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TIME-RESOLVED ANALYSIS OF THE BASE REGION IN COOLED TRANSONIC TURBINE AIRFOILS

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Abstract. *High pressure turbine stages often work in the transonic regime. Hence the flow may be dominated by airfoil trailing edge shocks. In this paper, a detailed analysis of a test case representative of the trailing edge region of an airfoil is presented. The analysis has been performed reproducing the main characteristics of the flow field occurring at the blade trailing edge. The numerical campaign has been performed using the in-house HybFlow CFD code. Hybrid unstructured grids have been prepared for the selected configurations and special attention have been paid to the wake region discretization. The study started with the steady analysis with null and continuous blowing at several density ratios, on a round trailing edge representative of actual turbine blades. A main-flow Mach number of 1.5 have been initially considered to enhance the compressibility effects. The steady analyses allowed to evaluate the shock intensity variation increasing the coolant density ratio. Then, unsteady simulations have been conducted with both continuous and pulsating coolant at different frequencies.*

Frequency domain analyses have been performed and the results have been compared with each other. The obtained vortex structures have been also compared with the open literature results. Furthermore, shock intensity variations have been studied and their inclination monitored. For each frequency, the change in the shock intensity have been individuated and compared with the reference value obtained with continuous cooling. The results clarified the effect of continuous blowing on the flow field even far from the blade surface. Furthermore, uncommon vortex shedding structures have been individuated and discussed, depending on the coolant mass-flow rate.

1 INTRODUCTION

Concerns about engine noise and pollution has driven turbomachinery towards higher efficiencies. Efficiency amelioration is achieved as we deepen the knowledge of complex aerodynamic phenomena. Transonic stages result from the need to minimize the turbine size. An increase in the vane outlet Mach number from 0.9 to 1.2 leads to a drop in efficiency of 4%[1]. Furthermore, vane shock impact on the rotor blade boundary layer may result in an intermittent apparition of separation bubbles, abating the rotor performance[2]. On the other hand, rotor force can fluctuate at the vane paning frequency to amplitudes of the order of 70% of the mean level[3]. The shock system considerably modifies the flow field downstream of the stage, generating pressure and temperature oscillations.

Due to the high turbine entry temperature compressed cold air is used to internally cool down both vanes and blades. Part of this coolant air is used for cooling the external surface, while the remaining coolant is then ejected at the trailing edge into the airfoil wake. The continuous trailing edge coolant blowing at the trailing edge lowers the trailing edge region temperature level. Research has been carried out on the effect of continuous trailing edge cooling on the overall blade performance[4,5,6,7]. Coolant flow ejection interacts with the main flow, altering the base region pressure level with respect to the one evaluated in the un-cooled case. In transonic regime, the coolant ejection also changes the expansion waves and shock system. Previously performed analysis showed how the presence of a forcing term can change the vortex structures and generate exotic shedding[8].

The present paper is devoted to the study of a simplified geometry representative of the blade trailing edge. The tuning of coolant injection function parameters evidences how the flow field and the shock intensity are affected by the jet.

2 GEOMETRY AND NUMERICAL SETUP

In order to study the flow behavior at trailing edge, a simplified geometry has been prepared representing the rear part of the transonic airfoil. A 2D hybrid unstructured grid has been generated: 20 prismatic layers have been used for the boundary layer evaluation and a refined mesh has been created in the wake/shock region to better represent the shock system and the base region. The simulations are carried out with the in-house Hybflow URANS solver[4,11,12]. The solver has been validated for unsteady applications in transonic turbines[9,10]. The spatial discretization is performed by means of a compressible method density based finite volume with up-winding for the convective terms of the Navier-Stokes equations. The up-wind[13] approach is the Roe's approximated solver of the Riemann problem, where the solution is reconstructed at cell interfaces using the MUSCL approach, by means of least-square method. The turbulence is modeled using the standard $k-\omega$ by Wilcox[14]. The inlet total temperature was set at 365.2K and the wall temperature at 250K, which have been chosen according to the scheduled experimental test setup. Supersonic inlet conditions have been implemented in the solver and two values of inlet Mach numbers have been considered, Mach 1.2 and Mach 1.5 .

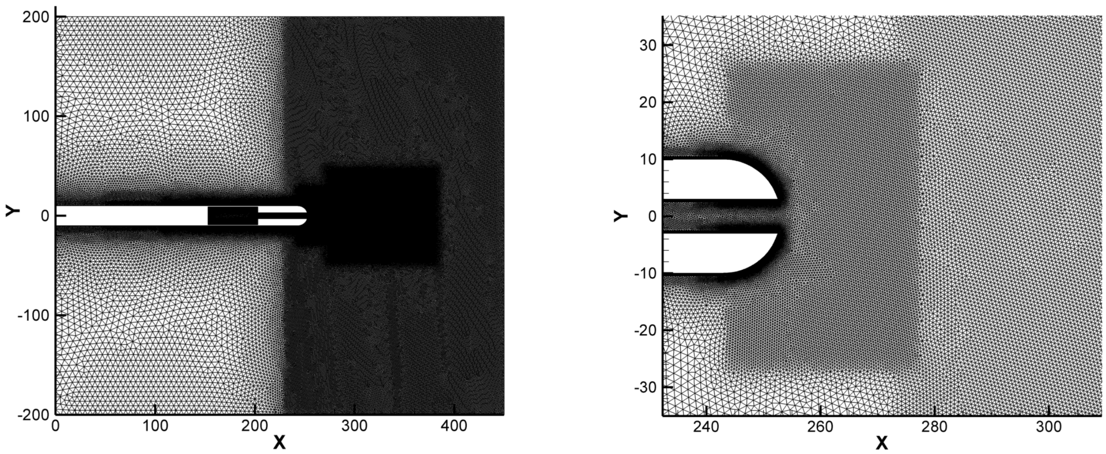

Figure 1: Geometry with rounded trailing edge (left) and detail of the grid refinement (right)

3 STEADY RESULTS ANALYSIS

A steady characterization of the trailing edge flow has been performed with different coolant density ratios. The main aim of this preliminary analysis is to understand the influence of the coolant mass-flow rate on the base region flow field and the shock intensity. The coolant density ratio is defined as $D.R. = \rho_c/\rho_b$ where ρ_c is the average coolant density at the midsection of coolant injection chamber and ρ_b is the average density in the base region. The operating conditions are listed in the table 1. The obtained density gradient magnitude is illustrated in figure 2 for the case at inlet Mach number equal to 1.5. Expansion fans occur at trailing edge curvature. At the interface between the shear layer delimiting the base region and curved trailing edge a lip shock appears. At high coolant rate, the lip shock joins the main one generated at the base region end. This is due to the increased thickness of the base region that decreases the curvature that the main flow sees at the trailing edge corner (see figure 3).

Mach	D.R.
1.2	1.60
1.5	1.09
1.5	1.18
1.5	1.39
1.5	1.76

Table 1: Operating conditions for the steady simulations

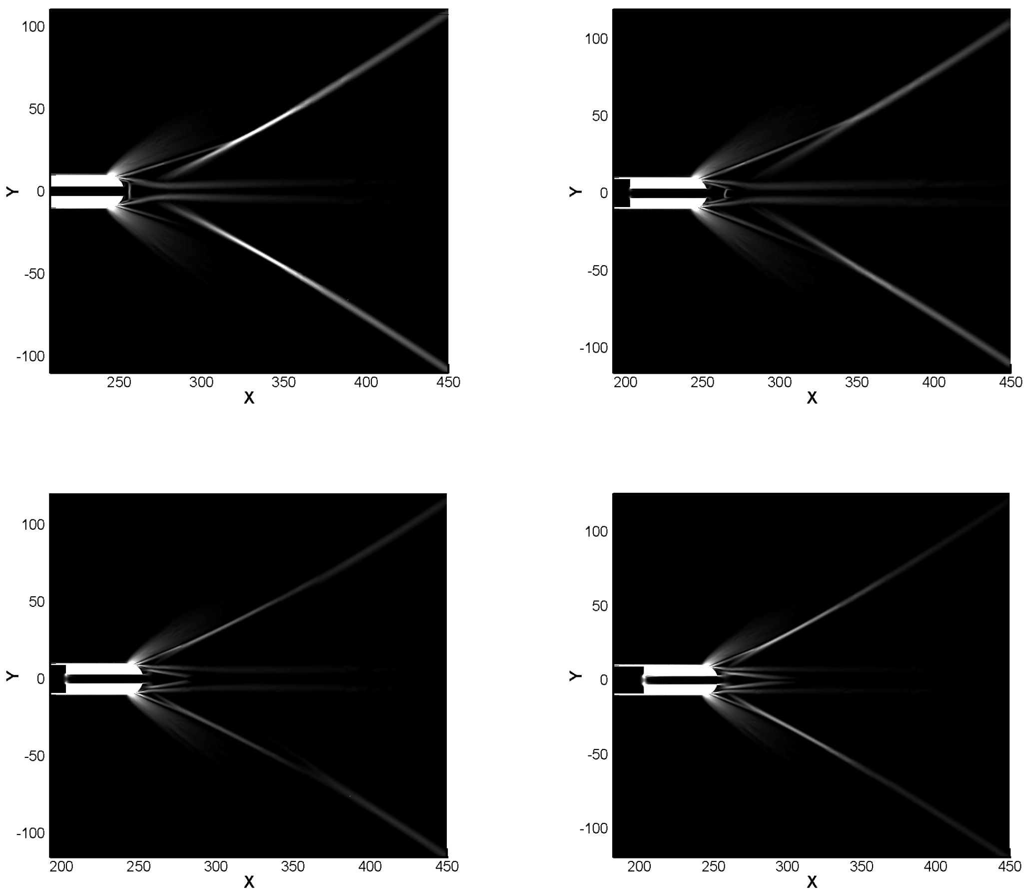

Figure 2: Density gradient magnitude for D.R.: 1.09, 1.18, 1.39, 1.76, (from left to right, top to bottom), $Mach_{in} = 1.5$

The intensity of the main shock decreases when the coolant blowing rate increases, as displayed by figure 4. The maximum of density gradient variation is divided by the value obtained for the the no-blowing case. The percentage variation of shock intensity is shown with respect to coolant to base region density ratio. The shock intensity variation is evaluated in a region far from the trailing edge. That section has been chosen since it is representative of the shock impingement on the adjacent blade. The shock reduction is very relevant with respect to the no-coolant blowing condition, up to 80% decrease for the higher coolant massflow rate.

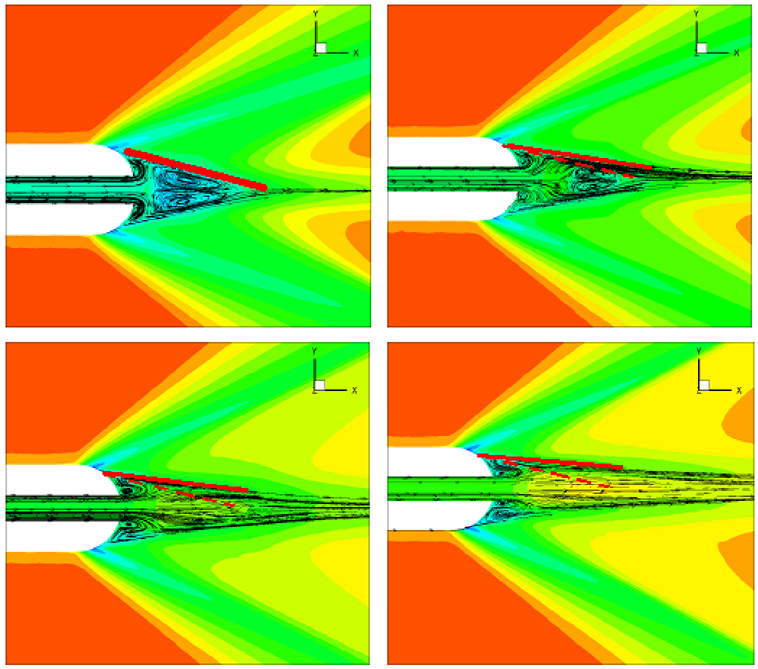

Figure 3: Pressure field and streamlines at $Mach_{in} = 1.5$, at the different density ratios.

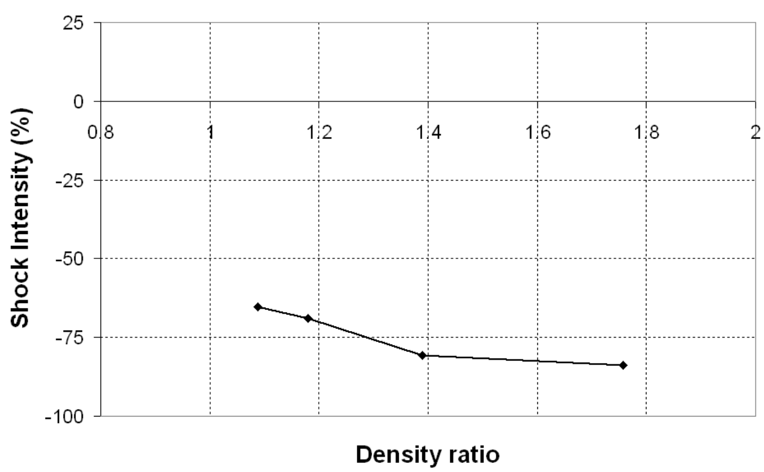

Figure 4: Shock intensity variation at $Mach_{in} = 1.5$

A lower inlet Mach number ($Mach_{in} = 1.2$) has been studied with one density ratio, to understand the influence of a lower free-stream Mach number on the the shock intensity reduction with coolant blowing. The shock intensity decreases also in this case and the same happens to the lip shock. At lower Mach number the effect of the coolant jet on the shock intensity reduction results to be higher, although the base pressure increase with respect to the respective no-blowing case is lower.

Mach	D.R.	ρ_b/ρ_b^*	Shock variation
1.2	1.60	1.32	-86.7%
1.5	1.39	1.44	-80.7%

Table 2: Comparison $Mach_{in} = 1.2 - 1.5$

4 TIME-RESOLVED ANALYSIS OF THE CONTINUOUS AND PULSATING COOLANT

Unsteady calculations with continuous and pulsating blowing of coolant have been performed on the configuration with $Mach_{in} = 1.2$. The boundary conditions applied to the coolant inlet is a function of stagnation pressure which is defined as follows:

$$P_{0c} = \overline{P}_{0c} + \Delta P \cdot \cos(2\pi f \cdot t) \quad (1)$$

where $\overline{P}_{0c}$ is the mean coolant total pressure, ΔP is the amplitude of the fluctuation and f is its frequency. The base configuration is that with $f_2 = 5$ kHz, $\overline{P}_{0c}$ corresponding to mean density ratio $\overline{D.R.} = 1.60$ and $\Delta P = 0.4$. The latter was chosen in order to have a minimum value of P_{0c} greater than the base pressure, neglecting the possibility of main-flow injestion from the base region into the coolant channel. Four frequencies have been tested for the jet pulsation: $f_1 = 1$ kHz,$f_2 = 5$ kHz, $f_3 = 10$ kHz and $f_4 = 15$ kHz with constant values of $\overline{P}_{0c}$ and ΔP.

4.1 Main flow pattern

The wake region vortical structures exhibit rather different patterns depending on the blowing rate. Considering the continuous blowing case, the coolant jet keeps the flows coming from the trailing edge upper and lower side separated, and their mixing happens only far downstream. The vortex shedding pattern is instead very complex when the coolant is pulsating. Figure 5 presents the density gradient field for a coolant pulsated at 1 kHz. The pattern is very similar at 5 kHz. Vortices shed both from the shear layer originated and from the coolant flow. Its pulsation can be interpreted as a forcing term for the generation of a vortex street. In fact, a non-negligible portion of the cooling flow departs from the main jet and generates a secondary vortex shedding. Further downstream the secondary vortex street is overwhelmed by the main one and they form a single vortex street. An evident difference from the von Karman vortex is that in this case the pairs are in phase and quite elongated. This behavior finds experimental evidence in the work by Carscallen and Gostelow[15].

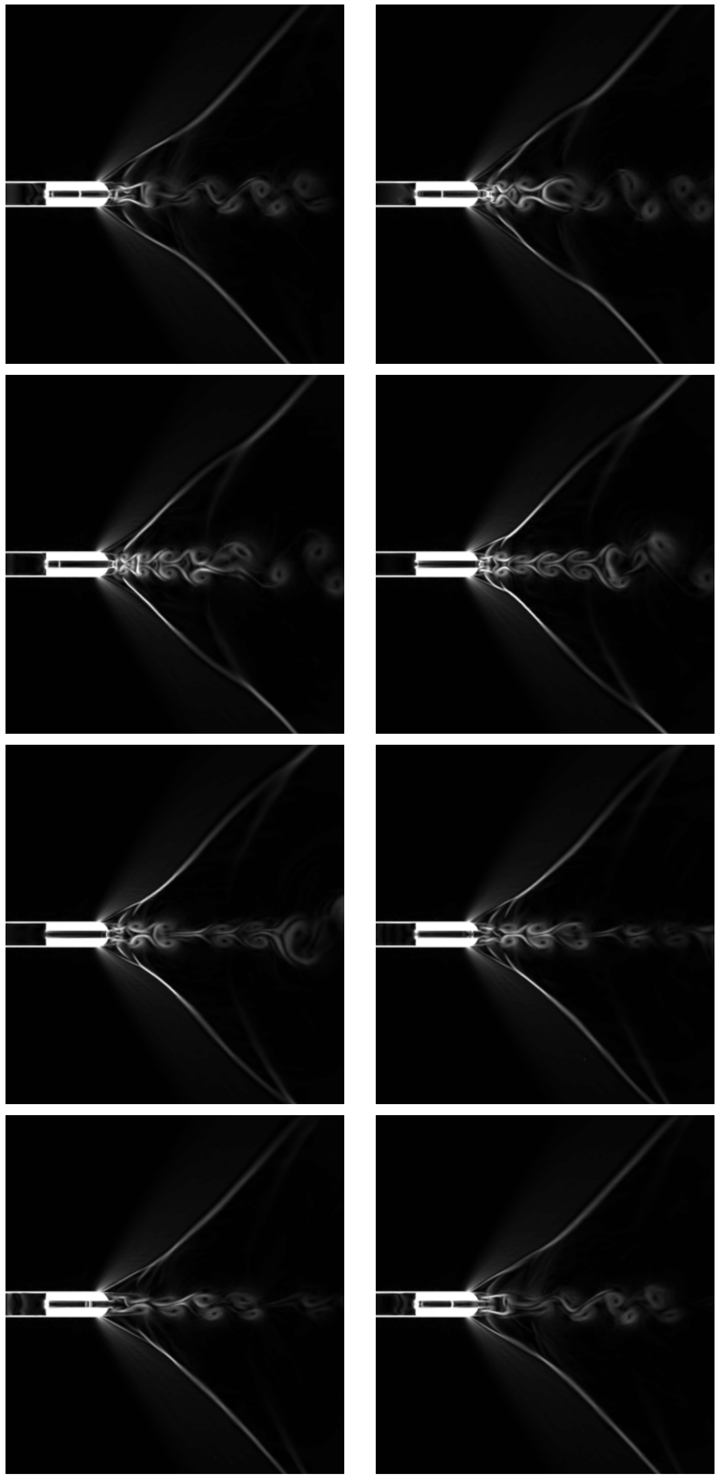

Figure 5: Density gradient magnitude field at trailing edge for $f_2 = 1$ kHz, 8 time steps in a whole pulsation period, from left to right, top to bottom

The complicated system of vorticity which originates downstream of the trailing edge strongly affects the shock and expansion fan system in this region. The formation of vortices changes the wake inclination that the main-flow sees at trailing edge end, thus changing the intensity of the expansion fan and the following shock that aligns the flow to the wake. The lip shock periodically disappears, i.e. at the moment of maximum vortex expansion, the latter "hiding" the trailing edge curvature.

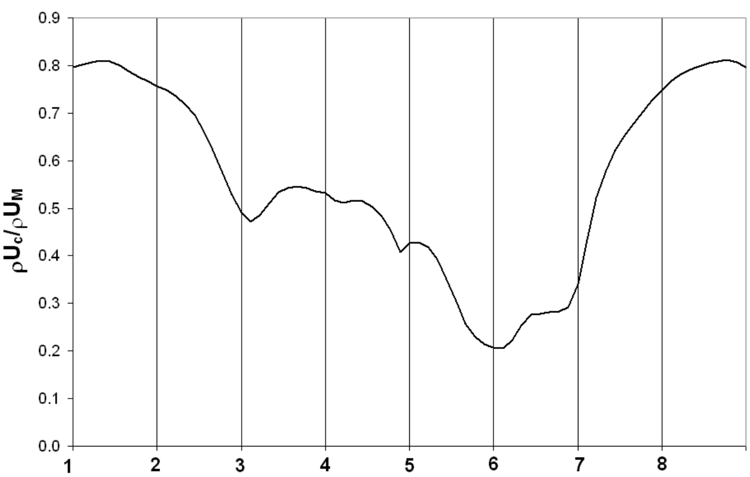

Figure 6: Coolant exit to main flow momentum ratio, $f_1 = 1$ kHz

In the case of $f_1 = 1$ kHz the effect of the pulsation is stronger on the jet and also on the vortices, since lower inertial effects allow the field to adapt to the changing flow conditions. The shock oscillates also at higher distances from the trailing edge. Figure 5 illustrates istantaneous contours of the density gradient magnitude near the channel exit for 8 time steps in a period (represented in figure 6). The maximum coolant ejection breaks down the compact vortical structures, which instead are highly promoted as the jet decreases its momentum. These coupled in-phase vortices persist until the new rise of coolant jet velocity occurs and its higher penetration dissolves them.

At the pulsation frequency $f_3 = 10$ kHz the vortices formation is notably clear and compact. The structures break down further downstream than for the previous frequencies. This may be ascribed to the fact that the actual frequency is closer to the intrinsic vortex shedding frequency of such main flow on this geometry ($St = 0.39$). The pulsating flow is nearly at the same frequency of the vortex shedding thus promoting instead of suppressing it as in the previous cases. Once again two vortical structures occur, one from the main flow and one from the coolant, which is then encompassed by the main one (figure. 7).

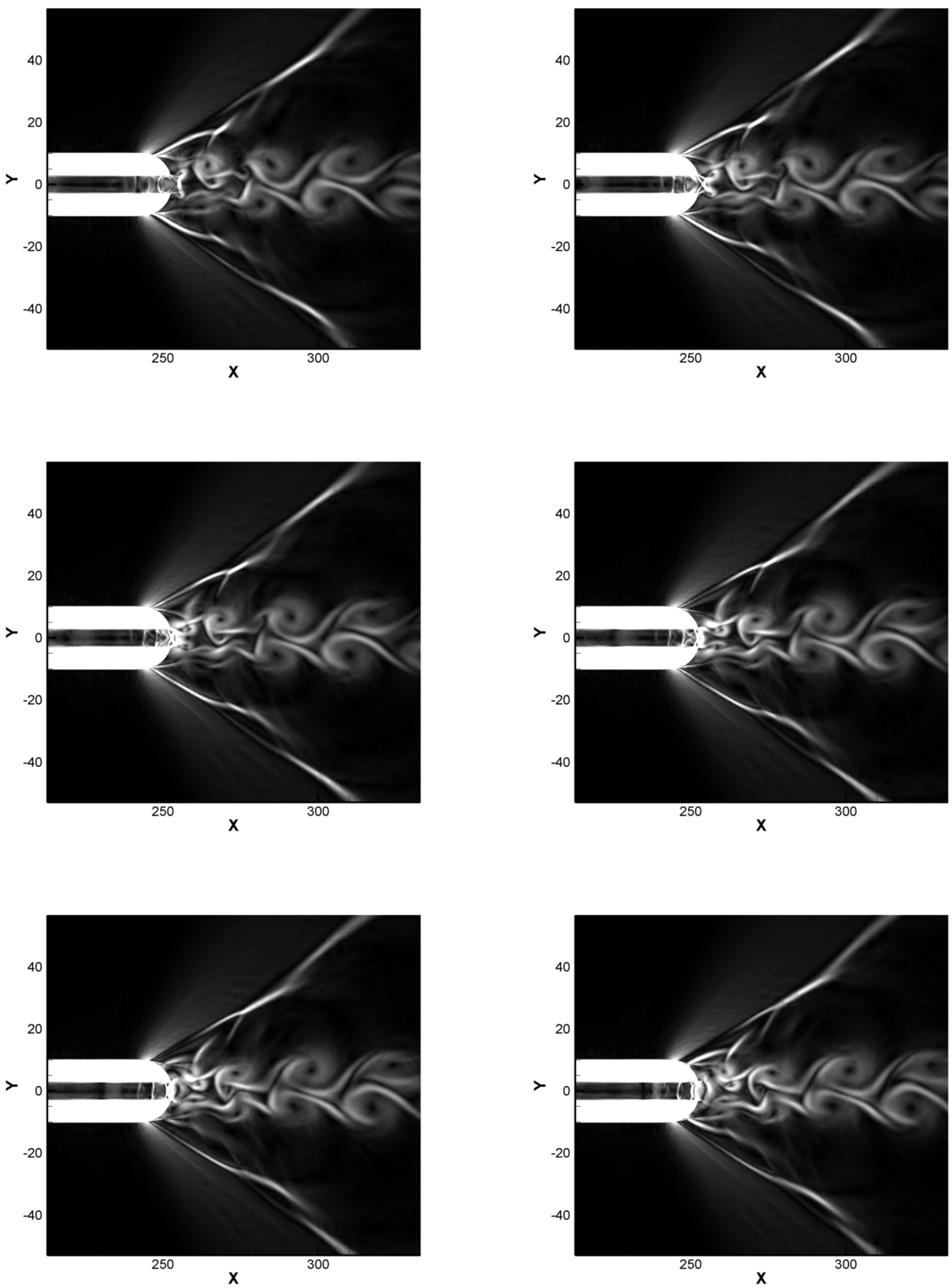

Figure 7: Density gradient magnitude field at trailing edge for f_3 = 10 kHz, 6 time steps in a whole pulsation period

4.2 Frequency analysis

The periodic nature of the pulsating coolant flows promotes the generation of oscillating phenomena in the main flow field. As it can be noticed from the density gradient magnitude fields, reflection waves arise inside the channel which results in the non-sinusoidal profile illustrated in figure 6. An FFT analysis of the coolant outlet mass-flow signal reveals pulsating frequency as the dominant and the harmonics. For the highest frequency cases, the first harmonic of the trasversal mode appears, since the width of the plenum renders this mode cut-on. This explains the slight non-symmetry of the flow of figure 7, which is transmitted downstream to the coolant channel exit. The transversal wave is clearly visible for the case at $f_4 = 15$ kHz, in the stagnation pressure field of figure 8. In this case the double channel width $2h$ is much larger than the wave length, which is the condition for the higher mode to be cut-on[16].

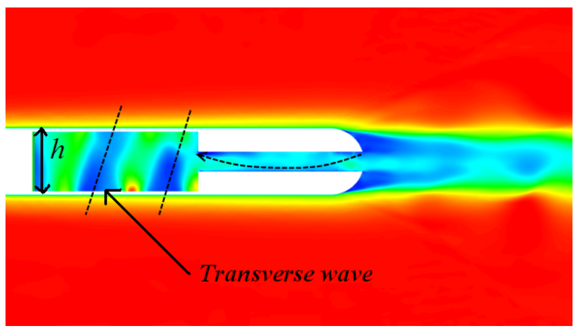

Figure 8: Stagnation pressure field in the coolant plenum for $f_4 = 15$ kHz with the transversal wave

Three pressure “probes” have been placed in the wake region, the first one in the centerline ($(x_1; y_1) = (270; 0)$mm) and the others positioned downstream and slightly misaligned ($(x_2; y_2) = (280; 5)$mm and $(x_3; y_3) = (285; 5)$mm). The pressure signal spectra show a high dispersion of the frequencies, particularly in the probe 1, the closest to coolant outlet, underlining the complex flow pattern in that zone.

On the contrary, probes 2 and 3 convey a very similar behavior indicating that downstream the flow reaches a more stable condition. Considering the $f_1 = 1$ kHz and $f_2 = 5$ kHz cases, the main frequencies for all the three probes are those coming from the coolant inlet pulsation and its harmonics (figure 9). In the $f_3 = 10$ kHz case another frequency arises in all probes, which is the vortex shedding frequency typical of the base geometry and main flow, as resulting from the continuous blowing case. It appears only in this case since the coolant frequency is very close to it and its generation is not abridged as in the other frequencies cases. This value gives a Strouhal number of 0.39, a value in agreement with experimental data referenced by Sieverding[17].

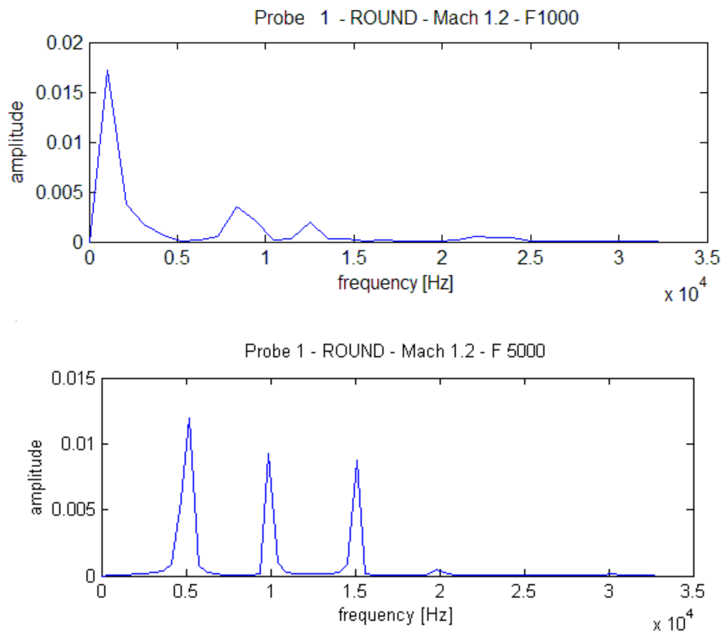

Figure 9: FFT of pressure signal at probe 1 ($(x_1; y_1) = (270; 0)$mm)

4.3 Shock intensity variation

A first qualitative evaluation of the shock intensity variation with pulsating coolant can be done calculating the variation in the Mach number. Hence, the so-called parameter Dsh is evaluated with the following equation as:

$$Dsh = \frac{(Mach_{max} - Mach_{min})}{(Mach_{max} - Mach_{min})^*} \tag{2}$$

where the symbol [*] indicates the reference steady no-blowing case, and the values of Mach number are calculated at a fixed y value, in the range of $x = [350; 450]$. Four sections are considered having locations displayed in figure 10.

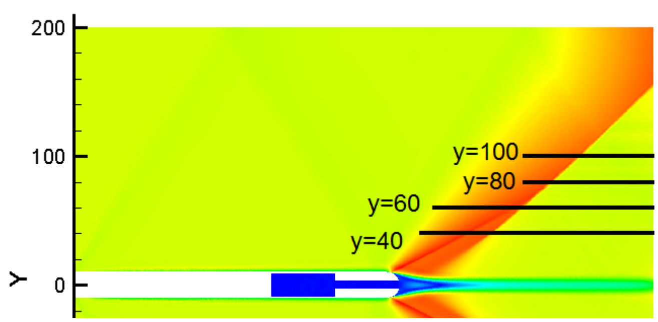

Figure 10: Sections for calculation of parameter Dsh

The time evolution of Dsh is reported in figure 11, together with the total pressure fluctuation at coolant inlet, in particular the case with frequency $f_2 = 5$ kHz, at different positions far from the trailing edge. Close to the trailing edge the shock intensity increases with respect to the continuous blowing, and the intensity reduction decreases from about 40% to 27%. Nevertheless, moving downstream (at higher values of y) the shock intensity decreases, reducing its intensity at 50% with respect to the no-blowing case, while for the continuous blowing the reduction is about 47%. The shock intensity oscillates at the same frequency of the coolant pulsation as arising from the FFT analysis. Generally for all frequencies, the pulsating coolant yields a strengthening of the shock close to the trailing edge, where it is affected by the high vorticity levels.

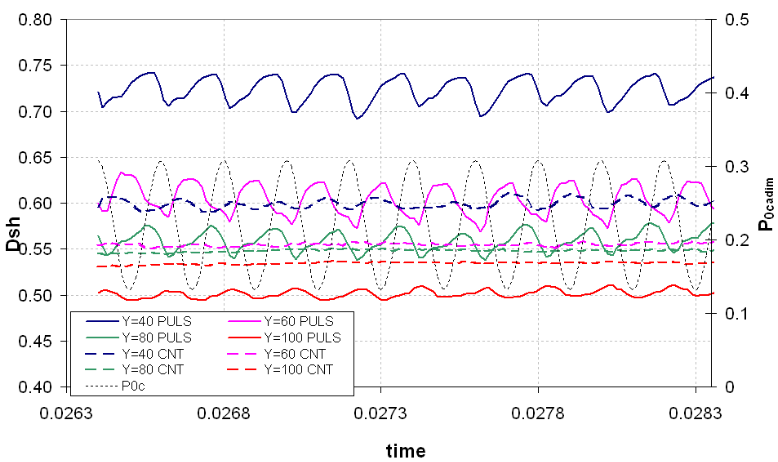

Figure 11: Variation of shock intensity with respect to the no-blowing case for $f_2 = 5$ kHz, $\overline{D.R.} = 1.60$

The effect of the coolant inlet pulsating function amplitude has also been considered, varying ΔP from 0.4 to 0.6 at the frequency $f_2 = 5$ kHz. Actually, the shock intensity reduction is not affected by this parameter. With this amplitude of the inlet function and frequency of 5 kHz, the mean density ratio $\overline{D.R.}$ was altered from the base value of 1.60 to 2.1. In both cases the same behavior of the shock previously noticed arises, except for a narrower oscillation for the higher mean coolant pressure value. The effect of these two parameters, mean value of pulsation and amplitude, is not as much important as the frequency, at least for the two couples of values considered.

5 CONCLUSIONS

The possibility of decreasing shock intensity in transonic stages has been evaluated by pulsating the coolant ejected at the trailing edge. The influence of pulsating frequency on the flow field has been mainly addressed, which highlighted that the vortex shedding pattern is very sensitive to this parameter, thus the shock system. The main and more interesting result of this study is that pulsating the coolant leads indeed to a relevant decrease in the shock intensity with respect to a continuous blowing. The lower the frequency, the higher is the effect on shock intensity reduction. This is a first step on the study of this methodology, which has shown promising results that will be further investigated and should be confirmed by experimental evidence. Unsteady numerical studies on the considered simplified geometry and on a full stage are ongoing that could indicate the best setting for the shock reduction, such as optimum frequency, amplitude and mean value of the coolant pulsation. Experiments on a full stator stage are scheduled at the von Karman Institute and some ad-hoc frequencies may be considered, as the blade-passing frequency. This may also suggest a low cost way of realizing such pulsation.

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