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EXTRACTING INFORMATION ABOUT COHERENCE IN JET FLOWS

V. Tesař*, V. Něnička*, J.Šonský*

Summary: *Several alternative approaches to processing flow visualization images were recently introduced by the authors. Their common feature is processing a sequence of 2D images to detect presence and evaluate development dynamics of vortical structures, which are recognised as regions that differ from the uncorrelated turbulent background in the processed pictures by their high negative values of correlation coefficient.*

1. Introduction

In the research project of the present authors, an essential task is to detect presence and evaluate development dynamics of vortical structures in jet flows – in particular in a jet impinging in perpendicular direction on a flat wall. The structures are formed in the mixing layer surrounding the core of the jet due to hydrodynamic instability of the flow. They have mostly helical character, initially quite regular but gradually fast disintegrating as they are carried away from the nozzle towards the wall. Their identification is made difficult by the surrounding chaotic turbulence of very high fluctuation amplitudes and relatively large scale of the turbulent eddies. Because of their unsteady character, the structures cannot be identified by the traditional method of statistical averaging, because they would be filtered away as if they were also turbulent.

Present authors have therefore develop their own method how to detect and study the structures. In principle, they process flow visualisation images obtained by scattering laser light on tiny water droplets, produced by water vapour condensation in the jet. The detection procedure uses the certain degree of coherence of the structures as opposed to stochastic character of turbulence: the structures are localised as regions of high negative coefficient of correlation between several images in a sequence.

2. Main features of the method

The method works with a sequence of monochrome images, each of them capturing a plane section through the jet. Their analysis is based on the idea of different rates of change of the identified object – helical structure - and of the surrounding chaotic motion. What is seen in the image is, of course, a plane section through the structure and the coherence means these cross-section areas do not change significantly between the individual frames of the sequence, taken at regular intervals of time.

The main task is to make these areas visually apparent. One of the basic steps is to convert the monochrome images into colour ones. This is done by processing the data of the

* Prof. Ing. Václav Tesař, CSc., RNDr. Václav Něnička CSc., Ing. Jiří Šonský. Ústav termomechaniky Akademie věd České republiky v.v.i.; Dolejškova 5, 182 00 Praha 8; tel.: +420 2 6605 2270, e-mail: tesar@it.cas.cz

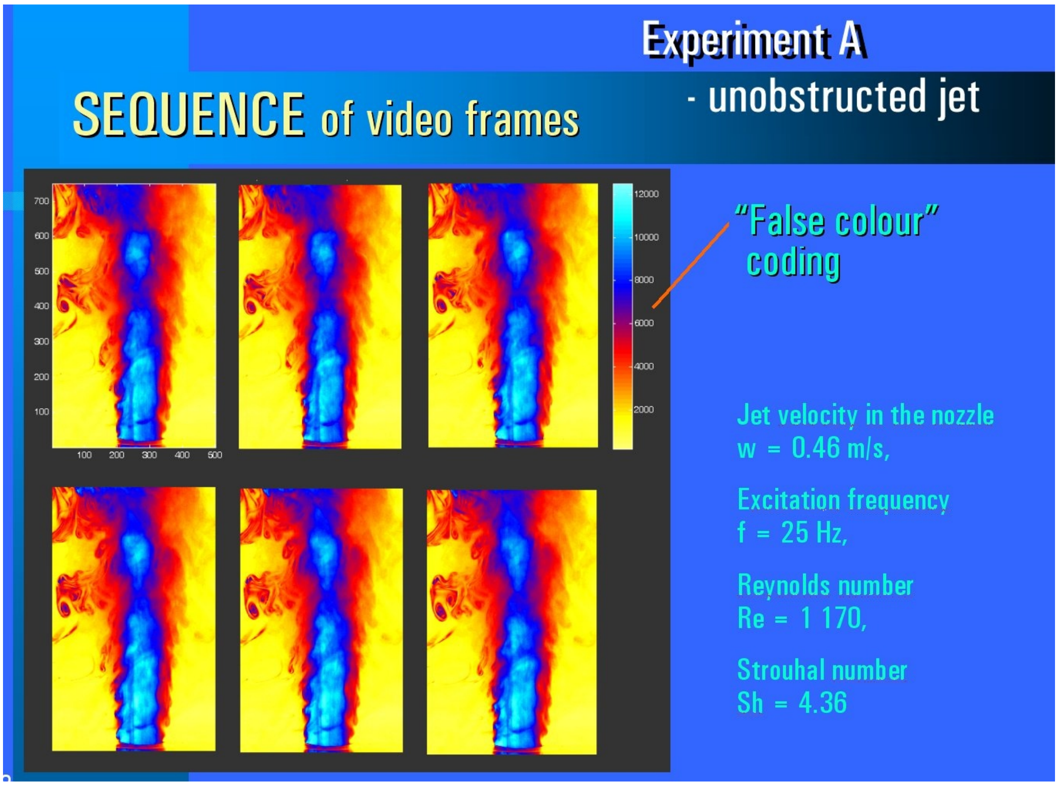

Figure 1 An example of image sequence obtained by fast camera recording of light scattered on water droplets in the "laser knife" section through an excited jet (issuing from nozzle exit of diameter 40 mm). The frames are presented in false colours allotted according to the colour bar to the various levels of the intensity of recorded light.

image in the form of a matrix of numerical values at each camera pixel. As shown in theexample of an image sequence in Fig. 1, showing recorded frames of an air jet periodically excited at relatively high frequency, the colouring is achieved by allotting to each intensity of light value an arbitrarily chosen false colour, following some one-to-one mapping function. In Fig. 1 this mapping function is presented in the form of colour bar.

Experience has shown that identifying visually a certain geometric feature, such as the area with particularly high absolute value of the correlation coefficient, may be not easy. It was found very helpful to change the continuous colouring scheme into a discrete one - by reducing the number of colours in the colour bar. This makes the individual areas in the image better recognizable. The procedure is called "posterisation". An example is presented in Fig. 2 on the next page. A jet picture taken from Fig. 1 is posterised by limiting the number of colours in the colourbar to only four. This makes the important regions of the jet more apparent. In principle, the advantage of posterisation is a strange effect: information contents of the image is in effect increased – and yet this is done by decreasing the number of colour bits (and therefore bits carrying the information).

Another alternative procedure in processing the images also used by the authors is called "apodisation" (the name meaning " removal of feet"). In general this name may be applied to removals in a more complex sense, but in the present context it is simply a removal of mean value evaluated for the sequence. Typically, as in Fig. 1, the sequence consists of six

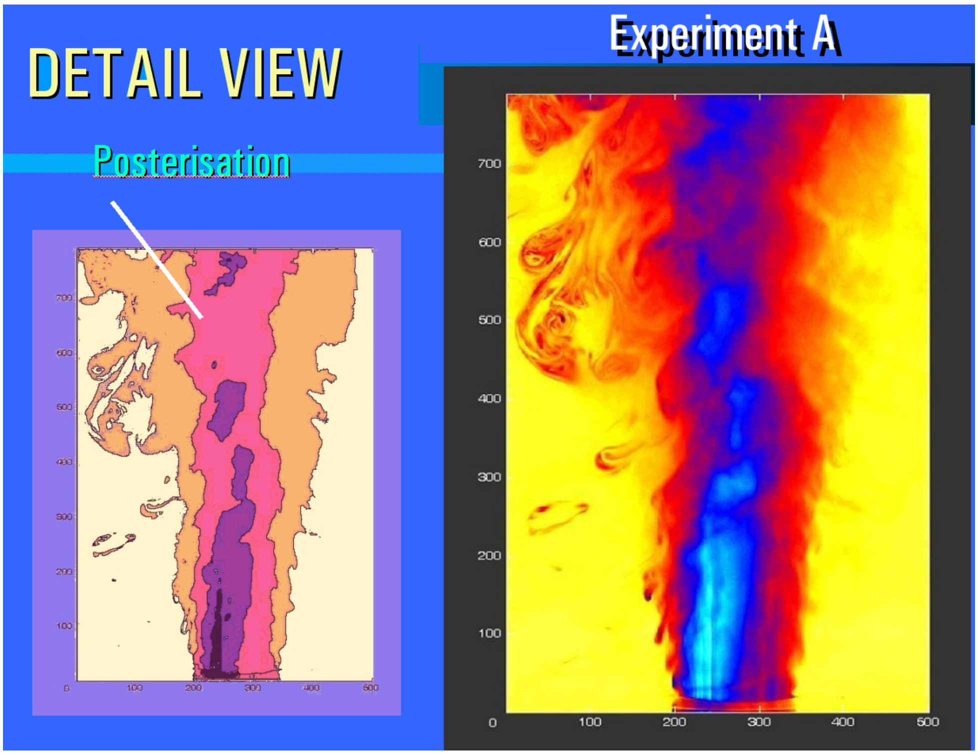

Figure 2 An example of one of the jet images from Fig. 2 processed by posterisation – drastic reducing the colour palette, here to mere four colours.

frames recorded at known instants of time and stored as six matrices. An element of the matrix is a number indicating the photographed intensity of scattered laser light. The apodisation processing of the data consists of evaluation of the mean value and then subtraction of the mean. First, all six values at an identical position in the matrix are summed. Then the sum is divided by six – with inevitable rounding off because the values are stored as binary values of relatively low order. When this result is subtracted from the value at the same position in a particular image of the sequence, the resultant difference indicates how fast the intensity of light there varies in time (because the time increment is constant). Again, a false colour coding is allotted to the computed values of the differences – which may be, of course, not only positive but also negative. An example of such evaluation of the local rate of change is presented in Fig. 3.

Of particular interest in apodised images are the areas coloured either light blue or yellow according to the colourbar in Fig. 3. These colours, at the end of the colour bar, are found at the locations where the photographed light intensity varies most rapidly. Because the water droplets in the air are very small, their motion relative to the air is minimal. The colour corresponding to the extreme ends of the colourbar therefore indicate the locations where there are high values of air velocity. Whether the result is light blue or yellow – i.e. positive or negative – depends on the direction (increase or decrease) of the change. In the example case of Fig. 3 there is no large coherent motion in the investigated jet. The image area is divided into a large number of small spots. This is due to the character of the particular flowfield which in this case is strongly distorted by the applied acoustic excitation – were the excitation missing, the jet at the quite low Reynolds number $Re = 1\ 170$ would be fully laminar, at least at the short distances from the nozzle, recorded in these images.

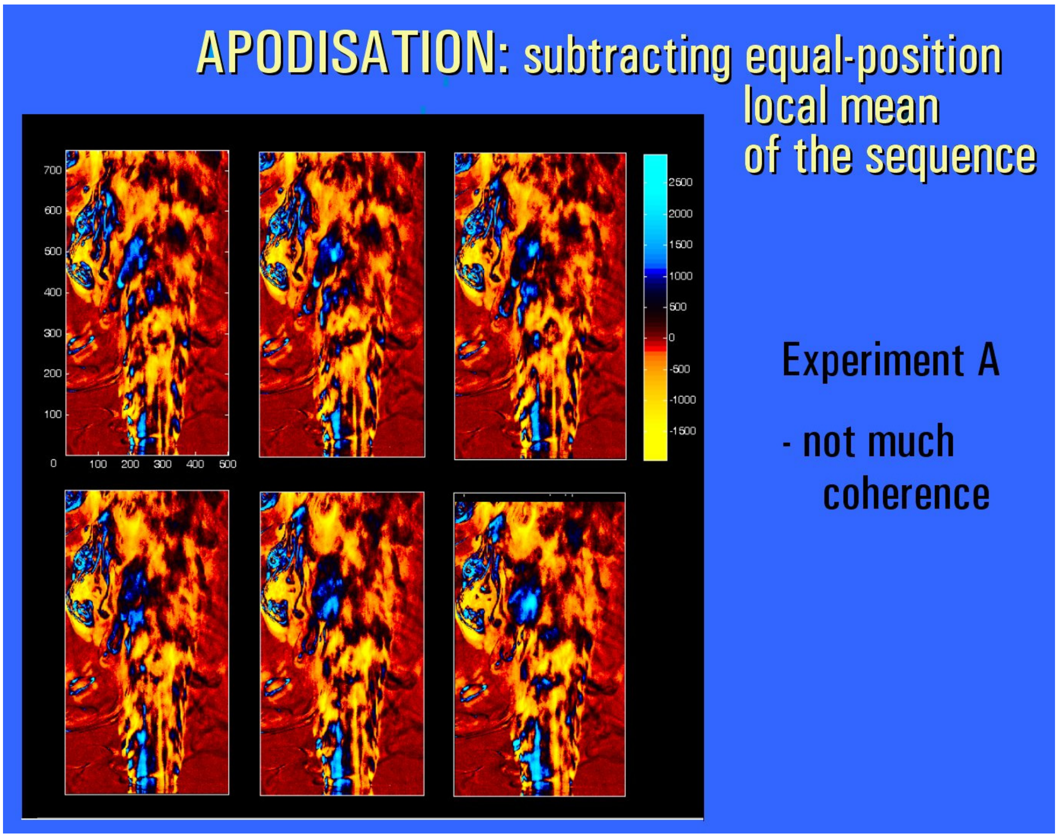

Figure 3 An example of jet images obtained by subtracting the local mean values of the sequence. The fast changing structures are revealed by extreme colours of the colour bar : light blue and yellow - depending on the direction of the change. Black coloured regions are stagnant; the dominant red colour of the background shows it is quite slowly changing in time.

Of course, the apodisation may be combined with the posterisation procedure. This is shown applied in Fig. 4: the apodised images from Fig. 3 were posterised - using five coloursin the colour bar. Because of the incoherent nature of the excitation effect, the areas generated by the posterisation are small and do not exhibit any simple overall impression – apart perhaps of the overwhelming presence of the yellow colour, which indicates the general upwards direction of flow of the jet.

There is yet another image processing method used by the present authors, which is actually the one that is of particular importance in the present context, It is evaluation of the correlation coefficient between a given pair of pictures. Again, as in the previous processing methods, the images are stored and handled as matrices and their processing is performed by taking each matrix element, one by one. The correlation actually uses pixels from the neighbourhood of the particular interrogated pixel. There are many alternatives as to the choices of the pair of images – and even more possibilities are offered by the possibilities of choice of the neighbouring pixels. Proper choice needs considerable experience which in this case was gained earlier by processing images of thermal plasma jets (Něnička, Hlína a Šonský 2005). Also for this method it may be useful to apply some combinations with other processing procedures – in particular, results that are often very interesting may be obtained by com-

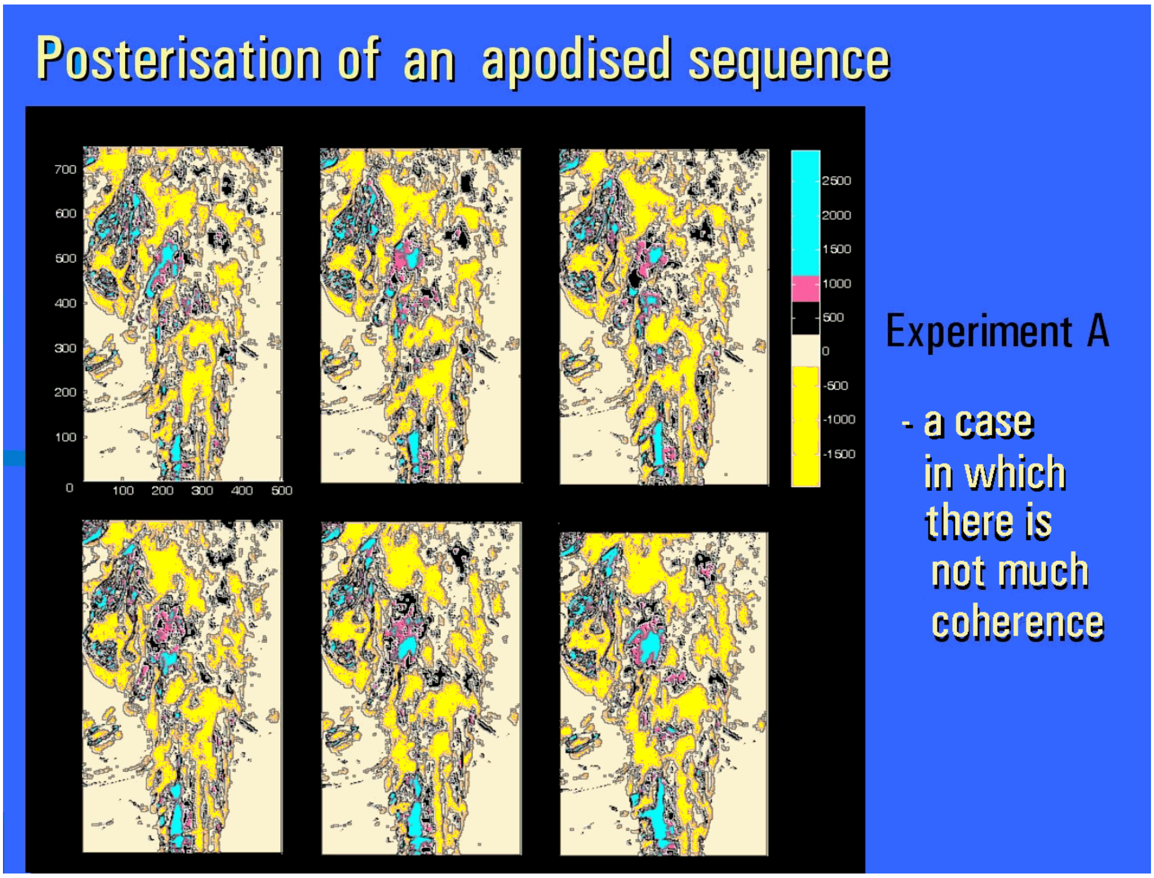

Figure 4 An example of jet images obtained from those in Fig. 3 by apodisation (subtraction of the local mean of the sequence) and subsequent posterisation. Apparent is the overwhelming change in the direction-coded yellow (i.e. with negative result of the subtraction) and only a few places in which there is (light-blue coded) opposite direction of the change. As noted in Fig. 3, in this case the high frequency of the excitation, in spite of the rather low Reynolds number (at which the unexcited jet would remain laminar), decomposes the jet into a highly incoherent flowfield. There is a small blue-coded elongated region immediately downstream from the nozzle exit, but the coherence there is simply a consequence of parallel character of the issuing flow.

puting the correlation between apodised images. Of course the results, again presented in the false colour coding, may be then posterised to make the detected coherent structures visually immediately apparent.

While in the example of Figs. 3 and 4 the highly excited jets did not show any large and significant coherent structure governing the flowfield, two other examples of weakly excited jet flows for another experiment B - in Figs. 5 and 6 – show a situation where the apodisation reveals interesting facts about the vortical structures in the investigated flow. In this case, the acoustic excitation was adjusted so that jet remained laminar when it leaves the nozzle exit and immediately downstream. Detecting the coherent structures may require more sophisticated approaches, but in the case presented in Fig. 5 the presence of an important structure is sufficiently demonstrated by mere apodisation. It shows a section through the structure in the light-blue colour slightly below the centre of the picture. The instability asso-

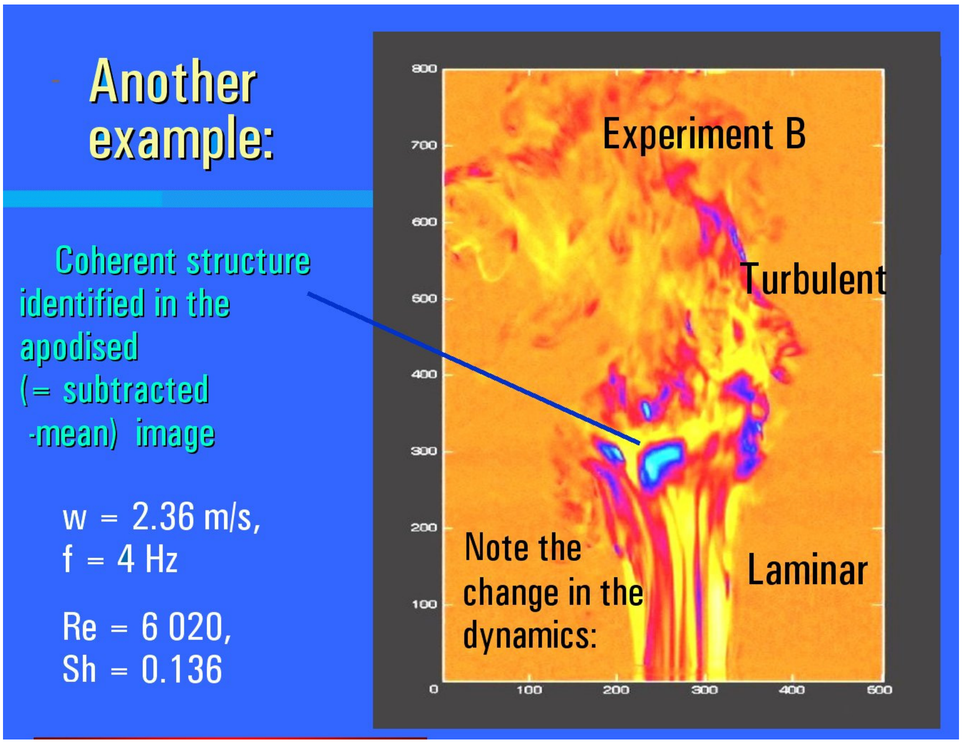

Figure 5 Another example – experiment B – with excitation at a lower frequency. The jet leaves the nozzle as a laminar flow but a hydrodynamic instability structure causes a rather rapid transition into turbulence.

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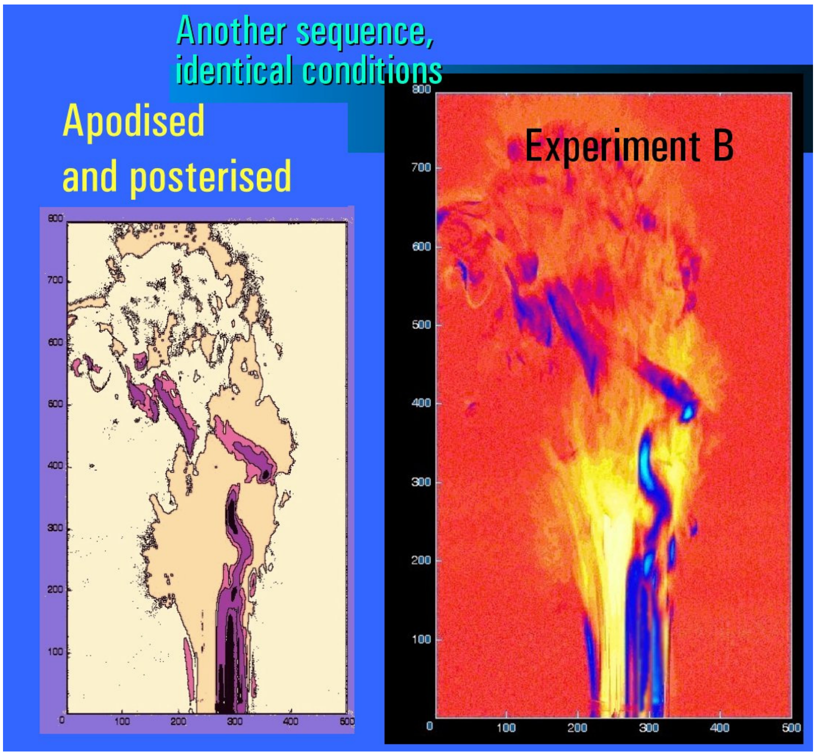

Figure 6 Another example – from a different sequence of experiment B – with instability structures clearly identified by the apodisation.

ciated with the structure causes a well recognisable change in the dynamics of the jet flow. Upstream from the structure the flow is clearly laminar and downstream from it its character is immediately recognised as turbulent.

3. Correlation method

More sophisticated – and also and for the visual identification more convincing detection criterion used by the present authors to identify the instability structures is the use of correlation techniques. This is based on using standard programs for evaluation of correlation between two vectors. The vectors are formed (see also Fig. 7) from the numerical values of the image matrix at a particular matrix element and it neighbourhood.

Let us assume a pair of images is stored as a matrix $\underline{A}$ for one frame and matrix $\underline{B}$ for the following frame. The matrices usually have the same number of elements, which are interrogated one by one. In the examples presented in this paper (cf. also the accompanying example in Fig. 7), for each interrogated pixel the evaluation procedure takes the surrounding 5×5 pixels. This selection leads to formation of the submatrix

$$\mathrm{sub}\,\underline{A} = \left[\begin{array}{c|c|c|c|c} A_{k-2,l-2} & A_{k-2,l-1} & A_{k-2,l} & A_{k-2,l+1} & A_{k-2,l+2} \\ A_{k-1,l-2} & A_{k-1,l-1} & A_{k-1,l} & A_{k-1,l+1} & A_{k-1,l+2} \\ A_{k,l-2} & A_{k,l-1} & A_{k,l} & A_{k,l+1} & A_{k,l+2} \\ A_{k+1,l-2} & A_{k+1,l-1} & A_{k+1,,} & A_{k+1,l+1} & A_{k+1,l+2} \\ A_{k+2,l-2} & A_{k+2,l-1} & A_{k-2,l} & A_{k+2,l+1} & A_{k+2,l+2} \end{array}\right] \qquad \ldots (1)$$

The comparison vector in the discussed examples was formed from the elements of this submatrix as follows:

$$\mathbf{A} = [\, A_{k-2,l-2},\ A_{k-2,l-1},\ A_{k-2,l},\ A_{k-2,l+1}, A_{k-2,l+2}, A_{k-1,l-2}, A_{k-1,l-1},\ A_{k-1,l},\ A_{k-1,l+1}, A_{k-1,l+2}, A_{k,l-2}, A_{k,l-1},\ A_{k,l},\ ,A_{k,l+1}, \\ A_{k,l+2},\ A_{k+1,l-2}, A_{k+1,l-1},\ A_{k+1,l}\,,\ A_{k+1,l+1}, A_{k+1,l+2},\ A_{k+2,l-2},\ A_{k+2,l-1},\ A_{k-2,l}\,,\ A_{k+2,l+1},\ A_{k+2,l+2}\ ]$$

and analogously in the comparison vector of the second frame there are

$$\mathbf{B} = [\, B_{k-2,l-2},\ B_{k-2,l-1},\ B_{k-2,l},\ B_{k-2,l+1}, B_{k-2,l+2}, B_{k-1,l-2}, B_{k-1,l-1},\ B_{k-1,l},\ B_{k-1,l+1}, B_{k-1,l+2}, B_{k,l-2}, B_{k,l-1},\ B_{k,l},\ ,B_{k,l+1}, \\ B_{k,l+2},\ B_{k+1,l-2}, B_{k+1,l-1},\ B_{k+1,l}\,,\ B_{k+1,l+1}, B_{k+1,l+2},\ B_{k+2,l-2},\ B_{k+2,l-1},\ B_{k-2,l}\,,\ B_{k+2,l+1},\ B_{k+2,l+2}]$$

The correlation coefficient R is then computed as

$$R = \frac{\mathbf{A}\,\mathbf{B}}{|\mathbf{A}||\mathbf{B}|} \qquad \ldots (2)$$

Because of the multidimensional character of the actual comparison vectors, interpretation of the meaning of eq. (2) is difficult to imagine. Nevertheless, the basic idea may be gained from consideration of an extremely simplified example of vectors having each only two components. Such vectors, of course, may be interpreted as straight lines in plane – and this interpretation is presented in Fig. 9 for three extreme cases of the correlation coefficient R value being 1, 0, or -1.

The high positive values of R represents identity. This is a value evaluated by the correlation procedure for the situation where the values stored in the pixels of an interrogated

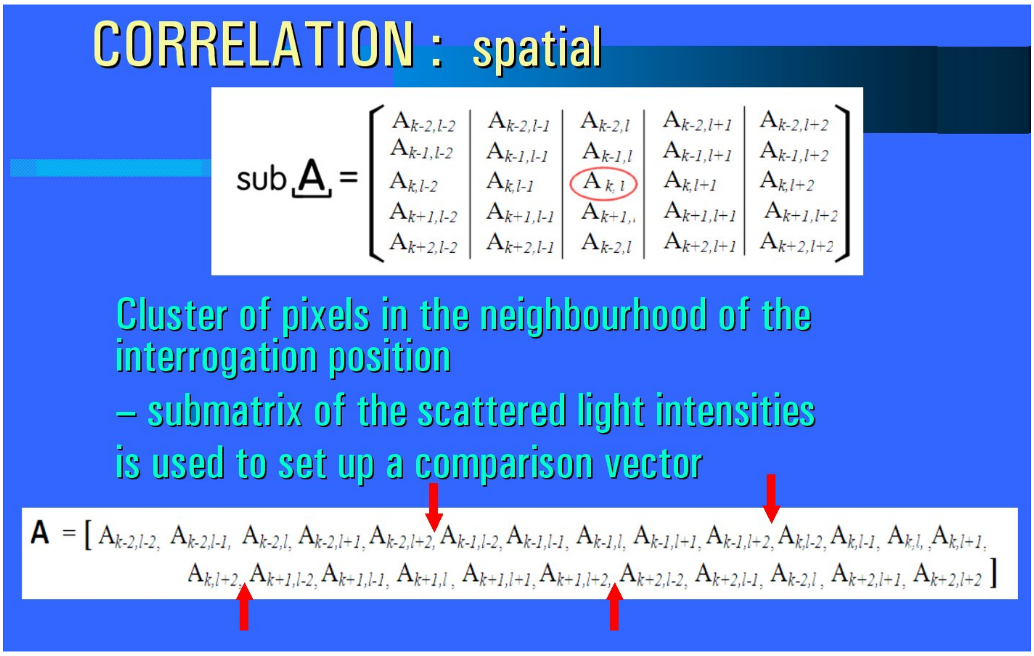

Figure 7 An example of generating the comparison vector to be processed by a standard library correlation algorithm. The interrogated pixel is marked by the red ellipse; the comparison vector is in this example formed from the values in the submatrix consisting of the 5 x 5 pixels in the immediate neighbourhood. The procedure is repeated for all the pixels in one frame.

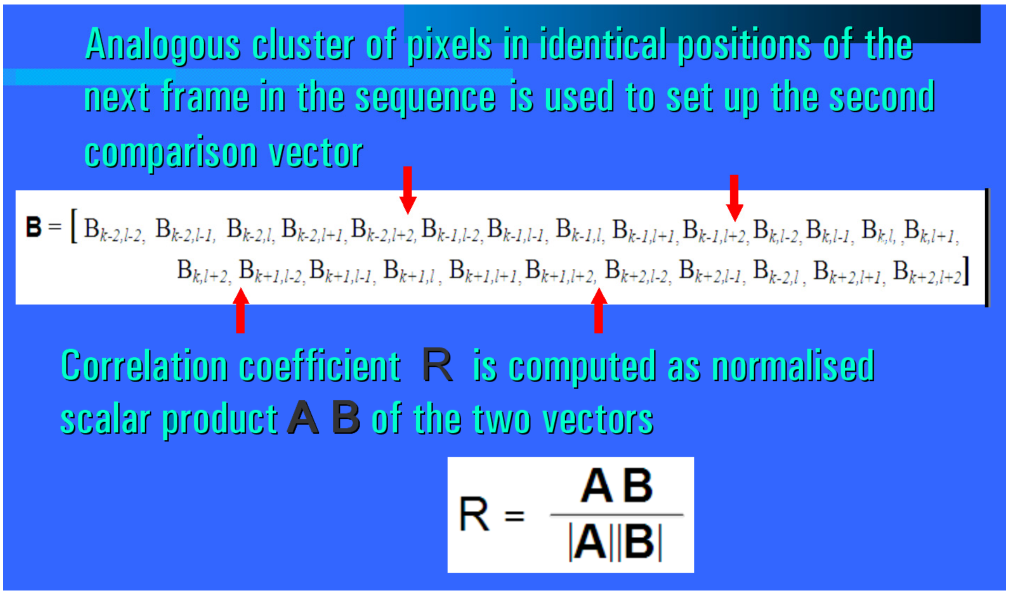

Figure 8 The same approach as in previous Fig. 7 is used to generate the comparison vector from the intensity values in the pixels of a second frame with which the first frame is correlated. Usually, the second frame is the one recorded later, either after the frame-grabbing period of the camera or, in experiments with external excitation, the frame recorded after the full excitation period. The correlation is evaluated by computing the scalar product of both comparison vectors.

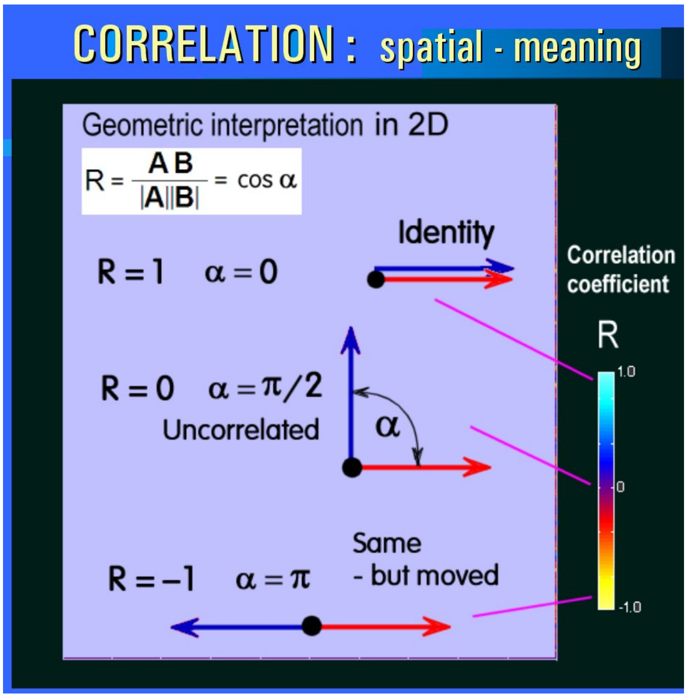

Figure 9 The meaning of the scalar product of the two comparison vectors from Figs. 7 and 8. Actual vectors in the present case have 25 elements and this makes difficult or impossible to represent the geometric relation. In this picture, for instructiveness, the process is explained on comparison vectors each having only 2 elements.

region do not vary during the two instants of time in which the frames were recorded. In Fig. 9 this situation, of R value being 1, the false colour coding allots to the particular interrogated pixel the light blue colour. Obviously, this is encountered in those areas of the frame in which the photographed object is the invariant background.

The zero value of R represents a situation in which the two vectors are mutually perpendicular – this means there is no correlation between them. The false colour coding allots to the particular interrogated pixel in which this condition is encountered the red (or very dark) colour. Obviously, this is encountered in those areas where there is an uncorrelated turbulence.

Finally, most interesting in the present context are the locations in which the comparison vectors from the two frames in the interrogation point are anti-parallel, as revealed by high negative absolute values of R near to –1. The corresponding areas are marked by the false colour algorithm in the bright yellow colour. This is usually indicative of coherent movement of instability structures. In particular, such a change is mainly found on the structure edges.

It may be useful to mention the considerable freedoms of choice associated with the correlation technique. By different choices of the pixels used for setting up the components of the comparison vectors it is possible to detect the direction in which the structure moves between two correlated image frames. The correlation may be also computed for the apodised pictures, obtained be removal of the local mean values of the sequence.

In particular, in their recent development of the image processing methods the authors use weighted correlations. These are characterised by the pixels distant from the interrogated ones given less weigh in the evaluation. In particular, a Gaussian weight function was found particularly useful.

Also possible is evaluation of temporal correlations – instead of generating the comparison vectors from the pixels spatially distributed in the neighbourhood of the interrogated one, it is possible to take selectively pixels from the same position in the matrix but from different time instants.

4. An example: impinging round jet

In an investigation of impinging jets with relatively short distance of the impingement wall (here at 100 mm, which is 2.5-times the size of the nozzle exit diameter), the jet was filled with water droplet particles that scattered incident light generated by laser with the cylindrical optics defining in the jet a meridional section plane. Of particular interest in this case of the flow are the vortical structures forming in the mixing layer on both sides of the jet core. In this location, the density of the water droplet particles gradually decreases from the high value in the core to the practically zero value in the nominally stagnant air surrounding the jet.

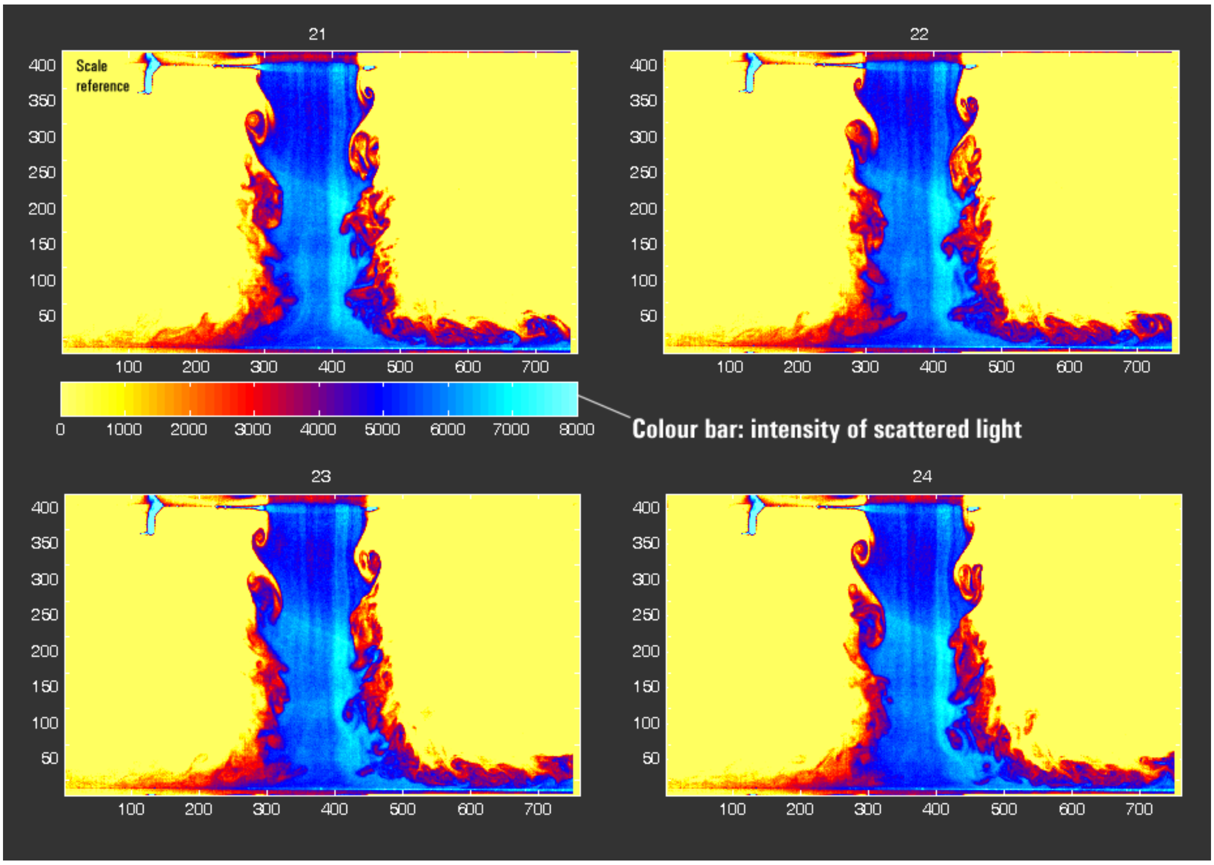

Figure 10 An example of the sequence of impinging jet images. The photographs record intensity of scattered light in the “laser knife” section through the jet with colours allotted according to the colour bar scale: absence of the scattering droplets is shown in yellow colour, high volumetric density of particles is shown in blue colour.

The frames shown in Fig. 10formed a sequence with 90 deg phase separation in the periodic process of vortex formation: the frame Nr. 21 was taken at zero phase shift, Nr. 22 at 90 deg shift after the beginning, Nr. 23 at 180 deg shift and Nr. 24 at the phase 270 deg. From the different axial distances of the vortices on the opposite sides of the jet, it is evident that the structures have helical character.

In the next Fig. 11, the frames from Fig. 10 were processed by apodisation – the same as was discussed in association with Figs. 3, 5, and 6. Essentially the same procedure is also shown applied to the same set of original frames in the next Fig. 12. The difference between

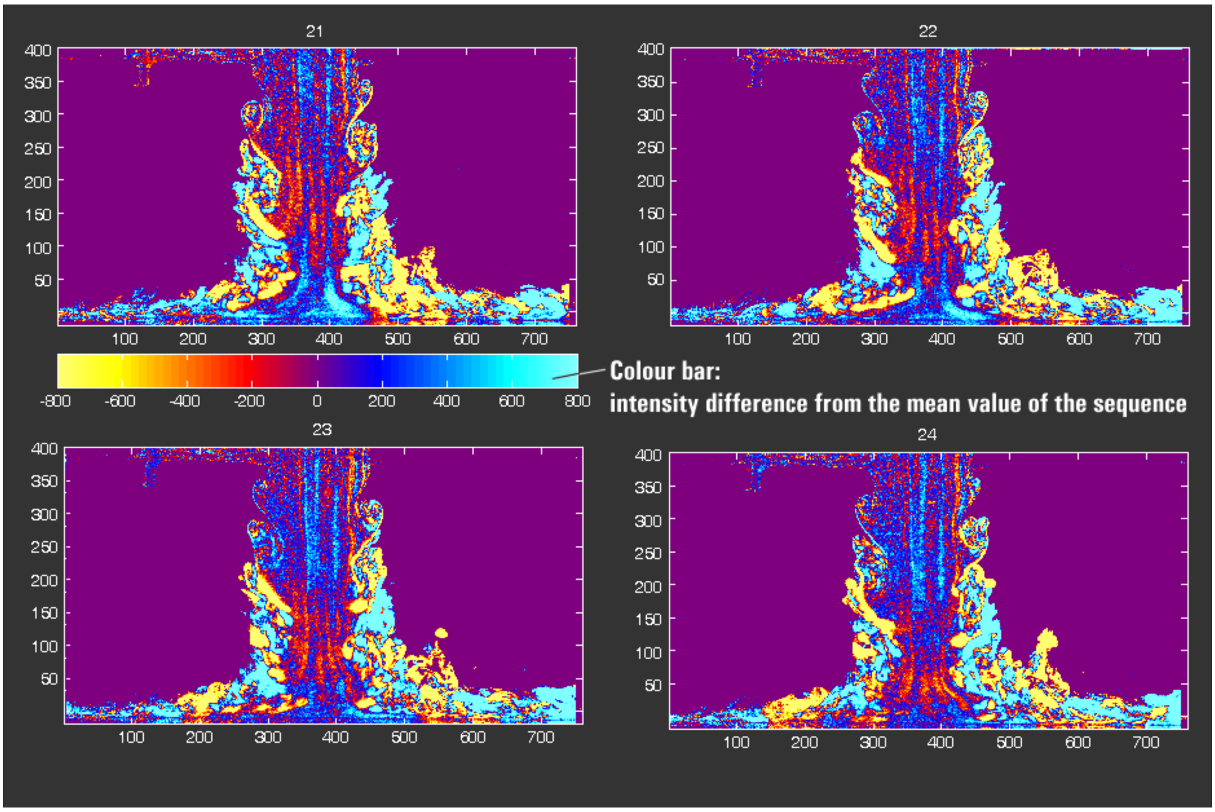

Figure 11 Result of apodisation (subtracting the sequence mean) applied to the four frames of the sequence shown in Fig. 10. The maximum values of the difference were chosen to be + 800 and – 800.

these two examples in the allocation function, characterised by the shown colour bar, is finer distinction between the details visible in Fig. 12. This demonstrates one of the freedoms that the processing of the frames has. Again, of particular interest in the apodised images are the regions with the extreme colours of the allocating colourbar – the light blue (indicating the large local positive change) and yellow colour (indicating the large negative change). Obviously, both these fast changes take place in the shear layer at the edges of the jet.

Figure 13 presents an example of extracting the demarcation lines between the colours and posterising the active colour palette to only two colour at the extreme ends of the allocation colour bar.

The last Fig. 14 then presents an example of computed correlations.

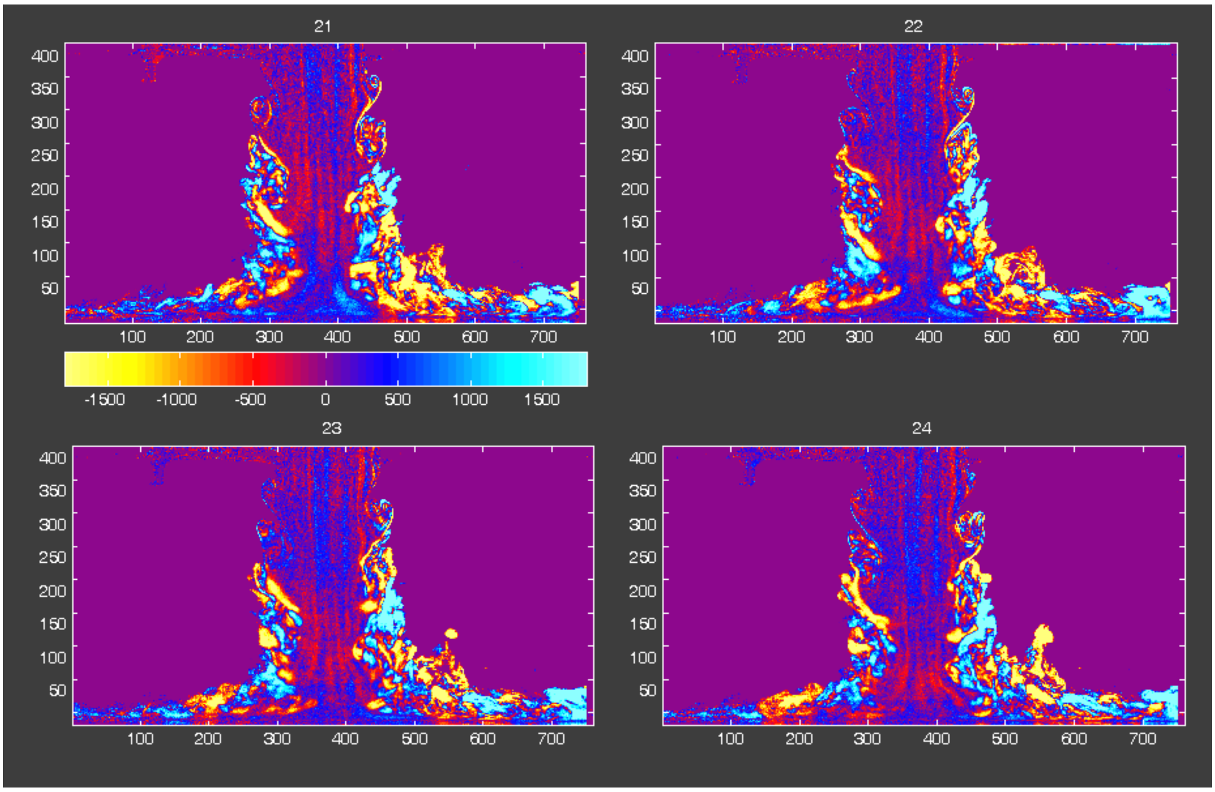

Figure 12 Result of essentially the same apodisation procedure, applied to the four frames of the sequence shown in Fig. 10 as in the previous Fig. 11, but this time with choosing a different allocation function, with the scale extended to twice as high maximum values of the differences, + 1 600 and – 1 600.

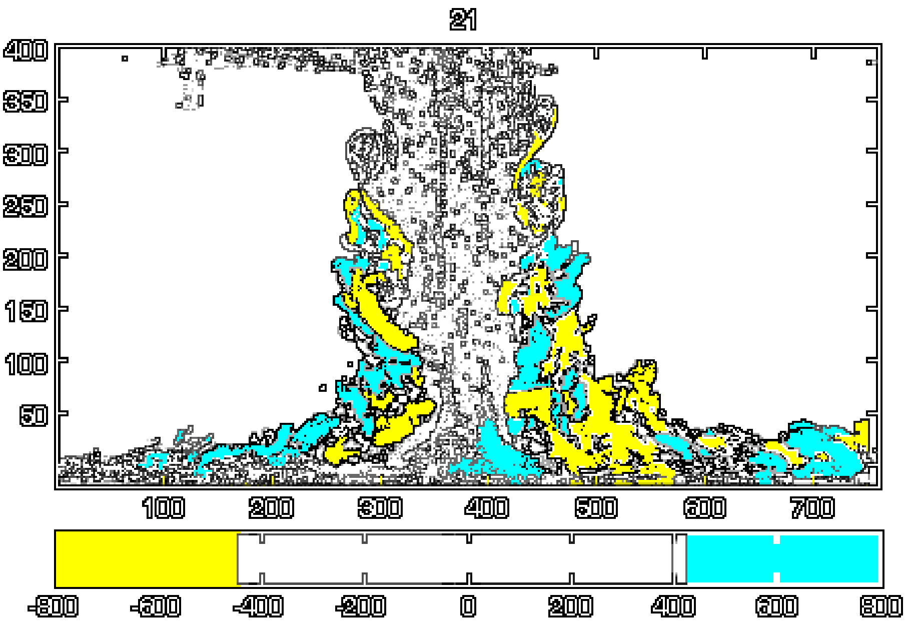

Figure 13 An example of application of the posterisation to an appodised picture of an impinging jet. In this case, the posterisation was applied to the frame Nr. 21 in Fig. 12. With other colours of the colourbar reduced to white, this result shows specifically the regions of fast changes.

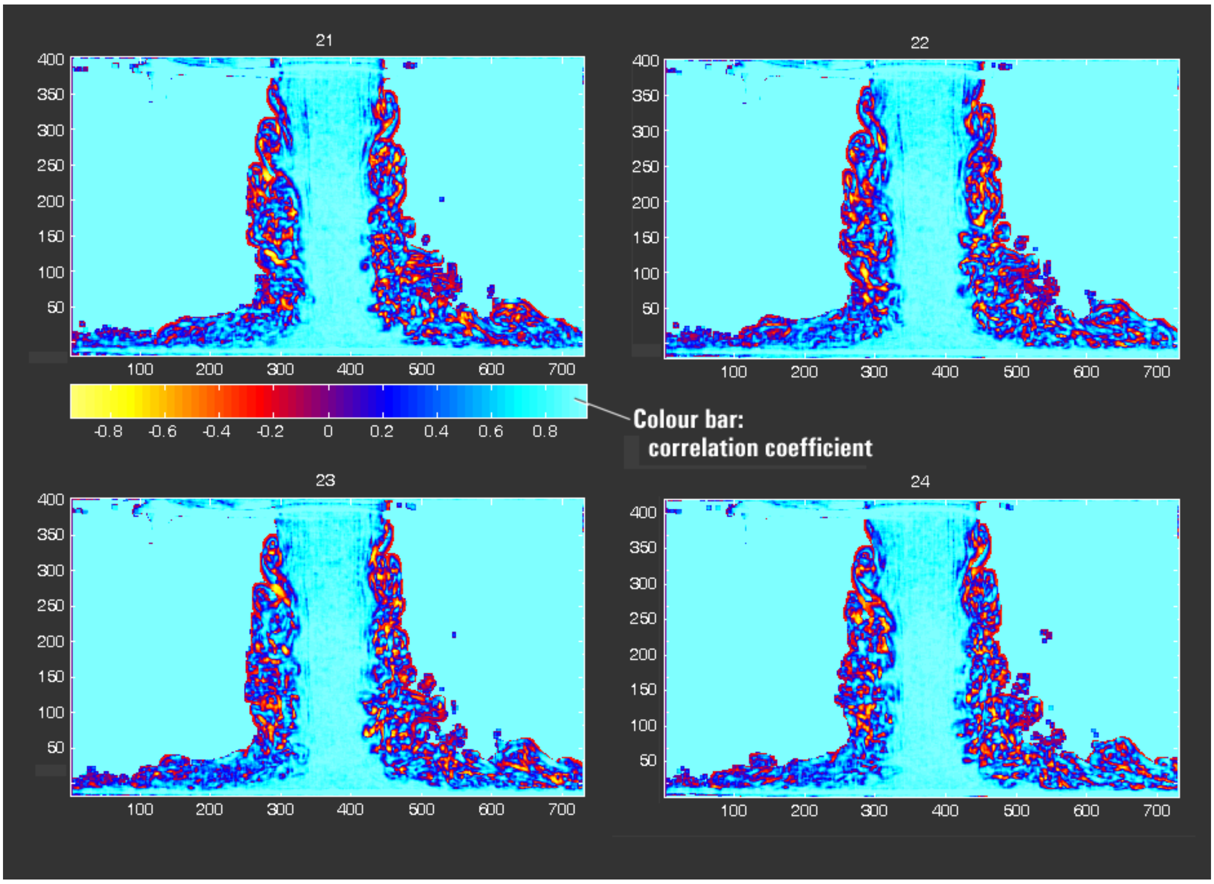

Figure 14 Processing the images from Fig. 19 by evaluating the spatial correlations between the neighbouring pairs of frames.

5. Conclusions

Paper discusses new image processing techniques introduced by the present authors for detecting instability structures in impinging jet flows and for evaluation of the dynamics of their development. The basic problem solved is how to extract an information about three-dimensional objects – in particular vortical structures – from two-dimensional flow visualisation images. The problem is made more difficult by the objects of interest appearing quasi-periodically (i.e. with large variations in the phase), being unsteady (moving as they are carried away with the flow), and submerged in stochastic turbulence that complicates even their mere identification. Because of the unsteady character of the detected objects, the turbulence cannot be simply filtered out by statistical averaging.

The discussed approach to solving these problems is analysis of the images using as the basic idea the difference in the rates of change of the identified object and of the surrounding chaos. Use of apodisation - subtraction of local mean values - and evaluation of correlation coefficients, supplemented by false colour coding and posterisation, can reveal interesting and significant information.

6. Acknowledgements

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