristics of the jet is water velocity, together with jet coherence and structure, features related to the velocity distribution on the cross section [1].
Water jet velocity measurements are fundamental to characterise the jet but also the efficiency of components as orifices, focusers and mixing chambers.
Accurate velocity measurements can validate simulations on the water jet behaviour and also be the source of diagnostic indexes for detecting orifice failures.
Among other investigated methods [2], Laser Doppler Velocimetry (LDV) [3] is particularly suitable for non invasive and direct measurements of multiphase streams moving at extremely high velocities, even if producers of LDV systems usually provide expensive instruments designed for low velocity measurements, commonly devoted to sprays and mixing processes characterisation.
A laser Doppler dual-incident-beam velocimeter in reference-beam configuration has been developed at the Water Jet Lab of the Dipartimento di Meccanica of the Politecnico di Milano [4,5] (Figure 1): this velocity measurement system has been studied in the present work in order to evaluate the combined standard uncertainty [6] of the pure water jet velocity *V*, called $u_c(v)$, basing on the LDV measurement model (1):

$$V = D \cdot F\,, \qquad (1)$$

where *D* is the fringes spacing in the measurement volume and *F* is the frequency of the light scattered by the jet passing through the fringes. Combined standard uncertainties of *D* and *F*, respectively $u_c(\delta)$ and $u_c(f)$, represent the main uncertainty components. The uncertainty $u_c(v)$ can be evaluated according to the law of propagation of the uncertainty [6] in the case of uncorrelated input quantities. The evaluation of $u_c(\delta)$ and $u_c(f)$ has to take into account their dependence on the input quantities, or contributors, characterising their measurement methods [4].

$$u_c(\delta) = g(u(x_1), u(x_2), ...), \qquad (2) \qquad\qquad u_c(f) = h(u(y_1), u(y_2), ...). \qquad (3)$$

In a previous work [7] we determined the uncertainty components of *D* and *F* and we applied the law of propagation of uncertainty to obtain a value of the water jet velocity uncertainty.
Thanks to our previous experimentation, we were able to determine the value of the uncertainty components due to the single contributors and also a comprehensive uncertainty component associated to each of the three measurands (fringe spacing *D*, Doppler frequency *F* and water jet velocity *V*).
An important issue has to be considered at this point: the experimentation [7] was not designed to put in evidence possible interactions among contributors of the uncertainties (2) and (3): the aim of this paper is to implement an analysis of variance targeted to quantify the variability effects of contributors and their interactions on the fringe spacing *D* and water jet velocity *V*.
The uncertainty components related to the Doppler frequency *F* will be neglected since the previous analysis [7] clearly indicated its very low effect on the uncertainty of the water jet velocity.

The study of the measurement uncertainty is important because it points out if and how further improvement of the developed laser Doppler velocity measurement system can take place.

2. UNCERTAINTY OF THE FRINGE SPACING δ AND OF THE DOPPLER FREQUECY *f*

The experimentation [7] quantified the uncertainty components of the fringe spacing δ and Doppler frequency *f*.
The Table 1 reports the constant parameters of the mentioned previous experimentation. These sources come from the set-up and measurement procedure typical for the developed laser Doppler velocimeter [4,7]: each step of such procedures was analysed in order to capture the related source of variability.
The next two subparagraphs indicate the uncertainty components of the fringe spacing δ and of the Doppler frequency *f* with their numerical values.

2.1 Components of the Uncertainty of the Fringe Spacing δ

Table 2 shows the main sources acting on the uncertainty of the fringe spacing δ.
The estimation of the components in the Table 2 was carried out accordingly to the standard [6] after a classification of type A and type B sources.
Column $u(v)$ in the Table 2 indicate the uncertainty of the water jet velocity v if only the components of δ are considered (the propagation law has been applied neglecting components of *f*).
This kind of analysis pointed out the magnitude of the single components but did not allow to understand if interactions among contributors take place and are statistically significant, topic of the present paper.

2.2 Components of the Uncertainty of the Doppler Frequency *f*

Table 3 shows the main sources acting on the uncertainty of the Doppler frequency *f*.
The same considerations drawn for the fringe spacing uncertainty estimation are correct also for the uncertainty of the frequency even if the component of the uncertainty of *f* (Table 3) demonstrated to be ineffective on the uncertainty of v; this way they will be neglected for the present analysis.

3. ANALYSIS OF VARIANCE OF FRINGE SPACING AND WATER JET VELOCITY

To confirm the results obtained through the experimentation described in paragraphs 2.1 and 2.2 evaluating the statistical significance of the uncertainty sources and their interactions on the fringe spacing δ and, consequently, on the water jet velocity v, we designed a random effects experimental plan implemented with the statistical software Minitab®. This kind of plan has been selected since these contributors can vary inside an infinity of possible values.
The factors of the ANOVA have been selected among the contributors reported in the Table 2.
Observing the uncertainty analysis described in the paragraph 2.1, it is clear how there are two type A most effective contributors on the fringe spacing uncertainty: the laser spot centring and alignment and the clearances between the webcam case and the cutting head (Figure 1).

This is the reason why we decided to apply the ANOVA analysis to these two factors.
This king of analysis can be applied only to type A factors we can control an set to specific levels: it is not possible to extend the analysis to each one of the components shown in the Table 2; for example, the CCD resolution is clearly one of the most effective factors affecting the uncertainty of the fringe spacing but, in order to apply the analysis of variance it is needed that the factor can vary through a selected range of values, which means, in case of the CCD resolution, to employ different webcam with different resolutions, not an available and cost effective solution.
Other sources, such as the inclinations of the CCD sensor, are easily and conveniently evaluated by means of a type B approach, which means without carrying out experiments; also such sources can not be considered for the analysis of variance since it requires an experimentation.
Before carrying out the experimentation, three levels for each factor have been selected.
The webcam clearance levels have been obtained putting the back of the webcam case at a distance of 0.5 mm from the surface of the lens support of the module 2 of the measuring system (Figure 2).
During an accurate set-up procedure, the back of the webcam (CCD) case should be in contact with the lens support in order to place the CCD sensor at a known distance from the lens: a source of error is due to an incorrect positioning, simulated by three levels of the webcam clearance factor (Figure 2):

- Level W1: the webcam case is rotated clockwise around the cutting head (Z axis) in order to contact the lens support starting from a constant clearance of 0.5 mm between the back of the case and the support.
- Level W2: the webcam case is set in order to allow a constant clearance between the back of the case and the lens support of the module 2.
- Level W3: it is the symmetrically opposite to the level W1, obtained rotating anticlockwise the webcam case around the Z axis.

The three levels of the laser spot centring and alignment were obtained by means of two needles (called A and B) fixed on the mirror’s adjusting screws and assuming two possible positions (1 and 2) (Figure 2):

- Level S1: obtained placing the A needle in position 1 and the B needle in position 1.
- Level S2: obtained placing the A needle in position 1 and the B needle in position 2.
- Level S3: obtained placing the A needle in position 2 and the B needle in position 2.

These levels have been selected in order to move the illuminating spot inside the measurement volume of the laser Doppler velocimeter at three known positions.
The experimental plan is composed by 27 combinations; two replications of each combination have been carried out in a random order.

3.1 Fringe Spacing Response

At first, we carried out the ANOVA basing on the complete model. The Figure 3 reports the scatterplot of data; to have a preliminary idea about the effects of the two factors and their

interaction on the response, a screening analysis can consider the main effects plot (Figure 4) and the interaction plot (Figure 5).
The main effects plot suggests that these two factors play a similar role on the fringe spacing variability.
Figure 5 shows that the interaction seems not to influence the response.
Using an α error equal to 5 % (1.67 % for each test), it is possible to state that there is not statistical evidence of the influence of the studied factors and their interaction. The hypotheses at the base of the ANOVA (normality, equal variance and independence of residuals) have been successfully verified.
Observing results in the Table 4, it is possible to note how the interaction variance has a negative value: this result is considered by the statistical literature [8], which suggests to repeat the ANOVA without considering the interaction.
The ANOVA analysis applied to the reduced model provides the results reported in the Table 5: both the two factors are significant with an α error of 5 %.
To validate this analysis, the three ANOVA hypotheses have been successfully verified.
The Figure 6 reports the residuals scatterplot proving the homogeneity of variances.
The ANOVA analysis has shown that both the laser spot centring and alignment and the webcam clearances influence the uncertainty of the fringe spacing while their interaction effect is not statistically significant.

3.2 Water Jet Velocity Response

Multiplying the values of fringes spacing δ and Doppler frequencies f, acquired during the experimentation described in paragraph 3, it was possible to calculate the water jet velocity obtained in each test of the plan.
This way, it was possible to carry out an analysis of variance to verify and quantify the influence of the two factors (the laser spot centring and alignment and the webcam clearances) on the water jet velocity.
This analysis has been performed on the complete model at first.
The main effects plot (Figure 7) suggests that the laser spot alignment is the factor that play the greatest influence on the response, as it is proved by the ANOVA results of the Table 6: applying a total α error of 5 %, it is possible to conclude that only the laser spot centring and alignment plays a statistically significant role.
As for the analysis of the fringe spacing, the interaction variance has a negative value: this fact suggests to carry out a new ANOVA on a reduced model, without the interaction term: results have been reported in the Table 7.
According to the analysis of the complete plan and applying an α error of 5 %, also this test indicates that there is a statistical evidence that only the laser spot alignment is significant.
The three ANOVA hypotheses have been verified (residuals scatterplot in the Figure 8 for the homogeneity of variance): this analysis has shown that, contrarily to the results obtained for the fringe spacing, only the laser spot alignment has an effective influence on the water jet velocity. The p_value associated to the webcam clearances has anyway a low value and this factor could be considered as effective applying a prudent approach.
It is important to point out as the method presented in this paper allows to determine the variability, and consequently the standard uncertainty, related to a studied factor: variances in the

Table 7 can be employed to calculate the standard deviation, which means the standard uncertainty.
Comparing to the uncertainty evaluation carried out in [7], the present study has lead to an overestimation of the components related to the laser spot centring and alignment and to the webcam case clearances with the cutting head: this is probably due to the fact that the selected level of these two factors of the present experimentation have been chosen in order to completely cover the set-up errors cases, without taking into account that a skilled operator probably reduces them, as it is proved by previous results [7] (Table 2). The random effect ANOVA demonstrates to be a powerful method, but levels of factors have to closely represent the reality in order to correctly estimate uncertainty.

4. CONCLUSIONS

The present study has been useful to complete the uncertainty analysis of the laser Doppler velocimeter developed at the Water Jet Lab of the Politecnico di Milano, started with the work reported in [7]. Even if the various uncertainty sources were analysed in [7], no data were available on their possible interaction.
The present paper describes how to apply a random effects ANOVA to obtain the needed answer.
Since the experimental approach for the evaluation of the uncertainty can be only applied to type A sources [6], only the laser centring and alignment and the webcam clearances sources have been considered as factor of the analysis.
Responses of the analysis have been the fringe spacing D and the water velocity itself; no analysis has been carried out on the Doppler frequency since it is known that its uncertainty is negligible [7].
The random effects ANOVA indicates how the two factors can be considered significant while their interaction can be neglected.
These results validate the approach applied in [7], where no interactions were considered.

5. ACKNOWLEDGMENTS

The authors are very grateful to Andrea Casaroli for their invaluable support.

6. REFERENCES

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7. NOMENCLATURE

D	fringe spacing
f	estimate of F
F	Doppler frequency
v	estimate of quantity V
V	mean water jet velocity
δ	estimate of D
$u(f)$	standard uncertainty of estimate f
$u(v)$	standard uncertainty of estimate v
$u(\delta)$	standard uncertainty of estimate δ
$u_c(f)$	combined standard uncertainty of estimate f
$u_c(v)$	combined standard uncertainty of estimate v
$u_c(\delta)$	combined standard uncertainty of estimate δ

7.1 Subscripts

Contributors of the uncertainty of δ:

PXL	dimension of the pixel of the CCD camera
L	water jet handling system
α	CCD sensor inclination around the X axis of the handling system
β	CCD sensor inclination around the Y axis of the handling system
Peaks	algorithm for the calculation of the distance of peaks inside a signal
Spot	laser spot centring and alignment
Web	clearances between webcam case and cutting head
Flu	laser/photodiode fluctuations

Contributors of the uncertainty of f:

Ampli	oscilloscope gain
Spectr	frequency resolution of the spectrum
Spot	laser spot centring and alignment
Interp	algorithm for the determination of the Doppler frequency
Pump-Op	pumping system and operator
Hand	water jet handling system

8. TABLES

Table 1. Constant parameters

Parameter	Symbol	Value
Laser source wavelength	λ	780 nm
Water nominal pressure	p	100 MPa
Orifice diameter	d	0.15 mm
Distance beam-splitter/cutting head	L	2581 mm
Distance beam-splitter/mirror	s	34.98 mm
Velocity measurement distance from the orifice exit	sod	60 mm

Table 2. Components of the uncertainty of δ

$u_c(\delta)$ **components**	**Type of uncertainty**	$u(\delta)$ **[µm]**	$u(v)$ **[m/s]**
$u_{PXL}(\delta)$	B	0.02	0.16
$u_L(\delta)$	A	0.04	0.31
$u_\beta(\delta)$	B	1.14	8.97
$u_\alpha(\delta)$	B	0.01	0.08
$u_{Peaks}(\delta)$	B	2.26	17.78
$u_{Spot}(\delta)$	A	0.10	0.79
$u_{Web}(\delta)$	A	0.10	0.79
$u_{Flu}(\delta)$	A	0.07	0.55

Table 3. Components of the uncertainty of f

$u_c(f)$ **components**	**Type of uncertainty**	$u(f)$ **[MHz]**	$u(v)$ **[m/s]**
photodiode	neglected	0	0
$u_{Ampli}(f)$	A	0.01	0.58
$u_{Spectr}(f)$	B	0.01	0.58
$u_{Spot}(f)$	A	0.01	0.58
$u_{Interp}(f)$	A	0.01	0.58
$u_{Pump\text{-}Op}(f)$	A	0.01	0.58
$u_{Hand}(f)$	A	0.01	0.58

Table 4. ANOVA results for fringe spacing (complete model)

Factors	**p_value**	σ^2
webcam clearances	0.018	0.1492
laser spot alignment	0.028	0.11176
interaction	0.736	-0.03739

Table 5. ANOVA results for fringe spacing (reduced model)

Factors	**p_value**	σ^2
webcam clearances	0.004	0.139
laser spot alignment	0.012	0.1016

Table 6. ANOVA results for the water jet velocity (complete model)

Factors	p_value	σ^2
webcam clearances	0.066	13.685
laser spot alignment	0.014	4.78
interaction	0.755	-3.331

Table 7. ANOVA results for the water jet velocity (reduced model)

Factors	p_value	σ^2
webcam clearances	0.069	3.872
laser spot alignment	0.003	17.77

9. GRAPHICS

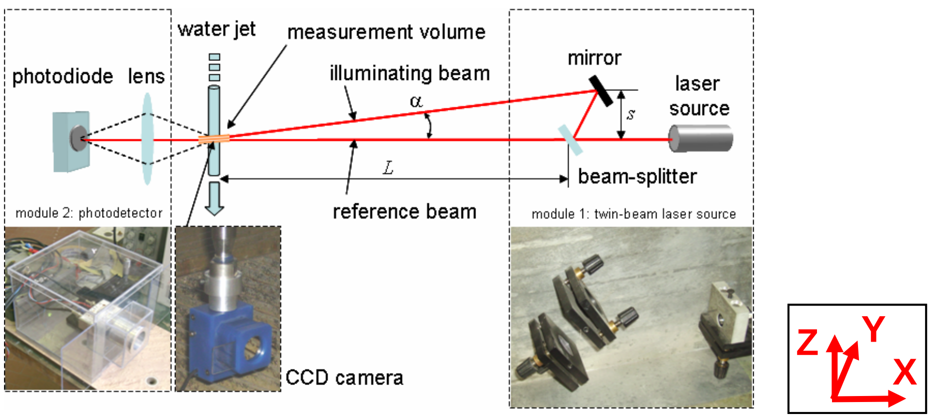

Figure 1. Laser Doppler dual-incident-beam velocimeter developed at the Water jet lab of the Dipartimento di Meccanica of the Politecnico di Milano.

a) b) c)

Figure 2. Webcam clearance level W2 (a); positions of the mirror adjusting screw A (b); positions of the mirror adjusting screw B (c).

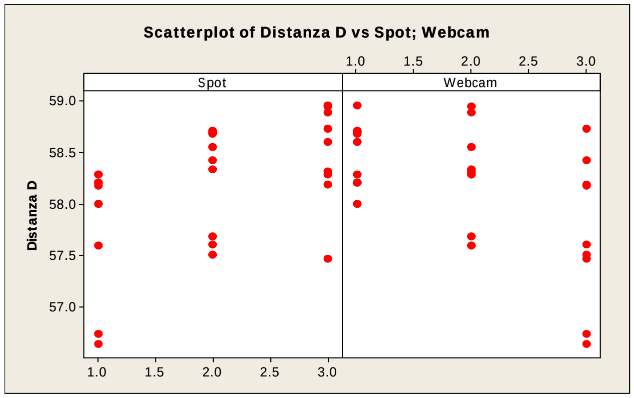

Figure 3. Scatterplot of fringes spacing vs. factors.

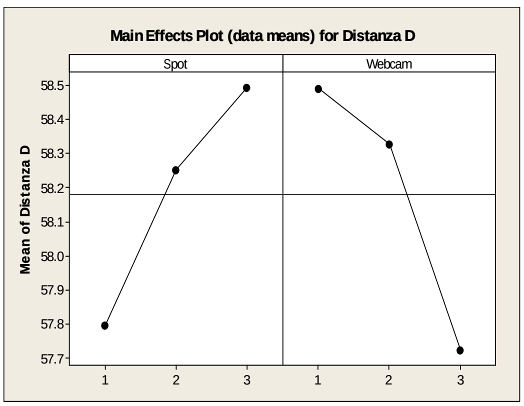

Figure 4. Main Effects Plot for δ.

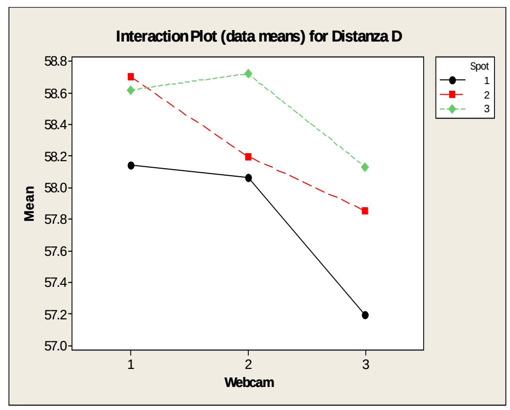

Figure 5. Interaction Plot of δ.

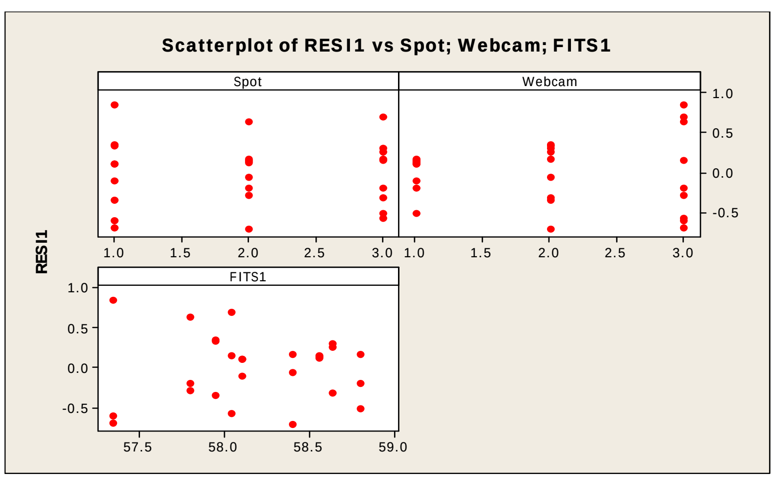

Figure 6. Residuals scatterplot vs. factors and fits (reduced model on δ).

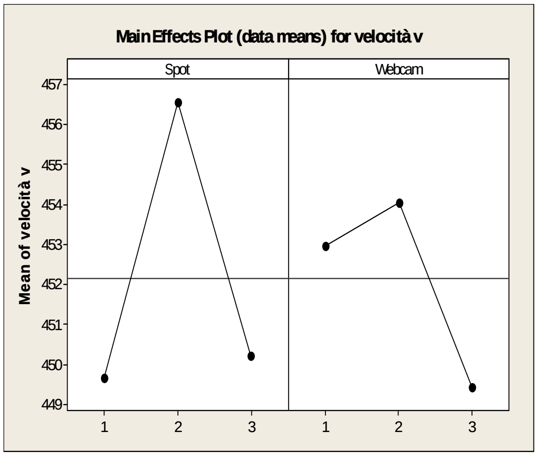

Figure 7. Main Effects Plot of *v*.

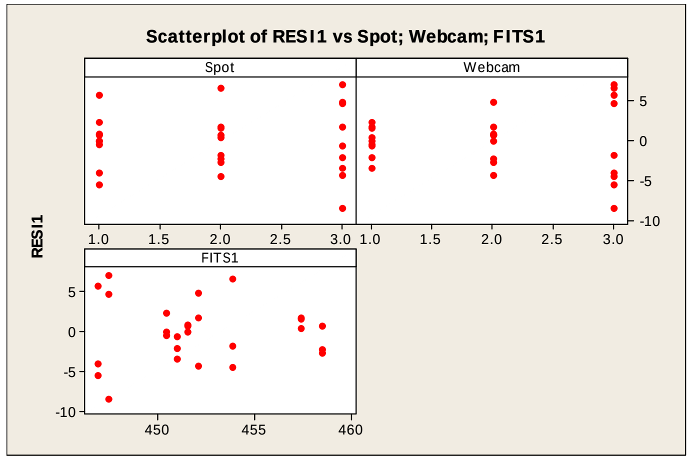

Figure 8. Residuals scatterplot vs. factors and fits (reduced model on *v*).