COMPOSED OPTICAL RECORDS TECHNIQUE

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ABSTRACT

The article introduces a new method of high-speed flows analysis – the Composed Optical Records Technique (CORT). The CORT principles as well as application possibilities are introduced. Three specific experiments focused on the issues of transonic aerodynamics (an oscillating airfoil, transonic instability in a turbine blade cascade and flow field periodicity assessment within a blade cascade) were carried out to provide the input data for subsequent CORT processing. Qualitative and quantitative CORT outcomes helped reveal some inexperienced flow field characteristics discussed in the text (the hysteresis of the shock wave oscillations, the transonic instability development, etc.).

INTRODUCTION

In the branch of experimental aerodynamics it is a commonly known fact that the possibility of the visual observation of high-speed flows is of significant value for researchers and helps them comprehend the nature of examined phenomena. Due to their essential principle – the change of the refractive index exploitation – the optical methods are extremely suitable for visualisation of compressible flows. Nevertheless, the most of the procedures employed to create a flow field image provide only qualitative information and the quantitative data have to be acquired by another manner.

Although a large number of measuring methods has been applied to the high subsonic, transonic and supersonic flows, there are still many theoretical as well as practical problems, the explanation of which is not within the scope of existing experimental techniques.

As the need for an efficient tool for specific features examination has been identified, a considerable effort has been made to create an instrument for the research of high-speed unsteady flow fields.

The new method provides original flow field depictions, through which the time or spatial connections between characteristic flow phenomena can be examined.

NOMENCLATURE

b	[mm]	…width
c	[mm]	…chord
f	[Hz]	…frequency
h	[mm]	…height
M	[1]	…Mach number
M_{2is}	[1]	…isentropic outlet Mach number
M_∞	[1]	…free stream Mach number
t	[mm]	…pitch
y_s	[mm]	…distance from the airfoil
α	[deg]	…angle of attack
α_1	[deg]	…inlet angle
α_2	[deg]	…outlet angle
δ	[deg]	…streak deflection

CORT INTRODUCTION

Composed Optical Records Technique represents a brand new approach to the analysis of the high subsonic, transonic and supersonic flows by means of optical methods of visualization [1].

The CORT ground lies in the exploitation of movie sequences depicting unsteady phenomena. It is obvious that a photograph – without any reference to its quality – allows a global insight into the flow field with all its features. (Certainly, the amount of visible details is given by applied system of visualization.) So the experimentalist gains a clear notion about the flow nature at a given instance.

There are some limited manners how to presume instabilities from a single picture. However, even though such a deduction is possible, the final assessment is merely a prediction of unsteady processes around an investigated body. Without a set of photographs it is not possible to acquire information about time dependence of the instable phenomena. Generally a photograph is an unsuitable form of results depiction when there are changing objects in the case.

On the other hand, movie sequences significantly extend the limits of analysis for they enable researchers to observe feature development in time. But it has to be pointed out that any movie sequence represents basically only a quick succession of photographs (projected usually at the speed of 25 frames per second).

One of the most important merits of optical methods lies in providing an all-encompassing view into the area of interest. Logical consequence of such an observation is potential information overloading of any observer when the images are too complicated as particularly transonic flows around aerodynamic bodies are quiet frequently.

Complexity of every single image is often so high that it is impossible to monitor all aspects – defined on every movie frame by their shape, size, colour and position – and evaluate them precisely (qualitatively or quantitatively). Many facts can be then omitted or observed unconsciously because a human eye is not simply able to notice them. The analysis as a whole could be then considerably degraded or unutilised.

The essential attribute of any analysis based on the CORT is partly to reduce the amount of information examined during one cycle of the procedure. But the main aim is to create an image revealing data related to the time/spatial changes. Therefore, relatively small areas containing chosen subjects of interest are identified. Separation of such parts of the picture from movie frames and their subsequent putting together according to specific rules provide a new flow field depiction. This composed *single* picture (photograph) depicts then a characteristic feature and its time/spatial *development*. Thus, a sole figure makes available a scrutiny of processes in flow (restricted with certain time/spatial extent) for arbitrarily long period.

Certain analogy to this way of presentation could be find in diagrams but the similarity fades when more than one point is examined. Even in the case such as this, the facts are presented by means of point position and colour. Moreover, any spot of finite size is also defined not only by its shape but also by dimensions when the CORT is applied.

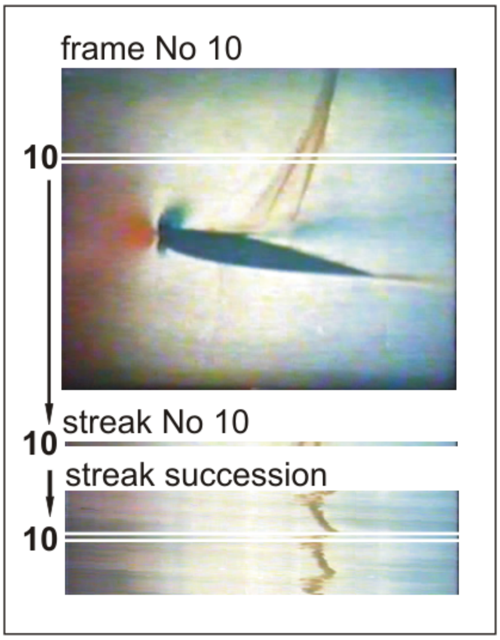


FIG.1: COMPOSED IMAGE COMPILATION.

Hence, the composed image provides much more information and remains intelligible at the same time.

Finally, it can be claimed that the composed flow field image reveals some information "beyond" a single movie sequence by offering an insight into the investigated area in both the time and space meanings.

CORT PROCEDURES

SELECTION OF EXAMINED REGION

At the very beginning of the CORT application a region with the subject of examination has to be specified. This early phase is of crucial importance for consequent processing because the amount of information contained in the final composed picture is determined exactly at this moment. The most significant aspect is the area extension. Basically two limiting cases can be defined. If a single point is selected, the only quality, which could be examined, is a colour change. An observation of the change of position would require definition of a streak in the direction in which the point movement would be measured. Further enlarging of the strip introduces another factors – shape and size variations. The second extreme is represented by selection of the whole movie frame. However, such a determination would result to exceptionally complicated composed pictures and all the advantages provided by the CORT, i.e. simplification and detail uncovering, would be dissipated.

So far the CORT testing has shown that the most suitable shape of the removed parts is a rectangular strip, the dimensions of which depend in part on the movie sequence quality, in part on the flow features themselves. Nevertheless, not only the strip size but also its placement and orientation have to be chosen.

COMPOSED IMAGE COMPILATION

The second step of the analysis is a compilation of extracted parts. At this point the processes diverge with respect to the analysis objectives.

If the examination is focused on unsteady features development, the parts of movie frames are lined up according a time succession as it is presented in Fig.1.

During the unsteady flows testing the time factor must be involved. It can be realised by means of reference time period related to the observed phenomena, e.g. the length of movie sequence expressed in seconds. This physical quantity is a source of quantitative information, for example for frequency examination of periodical processes.

Another CORT application, which has been tested up to now, is concentrated on the periodicity of flow field features. The flow periodicity in the test section with a multi-conduit model (e.g. a blade cascade) is discussed from the viewpoint of feature repetition "in space" or "in time".

The spatial periodicity assessment helps reveal model imperfections or flow deviations across the test section. In this particular case a single photograph is scrutinised and its parts are extracted from the geometrically corresponding places (Fig.2). Aligning of the streaks is similar to that one for unsteady flow analysis but the physical interpretation is completely different.

Certainly, the definition of deviations from periodicity is quite disputable. While the 100% periodicity is easy to define qualitatively, the basic question is how to quantify any deviation. It will be shown later that the definition of a reference dimension and a proper placement of a coordinate system are necessary. Possible solution can be the choice of the reference length (e.g. pitch t, blade chord c, etc.). The *y*-axis should be then placed parallel to the connecting line of leading edges at given position upstream the model (Fig.2).

A distance from the centre of coordinates expresses any shift of one observed point with respect to the other. If the distances are different, the measure of periodicity is given by a ratio of the maximum difference and reference length.

For clear understanding a simple example follows. Let the model consist of three profiles mounted – one above the other – into the test section at given even intervals. The chord length of the profiles is 100 mm. The two channels created by the model should be the same. Nevertheless, the photograph of the flow in the channels reveals different distances of corresponding points (for instance a part of the terminal shock wave) from the *y*-axis.

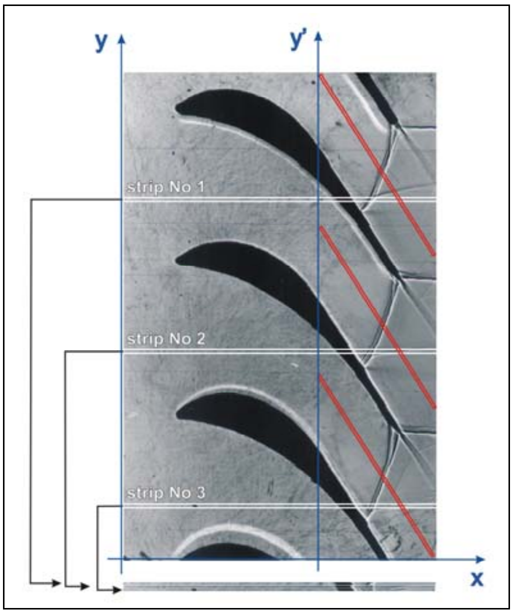


FIG. 2: CORT – PERIODICITY ASSESSMENT.

It is up to researcher to choose which dimension will be the reference one. In this case, the chord length is used for this purpose.

Let the distance between the terminal shock wave and the *y*-axis equal 150 mm in the upper channel. Suppose a value of 157 mm when the distance is measured in the bottom channel.
Then the maximum difference is 157 – 150 = 7 mm and the deviation from periodicity related to the chord length is 7/100 = 0.07 or 7% of the chord length.

The two possible elucidations are: the profiles are not of the same shape or are not mounted precisely (and inspection of the model dimensions should prove the fact) or the flow across the test section varies and boundary conditions should be revised. Combination of both the factors is conceivable as well.

In contrast to the previous case the "time" periodicity testing requires a movie sequence instead of a single photograph. For the proper examination a specific area is selected according to the previous section. Even the choice of the reference dimension is practised as it was introduced above. Actually, the time factor is involved by repetition of the spatial periodicity evaluation. The only fundamental difference is rooted in the fact that the analysis is applied to the corresponding strips in every movie frame. The maximum differences are evaluated from all streaks in the time period defined by the length of the sequence.

Resulting images are similar again to those of simple spatial periodicity analysis and the procedure enhancing is realised by drawing a comparison of composed pictures related to the same sequence.

FURTHER PROCESSING

The composed image contains areas distinguished either by colour or by grey-scale shades. With respect to the shape and size of the extracted region, any coloured area represents a particular flow field feature. At this instant it must be pointed out that any composed image loses its relevance as a source of information if it is not carefully and systematically compared with the original photograph/movie sequence. Only then the proper interpretation of depicted lines and areas can be assured.

One of the main CORT objectives was not only to extend the range of qualitative data provided by optical methods of visualization but above all to acquire quantitative results, which are unachievable by standard experimental procedures. Suchlike study has to involve an appropriate mathematical tool necessarily.

Regarding composed pictures, every hue represents in fact a line across the image and its waveform could be investigated. Definitely, the Fourier transformation as a solution of the problem is apparent. The fundamental obstacle could be found in the definition of the particular line in the image. Problem solving is realised by selection of the points of the same colour or grey-scale tint. The research worker can practise the whole process by hand theoretically but the analysis would become extremely laborious. Therefore, the special software has been created.

Once a line within the composed image is selected, the use of Fourier transformation is straightforward.

CORT APPLICATION – OSCILLATING AIRFOIL

EXPERIMENTAL SET-UP AND MODEL

The experiment concentrated on an oscillating airfoil was carried out using a continuous transonic wind tunnel for single airfoils. The dimensions of the test section are 0.14 × 0.32 m.

The records were taken by means of the portable schlieren device, which is schematically depicted in Fig.3, and the high-speed camera, which was able to operate with the frequency up to 1000 frames per second.

A hydraulic oscillating device was placed on the outer side of the tunnel behind the aluminised window. The apparatus was used to generate harmonic oscillations of the model within the range of frequencies f = 1 to 45 Hz.

For the transonic flow filed investigation around a body in the test section the NACA 0012 airfoil was employed. The chord length of the model has been c = 0.1 m and the span has been delimited by the test section width b = 0.14 m, the centre of rotation has been placed to the position c_r = 0.3 (30%) of the chord length.

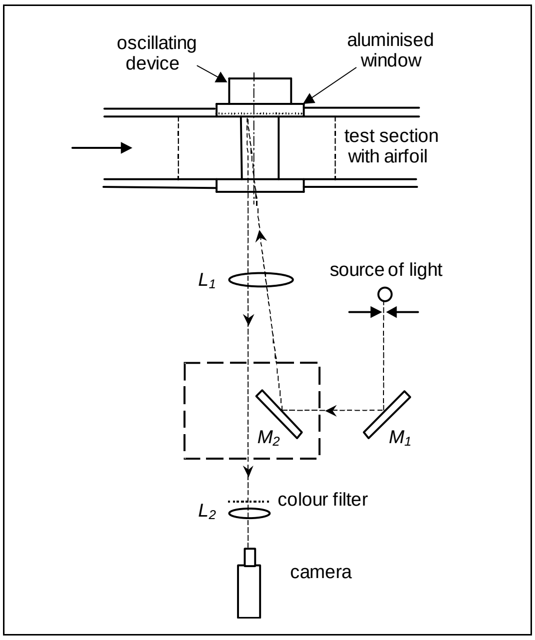


FIG.3: OPTICAL ARRANGEMENT FOR SCHLIEREN METHOD .

OPTICAL RESULTS ANALYSIS

Optical measurement results are represented by a movie sequence, which gives an idea about the flow development in the vicinity of the NACA 0012 airfoil oscillating under transonic conditions.

The boundary conditions were defined by the initial angle of attack α = 0 deg, the amplitude of oscillation $\Delta\alpha$ = ±3 deg, the free stream Mach number M_∞ = 0.9 and the frequency of model oscillation f = 30 Hz. The records were taken with the frequency f = 1000 Hz.

Detailed description of the flow field phenomena development is in [2]. There are three characteristic positions of the airfoil in Fig.4a-c for better conception of the flow nature.

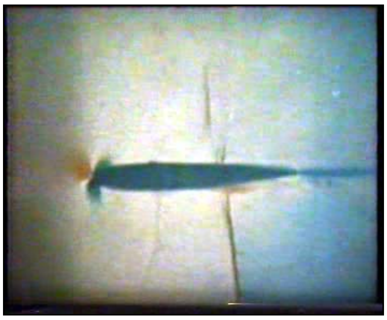


FIG.4a: BOTTOM DEAD CENTRE.

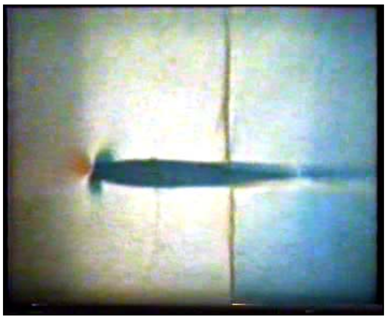


FIG.4b: CENTRAL POSITION.

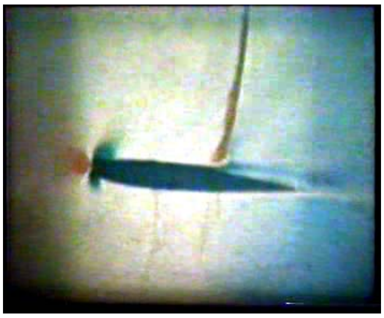


FIG.4c: TOP DEAD CENTRE.

CORT EMPLOYMENT

The main objective of the CORT employment was the examination of the shock wave response to the variable boundary condition.

At the beginning of the CORT application the regions of interest were defined within the recorded area. It was decided to determine three levels over the airfoil in order to examine the flow features variation with respect to the increasing distance.

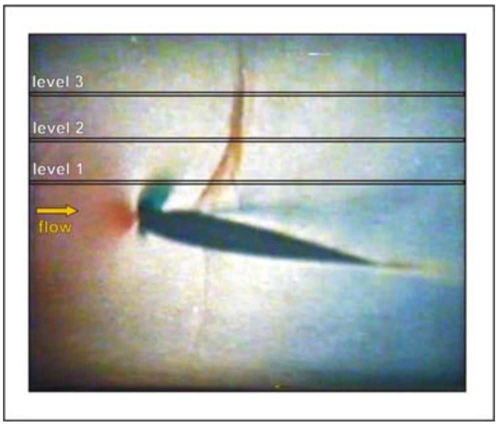


FIG.5: DEFINITION OF THE EXTRACTED PARTS.

The suction side was chosen due to the shock presence during the whole oscillation cycle.

The crucial factors affecting the CORT results have been identified in this case as follows: the free stream Mach number M_∞, the angle of attack α, the amplitude of oscillation $\Delta\alpha$, the frequency of model oscillation f, the streak height h and deflection δ and the distance from the airfoil y_s.

The rectangular streaks were extracted from every movie frame according to Fig.5.

The *x*-axis was defined in the free stream direction. Unfortunately, the centre of rotation could not be identified in the records and another suitable point – the leading edge – was scarcely visible in some positions. Therefore, the centre of the coordinate system was placed to the highest point of the upper surface in the top dead centre position.

For the analysis only the changes of the *x*-coordinate and the absolute values of the *y*-coordinate were relevant to the problem solution. The streak positions along the *y*-axis are registered in Tab.1.

level No	y_s [mm]	Δy_s [mm]
1	11.8	11.8
2	35.5	23.7
3	59.2	23.7

TAB.1: DEFINITION OF THE EXTRACTED PARTS; THE STREAK DISTANCE.

The height of the streaks was ruled by the thickness of a single row in the image (h = 0.5 mm). The streak deflection δ was set to respect the camera position towards the free stream direction. Such a correction required deflections δ = 1 deg.

The CORT outcomes related to the investigated regime are depicted in Fig.6. In the case of the oscillating airfoil the CORT results sheet consists of one figure (Figs.6a) depicting the terminal shock wave development at given distance y_s and two graphs (Figs.6b, c). Figure 6a introduces the composed image in which the "upstream" contour of the shock is examined. The products of the discrete Fourier transformation – the amplitude and phase shift dependence on the frequency – are in the diagrams in Figs.6b, c.

Regarding the CORT results sheet the following aspects could be examined:

- shock wave response to the model oscillation;
- shock wave position hysteresis;
- shock wave insensitivity to the angle of attack;
- shock wave intensity.

From the possible results the shock wave hysteresis has been chosen for further investigation.

The phenomenon has been revealed during the investigation of the level No 2. The scrutiny of the CORT results sheet (Fig.6) enable to unveil a relation between the shock wave position and instantaneous angle of attack. The first step of such a study is a definition of the shock wave position related to the chord at the particular angle of attack. The relative changes of the *x*-coordinate expressed by the red line curvature in Fig.6a are then measured for the period of one cycle. Figure 7 depicts the resulting graph in which the red arrows show the direction of shock wave movement during the model oscillation. The area circumscribed by the curve in Fig. 7 defines a hysteresis degree. In an ideal case with no hysteresis effect the curve would transform to a simple line. It is obvious that the shock wave hysteresis is nearly 10% of the chord length when c = 0 deg.

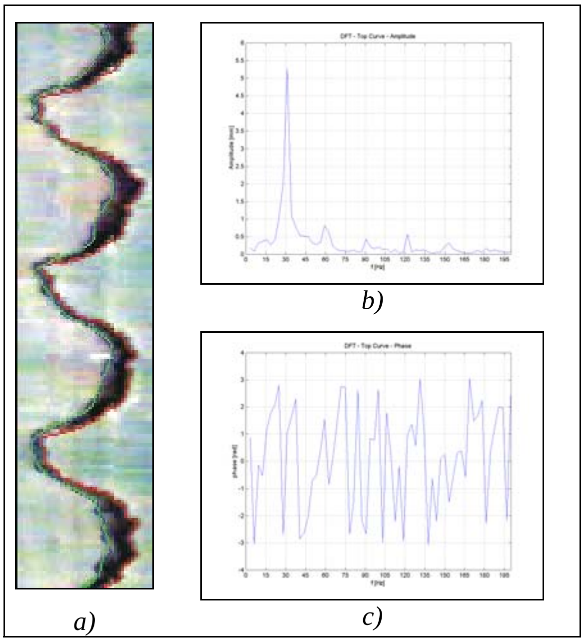


FIG.6: CORT RESULTS SHEET – OSCILLATING NACA 0012 AIRFOIL; level No 2 (y_s = 35.5 mm).

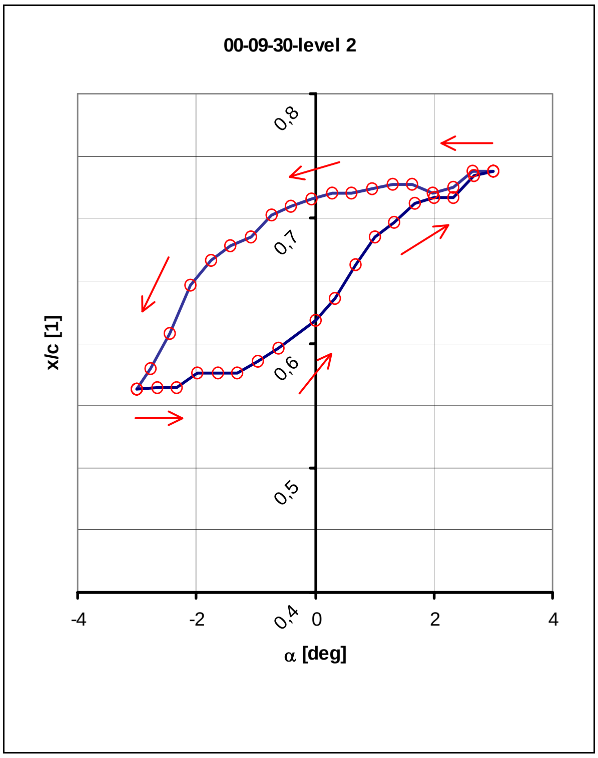


FIG. 7: SHOCK WAVE HYSTERESIS;
level No 2 (y_s = 35.5 mm),

CORT APPLICATION – TRANSONIC INSTABILITY

EXPERIMENTAL SET-UP AND MODEL

The experiments focused on the transonic instability recording were accomplished using a special transonic continuous wind tunnel designed for the examination of straight blade cascades (Fig.8). The tunnel has a test section of 0.1 × 0.4 m equipped with optical windows, which are suitable for the schlieren method employment.

For the flow visualisation the ZEISS 80 schlieren device was utilised. The ZEISS 80 was designed to visualise a circular area of interest with diameter of 80 mm. This technological restriction limited the number of inter-blade channels observed during one stage of the experiment.

The optical results were recorded with a standard colour video camera, which took the images with the frequency of 25 Hz.

A straight blade cascade composed of stator turbine profiles was used as an aerodynamic model. There were eight vanes mounted into the test section. The flow visualization was accomplished in the vicinity of the central (fourth) inter-blade channel.

OPTICAL RESULTS ANALYSIS

For the purpose of the CORT test application the optical results were taken under the following flow conditions: the inlet angle α_1 = 0 deg, the outlet angle α_2 = 75 deg and the isentropic outlet Mach number M_{2is}= 0.90 to 1.08.

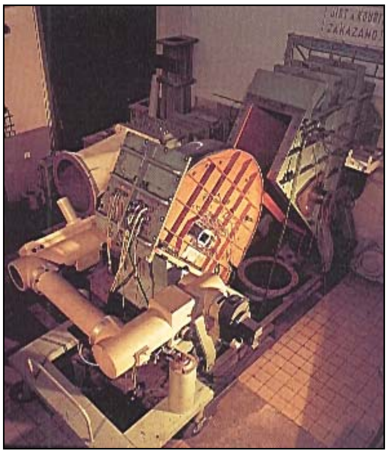


FIG.8: TRANSONIC CONTINUOUS WIND TUNNEL
& THE ZEISS 80 SCHLIEREN DEVICE.

The flow development in the central inter-blade channel was observed and recorded when the Mach number in the test section was gradually increased.

The examined area covers almost the whole inter-blade channel. Unfortunately, the vicinity of leading edges of the blades is not contained in the records. The trailing edge region is visualised in the upper left part of the image, where the first depicted blade is situated. The central part of the neighbouring blade is on the right. There is also a pressure probe visible in the bottom left part of the image.

The flow comes from above and copies the surface of the vanes. The flow direction is depicted by the yellow arrow placed close to the trailing edges (Fig.9).

During the increase of the inlet velocity it is possible to survey the progress of typical subsonic and transonic flow features.

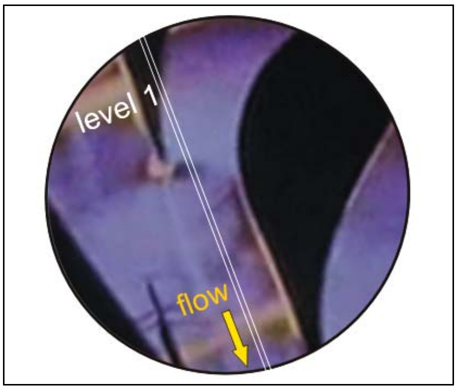


FIG.9: TRANSONIC FLOW PAST
STRAIGHT BLADE CASCADE.
M_{2is} = 1.08, α_2 = 75 deg

The terminal shock perpendicular to the suction side of the blade occurs when the outlet Mach number is approximately 0.85. The weak shocks have a dark violet tone. The separation point is at the spot of the shock and boundary layer interaction. The shear layer is depicted by a violet colour and the region of separated flow is grey. The wake is of a light blue hue.

The shock wave intensity increases according to the raising Mach number and it gets the same tone as the separated flow.

The transonic instability comes into view when the inlet Mach number reaches the value of 0.9. Although the inlet flow parameters remains constant, the response of the flow field in the inter-blade channel is unsteady. The phenomenon has been recorded at the regimes defined by outlet Mach number values M_{2is} = 0.90, 0.95, 1.00, 1.08.

CORT EMPLOYMENT

In the case of transonic instability the CORT application was reduced to examination of the shock wave oscillation by means of the Fourier transformation. Therefore, the level No 1 was defined in the middle of the inter-blade channel (Fig.9). The only independent variable, the influence of which was tested, was the isentropic outlet Mach number M_{2is}.

The *x*-axis was oriented in the stream direction at the outlet from the channel. The position of the centre of coordinates was not important for the instability investigation because only the relative changes of *x*-values and a constant *y*-value were taken into account.

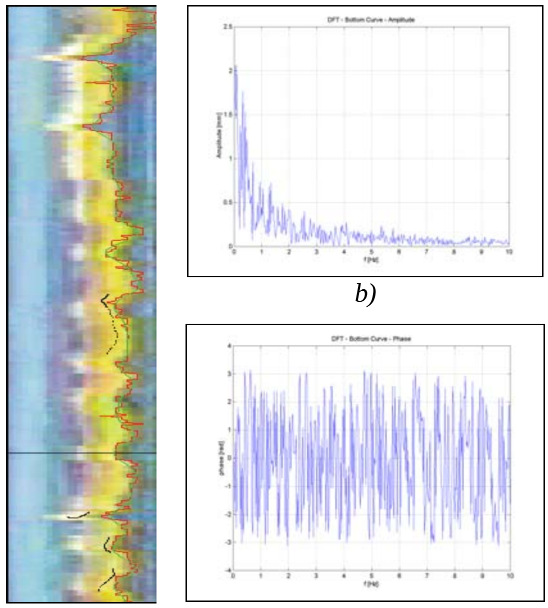
The height of the streak extracted from every movie frame equalled the thickness of a single row in the image h = 0.5 mm.

The outcomes of the analysis were arranged according to example in Fig.10. The composed image, compiled from extracted streaks, is presented in the left part of the sheet. The overview graphs are placed on the right. At the bottom of the CORT result sheet the amplitude of oscillation is mentioned.

In all investigated cases the amplitudes of the shock wave oscillations are relatively small; the maximum value is only 3.85% of the chord length. The graph in Fig.11 introduces the amplitude development with respect to the isentropic outlet Mach number. The growing trend of the amplitudes up to M_{2is} = 1, as well as the subsequent decrease (when the Mach number value is above unity) is supposed to be caused by the flow nature development across the transonic region. Nevertheless, no ultimate explanation could be formulated upon the outcomes of a single experiment. The existing survey of frequencies related to the maximum amplitudes does not reveal any noteworthy trend.

Finally it can be stated that the experiment proved the CORT capability to contribute to the issue of transonic instability.

Since the problems of transonic instability are scarcely discussed in the specialised literature – although the phenomenon is of major importance for the turbomachinery designers – the future CORT application to a series of optical results



a) b) c)

amplitude ± 2.04 % of the chord length

FIG.10: CORT RESULTS SHEET – TRANSONIC INSTABILITY.
level No 1, M_{2is} = 1.08, α_2 = 75 deg

taken under different flow conditions and employing different models seems to be highly advisable for the phenomenon understanding.

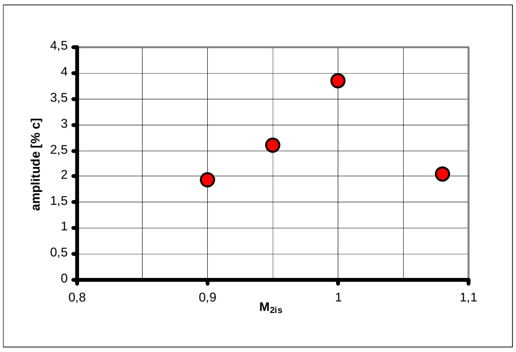


FIG.11: TRANSONIC INSTABILITY DEVELOPMENT.
level No 1, M_{2is} = 0.90, 0.95, 1.00, 1.08, α_2 = 75 deg

CORT APPLICATION – FLOW PERIODICITY

EXPERIMENTAL SET-UP AND MODEL

The basic experimental set-up for the spatial periodicity assessment of the flow was the same as that one for the instability investigation.

Instead of the schlieren visualization method the shadowgraph technique was used to record selected regimes of the transonic flow through a straight turbine blade cascade.

As a source of light the spark generator was employed. The distance between the model and the light source was set for 3.5 m.

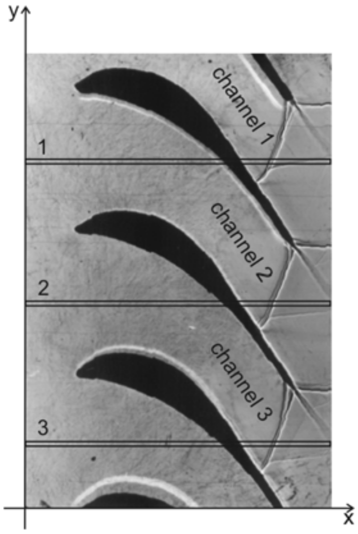


FIG.12: SHADOWGRAM OF THE TRANSONIC FLOW PAST THE SE1050 BLADE CASCADE.
regime No 1

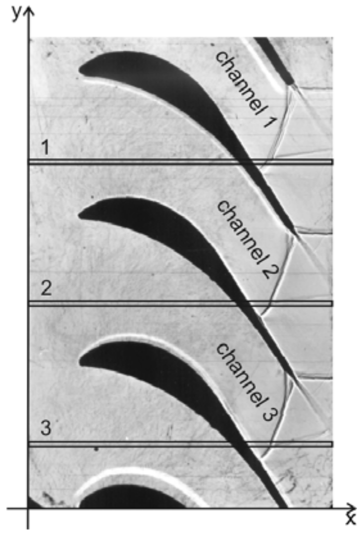


FIG.13: SHADOWGRAM OF THE TRANSONIC FLOW PAST THE SE1050 BLADE CASCADE.
regime No 2

For the flow field recording a special aerial camera was adapted. Contrary to the previous arrangement the method provided only single photographs.

OPTICAL RESULTS ANALYSIS

For the purpose of the periodicity assessment it was necessary to record several inter-blade channels in one picture. The photographs introduced in Figs.12, 13 depict five blades in the cascade. The experimental configuration allows observing of two inter-blade channels. The outlet part of the upper channel as well as the inlet to the bottom channel is depicted too.

The examined flows are characterised by the inlet angle $\alpha_1 = 0$ deg (regimes No 1,2), the outlet Mach number $M_2 = 1.13$ (regime No 1), 1.20 (regime No 2) and the Reynolds number $Re = 720 \times 10^3$ (regime No 1), 640×10^3 (regime No 2). The regimes have been chosen for their distinctive shock wave and wake definition.

The outer branch of the shock is formed on the suction side of every blade close to the trailing edge. The inner branch of the shock interacts with the boundary layer of the neighbouring profile in all channels. The shock reflection from the profile suction side is obvious. Unfortunately, the interaction between the shock and wake is not within the picture. It is possible to distinguish inhomogenous structure of the wake.

CORT EMPLOYMENT

The flow periodicity evaluation was focused on the inner branch of the shocks. Three levels were defined in Figs.12, 13 to delimit strips for composed images creation. The streaks placement was ruled by the geometrically same position with respect to the particular inter-blade channel.

Compilation of the streaks provided composed images as they are shown in Figs.14, 15. The spatial periodicity assessment was accomplished according to the description in section CORT INTRODUCTION. The profile chord c was chosen as a reference value in this case. The results presented in Tab.2 demonstrate that the maximum deviation from the periodicity was 3.4% c (regime No 1) and 2.6% c (regime No 2).

Considering these values it can be declared that the periodicity of both the flows is very good and no significant deviations occur in the region of the central part of the model, where the flow is usually investigated by means of another experimental methods. Nevertheless, it should be mentioned that only one aspect of the flow field has been investigated and more levels should be defined and examined for better evaluation.

FIG.14: COMPOSED IMAGE.
regime No 1

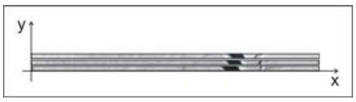


FIG.15: COMPOSED IMAGE.
regime No 2

REGIME No 1	s_{ref} [mm]	(chord length)	REGIME No 2	s_{ref} [mm]	(chord length)
reference length	70		reference length	70	
	s [mm]			s [mm]	
strip No 1	62.76	s_{min}	strip No 1	61.55	s_{min}
strip No 2	63.96		strip No 2	62.76	
strip No 3	65.17	s_{max}	strip No 3	63.35	s_{max}
$\Delta s = s_{max} - s_{min}$ [mm]	2.41		$\Delta s = s_{max} - s_{min}$ [mm]	1.80	
$\Delta s / s_{ref}$	0.034	(3.4% s_{ref})	$\Delta s / s_{ref}$	0.026	(2.6% s_{ref})

TAB.2: RESULTS OF THE FLOW PERIODICITY ASSESSMENT.

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