Transition Effect on the Shock Wave / Boundary Layer Interaction Region and the Wake at Low Supersonic Mach Number

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Workshop on Non-equilibrium Flow Phenomena
in Honor of Mikhail Ivanov's 70th Birthday
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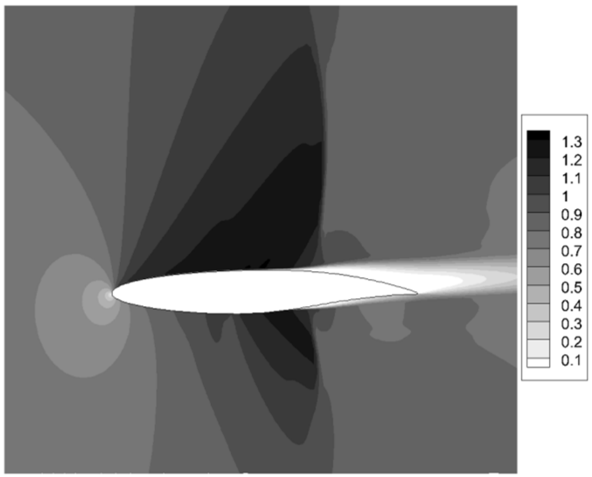
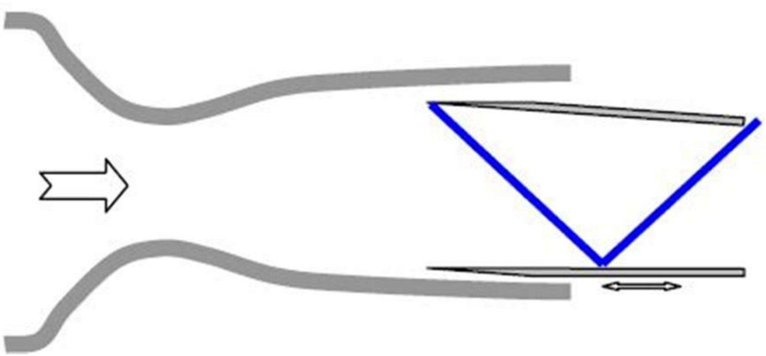
SEVENTH FRAMEWORK PROGRAMME

Object of study



Example of High speed Natural Laminar Flow airfoil

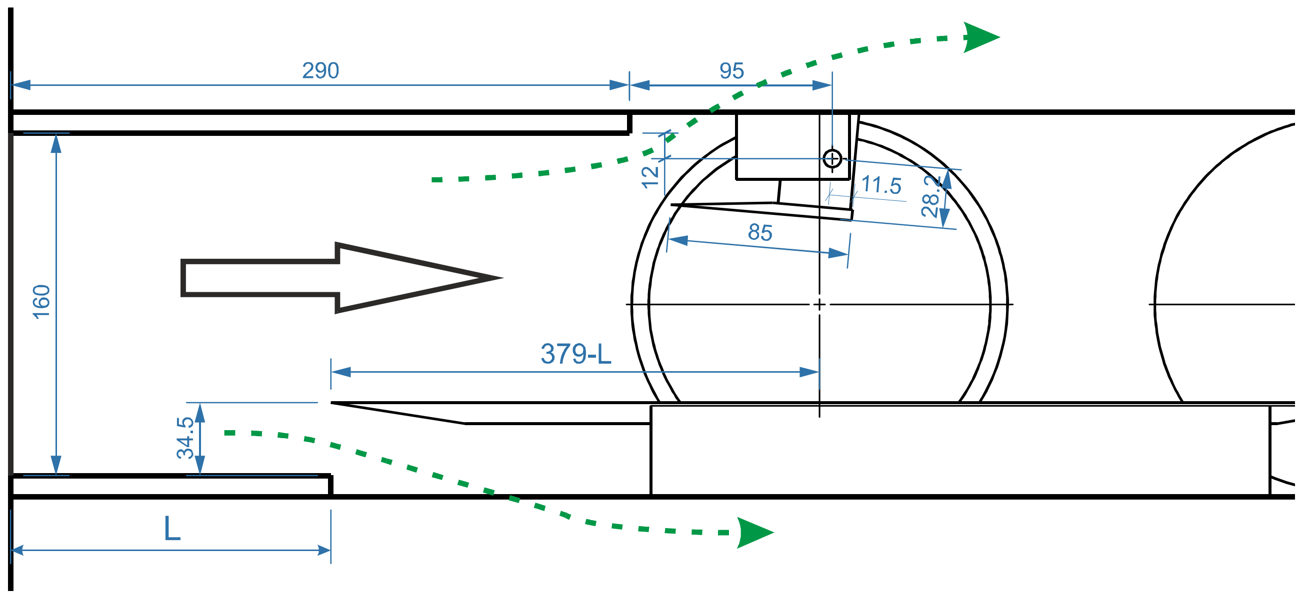


Task of ITAM

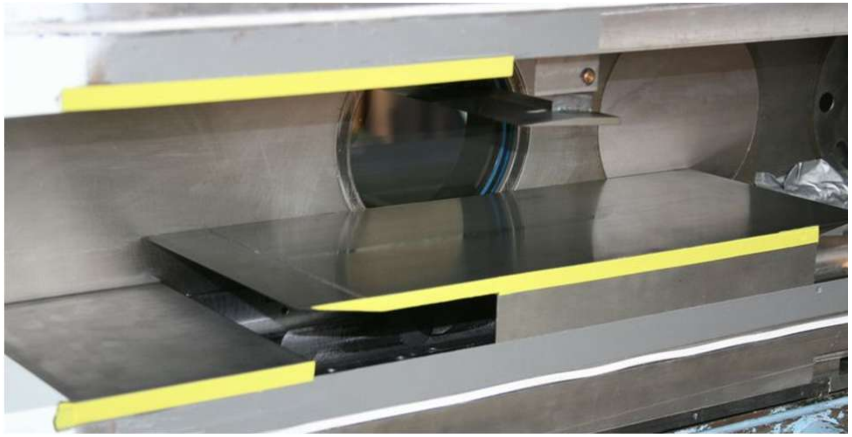
- Commercial airplanes of the next generations may be equipped with a laminar wing.
- Laminar boundary layer has weak resistance to adverse pressure gradients especially ones produced by shock waves, in contrast to the turbulent boundary layer.
- Therefore it is necessary to estimate the difference between steady and unsteady parameters of the separation zone for various positions of the laminar-turbulent transition relative to the zone of shock wave boundary layer interaction (SWBLI) for moderate Mach numbers.
- The study is carried out in the framework of project TFAST (16 partners, http://tfast.eu/).

Experimental setup

- Experiments were done for the flow parameters: **M=1.47, Re_1=8.5, 11, 13.5, 15.5 E6 1/m, T_0 = 285-290 K**
- The **model position** was varied to achieve **laminar**, **transitional** and **turbulent** state of the boundary layer at the interaction zone
- The following test cases were defined after preliminary experiments:
  - “Laminar” (L=250mm, β **= 3-4**°)
  - “Transitional” (L=200mm β **= 3-4**°)
  - “Turbulent natural” (L=100mm , β **= 3-4**°)
- The several samples of roughness were used for control of separation.



Experimental parameters



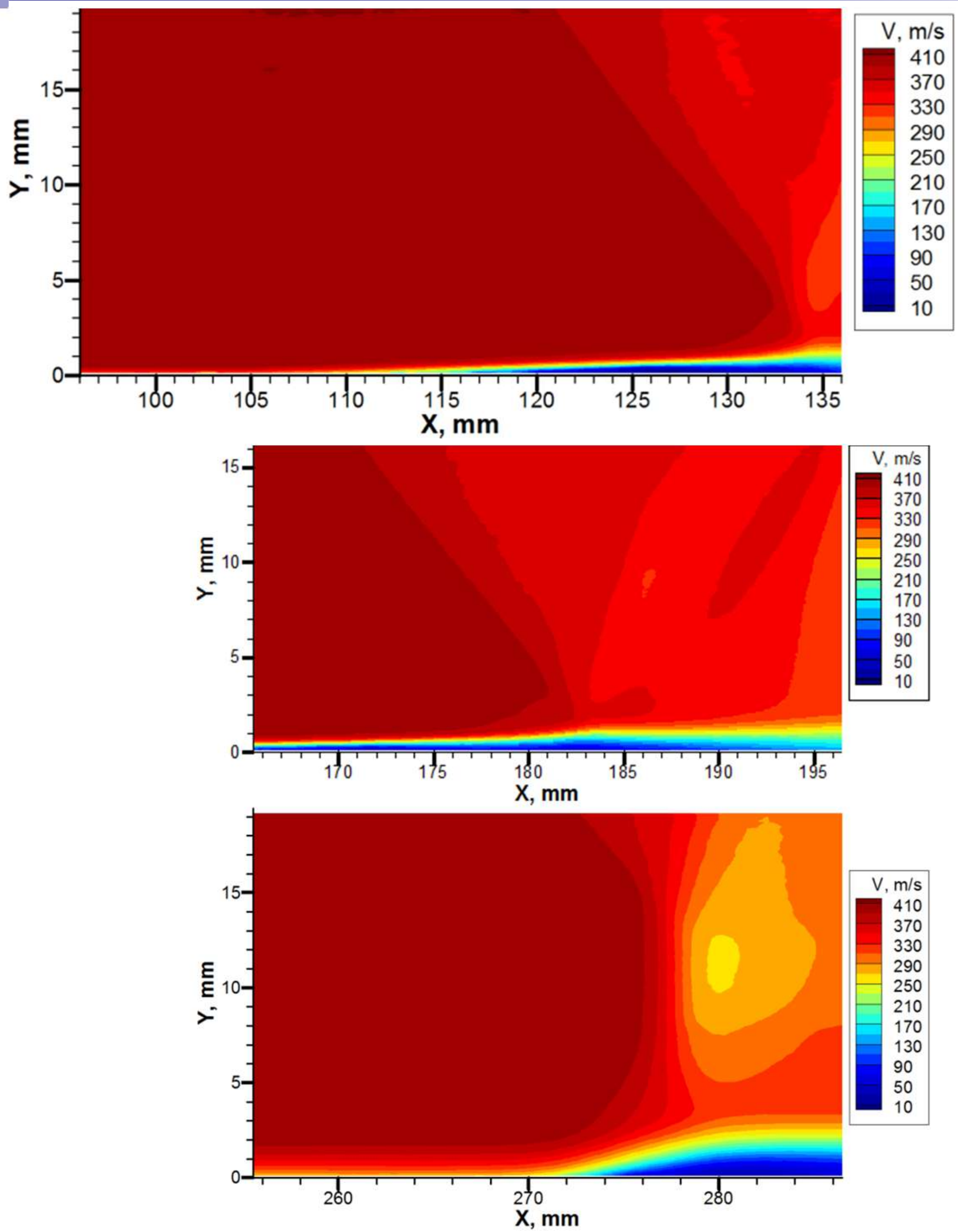
The most of experiments involved PIV technique in symmetry plane of the model.

Dantec Dynamics PIV system including Litron NanoL 135-15 laser and Phantom V310m camera was used.

Normal (dX=32-45 mm) and extended (dX=62mm) scale measurement were performed.

M	P_0, bar	T_0, K	Re_1, 10^6	L_{imp}, mm	β	Re_{Limp}, 10^3	δ*, mm	L_{per}, mm	Regime
1.42	0.694	286.4	10.922	288	4°	3145.6	0.53	12.7	Turb.
1.42	0.847	280.8	13.705	290	4°	3974.4	0.425	11	Turb.
1.42	0.984	284.2	15.652	290	4°	4538.9	0.458	11.9	Turb.
1.43	0.553	284.7	8.767	183	4°	1604.4	-	-	Tran.
1.43	0.688	284.5	10.910	183	4°	1996.6	0.369	24.8	Tran.
1.43	0.841	285.6	13.268	183.5	4°	2434.7	0.309	20.2	Tran.
1.43	0.976	286.5	15.325	183.5	4°	2812.1	0.239	10.7	Tran.
1.43	0.551	291	8.476	132	4°	1118.8	0.3	34	Lam.
1.43	0.694	290.4	10.699	133	4°	1423.0	0.27	28.5	Lam.
1.43	0.834	286.3	13.108	134	4°	1756.5	0.25	24.5	Lam.
1.43	0.978	285.1	15.461	134	4°	2071.8	0.22	22	Lam.

Velocity field (Re1 = 13.5E6 1/m)



With an increase in X regime of inflow boundary layer changes from laminar to turbulent.

For laminar and transitional case reflected (separation) shock wave is weak.

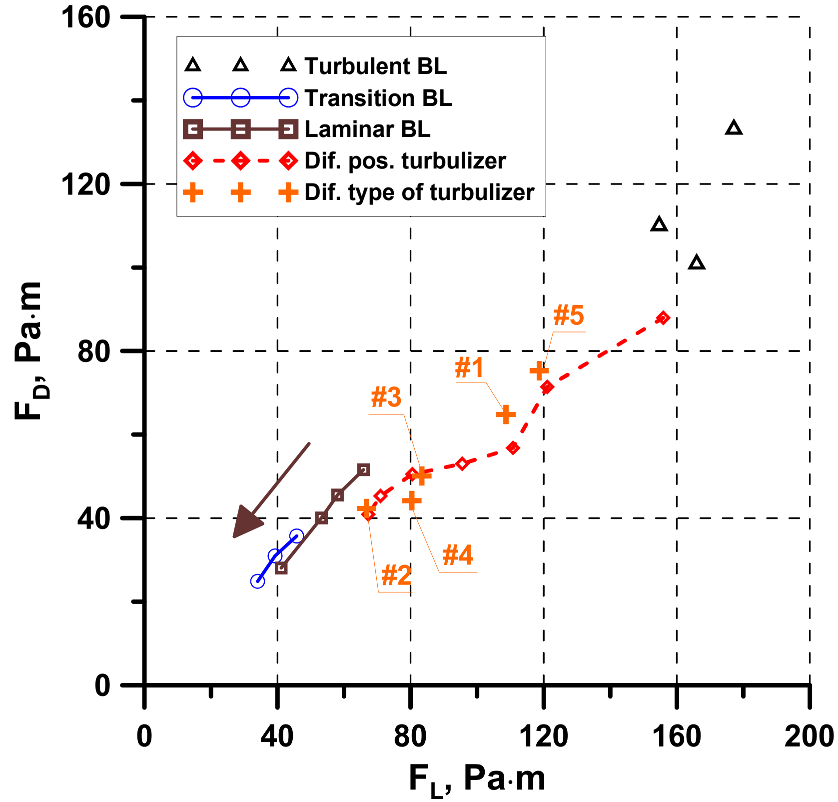
For the most of turbulent test cases small Mach stem was discovered

It is necessary to define the parameters of SWBLI to compare different regimes of inflow BL.

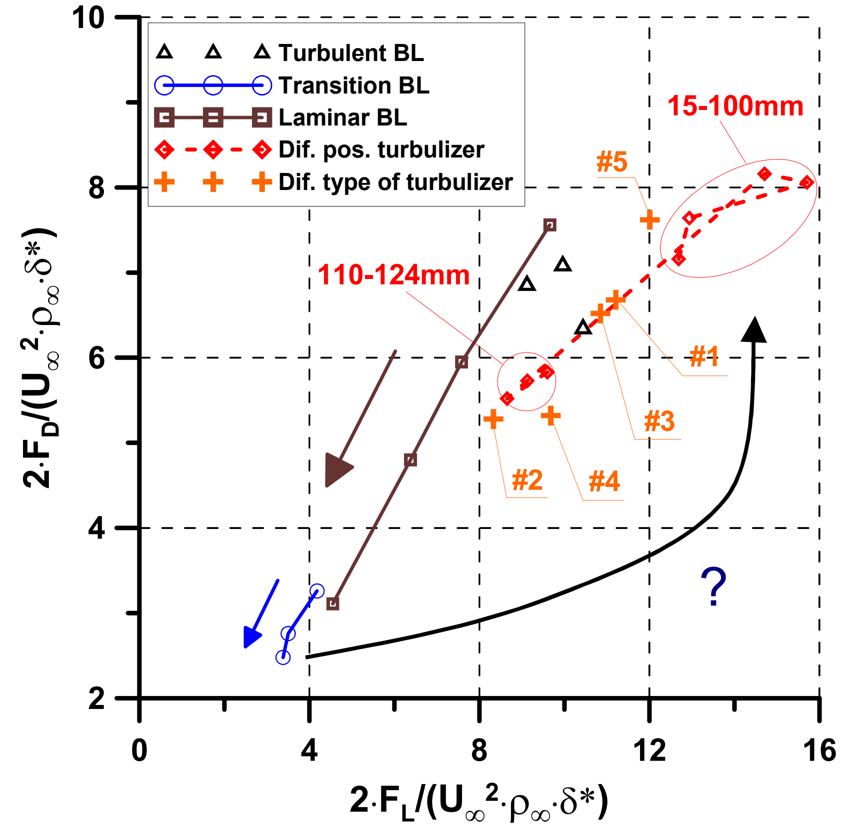
Quantitative analysis of SWBLI

As a quantitative analogue of Lper: $$F_L = \int_{X_{in}}^{X_{imp}} \left(P_{st} - P_{st_{in}}\right) dx$$

As the quantitative analogue of Hper: $$F_D = \int_0^y P_{0_{in}}\, dy - \int_0^y P_0\, dy$$



Dimension



Dimensionless

Preliminary conclusion

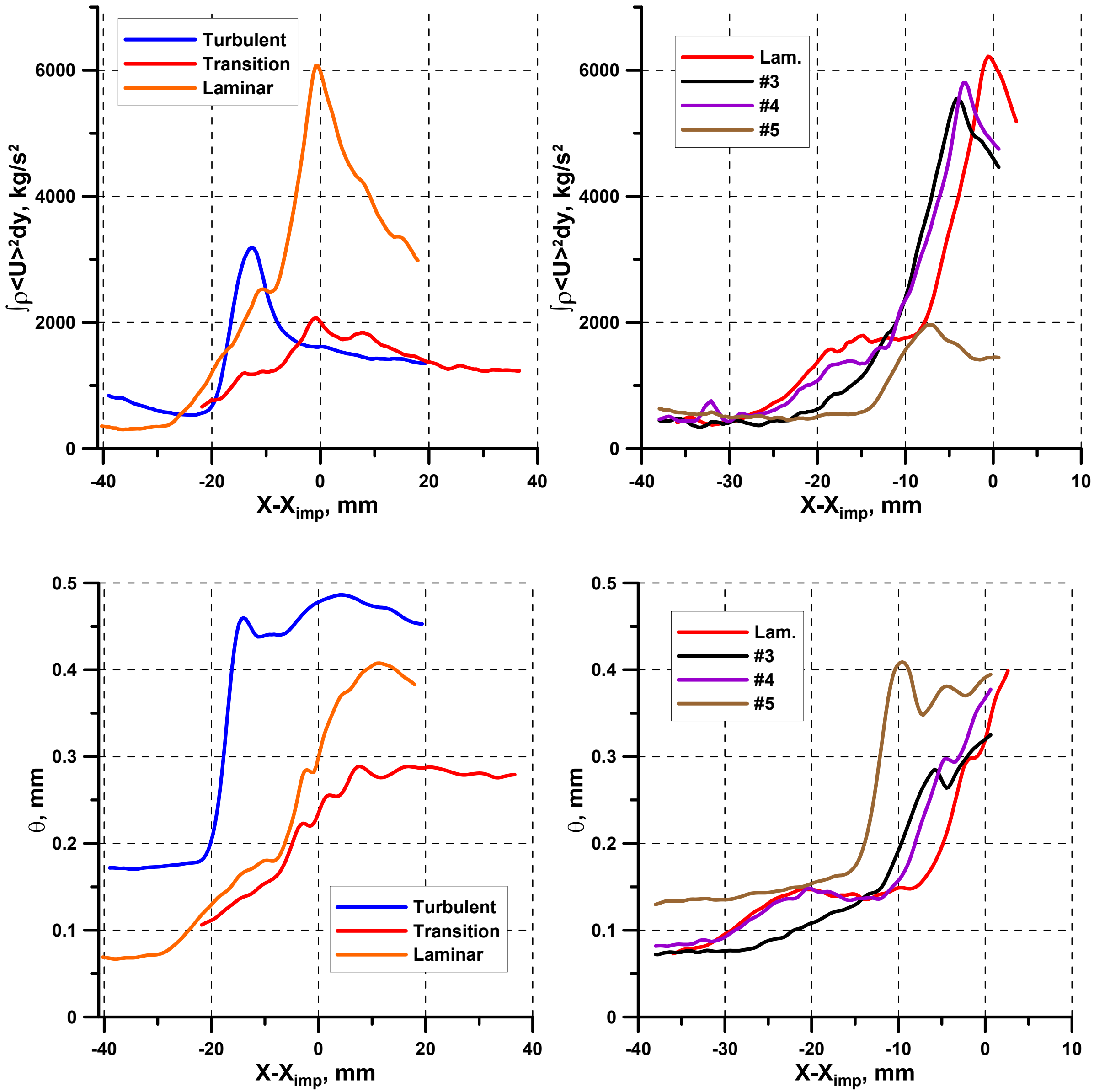
- The optimal is to provide SWBLI in the area of laminar-turbulent transition.
- The steady parameters of SWBLI for the laminar case is not worse than the parameters of the turbulent case.

What's the pulsations and flow in the wake?

Integral parameters of SWBLI (Re1 = 13.5E6)

The integral of the pulsations

The momentum thickness

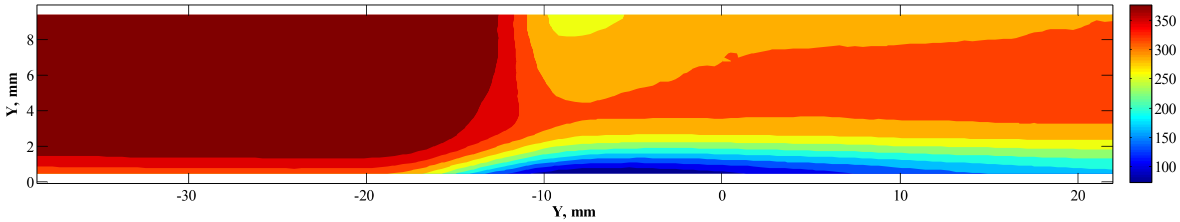


For case of laminar inflow boundary layer is observed the strongest increase the integrated pulsations in the zone of SWBLI. The maximum level of integrated pulsations in the interaction zone for laminar case more than in turbulent case.

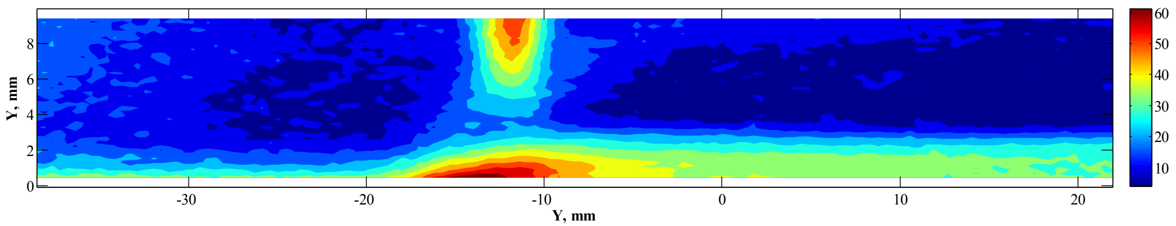
Perhaps this is the reason of equalization the momentum thickness in the wake for the laminar and turbulent cases.

The smallest increase the momentum thickness and pulsations in the zone of SWBLI is observed for the transitional case.

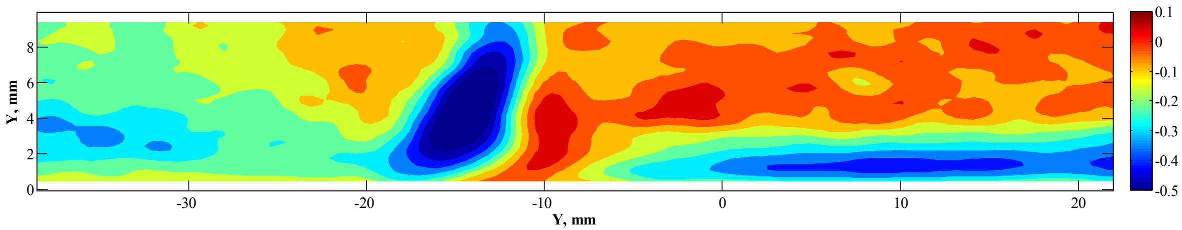
Turbulent case



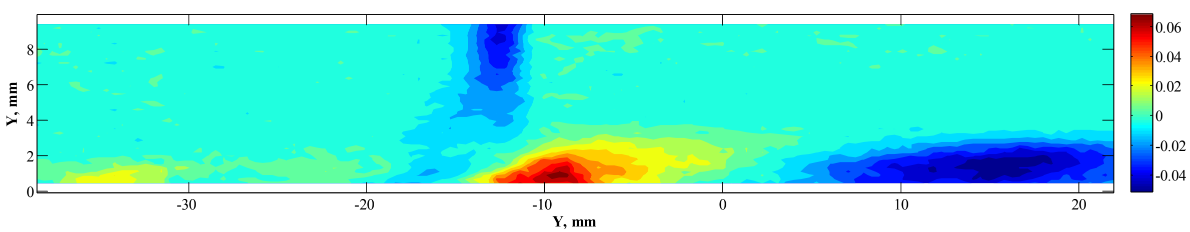
Mean velocity



RMS of longitudinal velocity



Correlation coef. R_{UV}



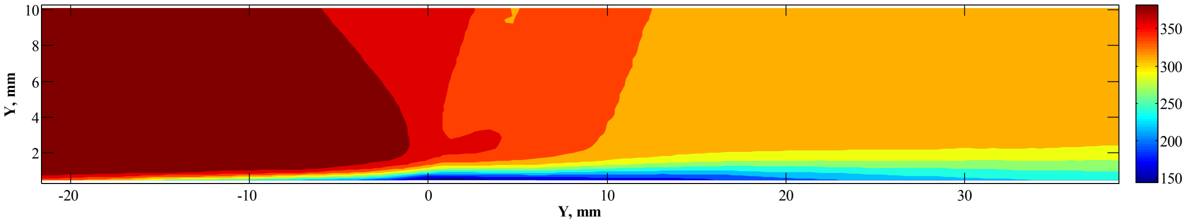
Example of POD

It is clearly seen that for the turbulent case the pulsation of the zone of interactions leads to oscillations of the Mach stem.

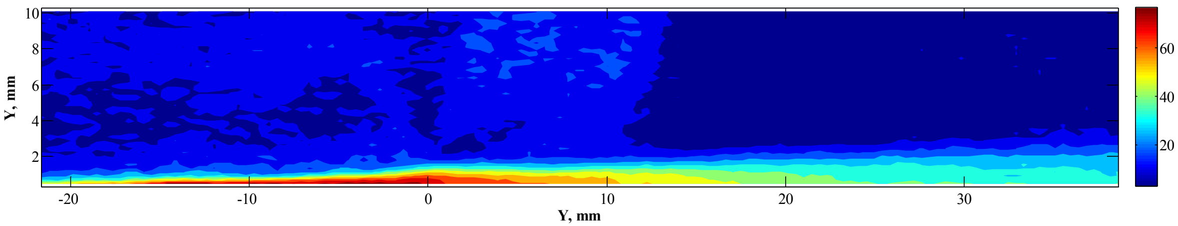
In the zone of SWBLI the R_{UV} significantly deviates from this value. In this zone non-equilibrium turbulent boundary layer occurs, but further downstream the correlation coefficient begins to recover.

Example of POD modes shows the presence of interconnected characteristic oscillations across the domain.

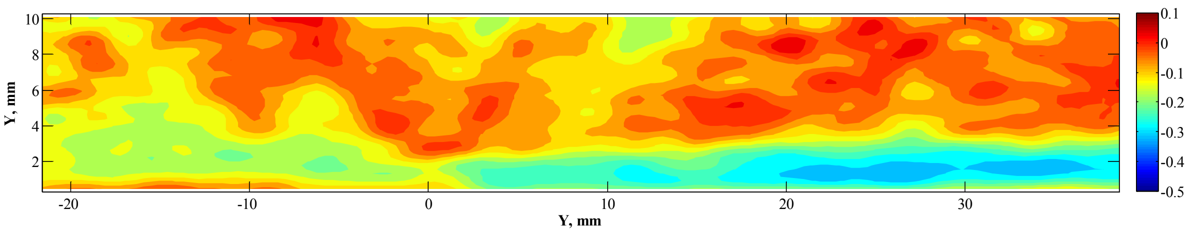
Transition case



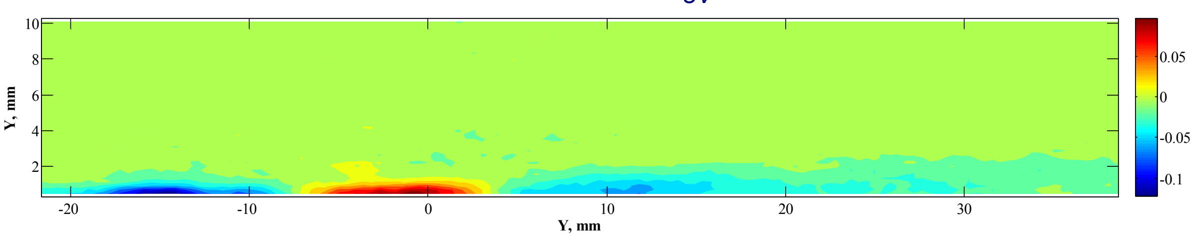
Mean velocity



RMS of longitudinal velocity



Correlation coef. R_{UV}



Example of POD

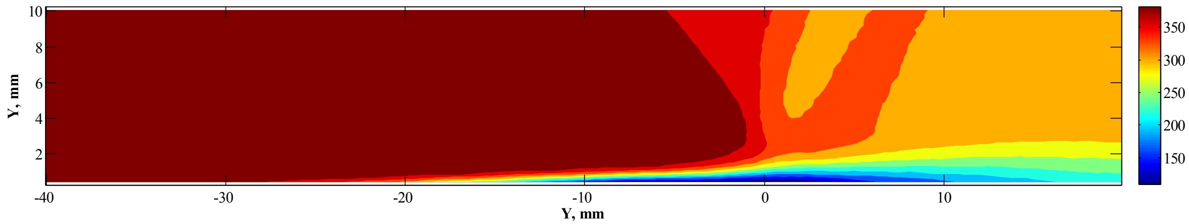
In contrast to the turbulent case where the maximum of pulsations occurs near the reflected shock wave for the transitional case the growth of pulsations is retained up to the point X_{imp}.

Further downstream fullness of the velocity profile and absolute value of the coefficient R_{UV} begins to grow.

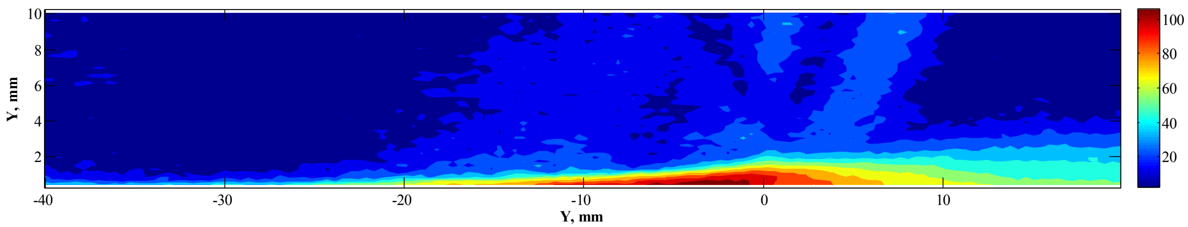
The coefficient R_{UV} near the end of the measured area is approximately equal to -0.2.

This means that the turbulent boundary layer is rapidly restored to equilibrium state.

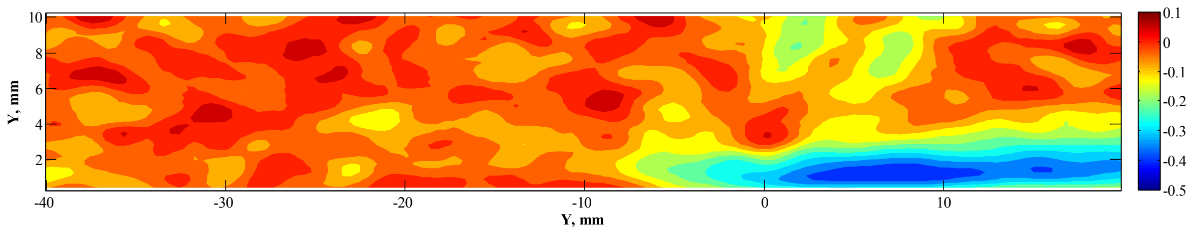
Laminar case



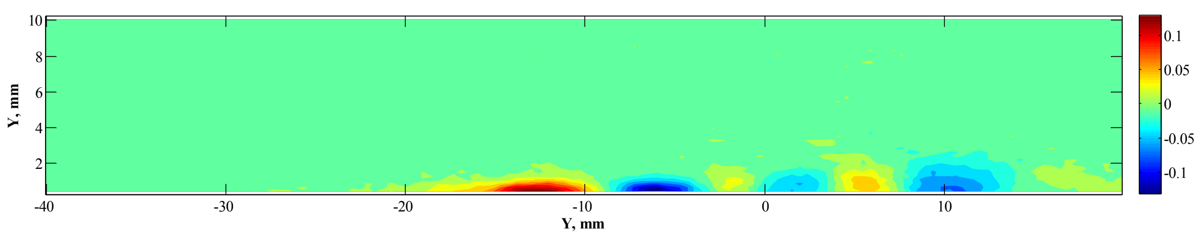
Mean velocity



RMS of longitudinal velocity



Correlation coef. R_{UV}



Example of POD

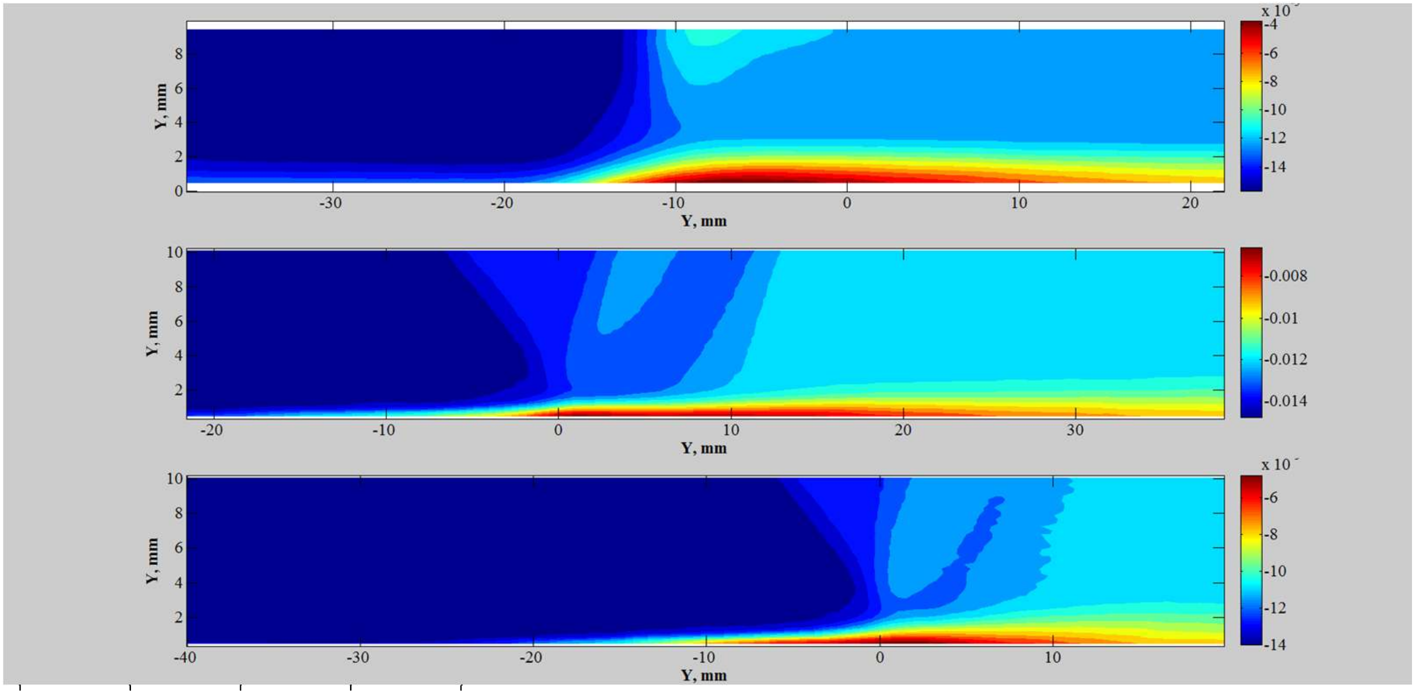
For the laminar case the flow pattern is similar to the transition case, but there are several significant differences:

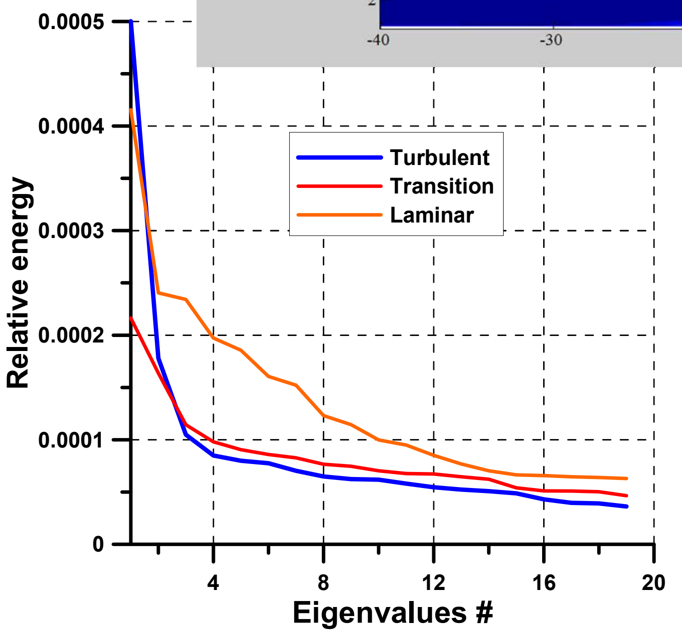
1) Significant growth of the pulsations and generation of thick turbulent boundary layer was found.

2) Absolut value of RUV increases dramatically in the zone of interaction.

3) A significant decrease of POD modes energy near the end of the measured zone was not found. It can be assumed that for the laminar case in the SWBLI zone strongly non-equilibrium turbulent boundary layer is generated.

Relative energy from POD

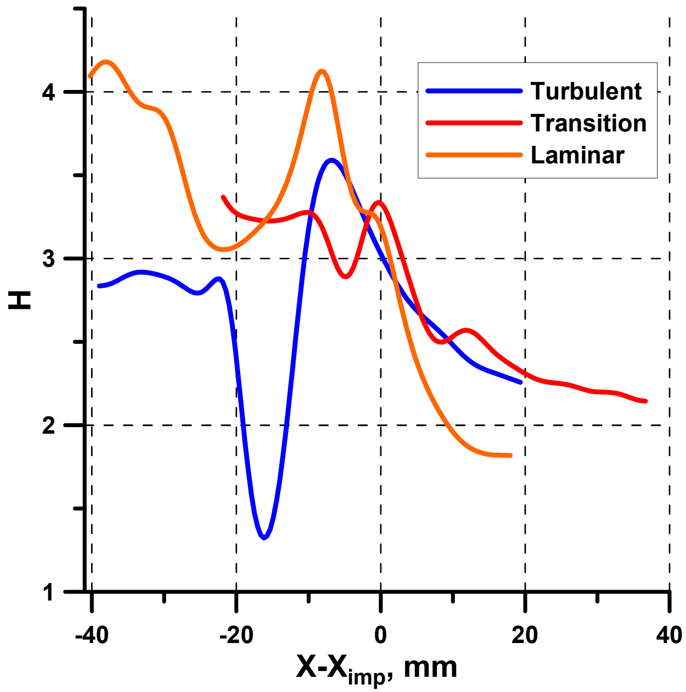




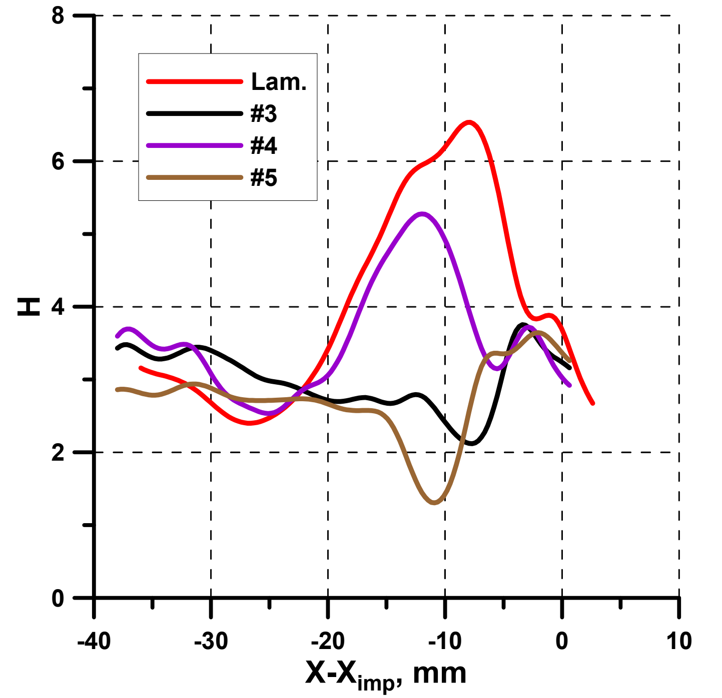
Relative energy associated with mode #m

The energy of structured oscillations of the flow for the laminar case significantly exceeds the values obtained for turbulent and transitional cases. Thus for laminar case the powerful coherent structures present in the interaction zone.

Shape factor



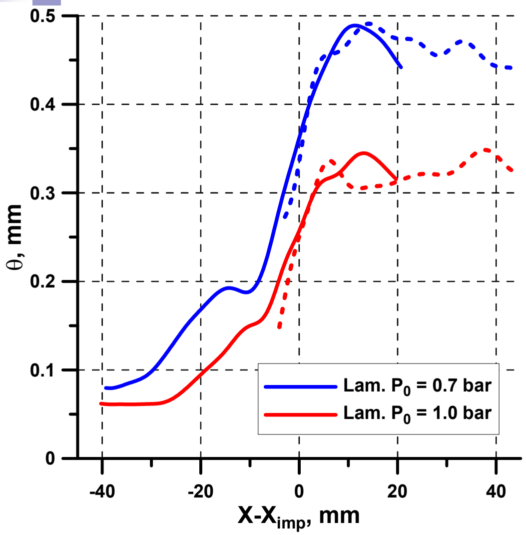
Natural conditions for Re_1 = 13.2e6 1/m



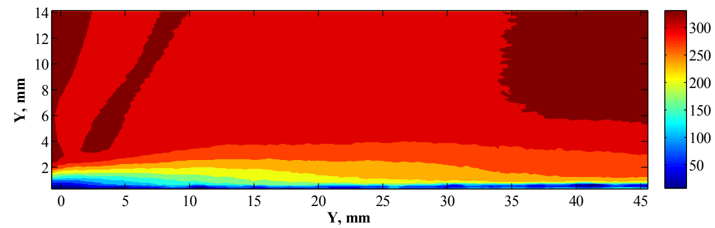
Different types of turbulators, Re_1 = 10.7e6 1/m

For the transitional and turbulent case the values of the shape factors in the wake are similar and decrease downstream. The sharp decrease of H in the interaction zone occurs for the laminar case. It is assumed that it varies slightly further downstream. This can be explained by the different development of the boundary layer in the wake.

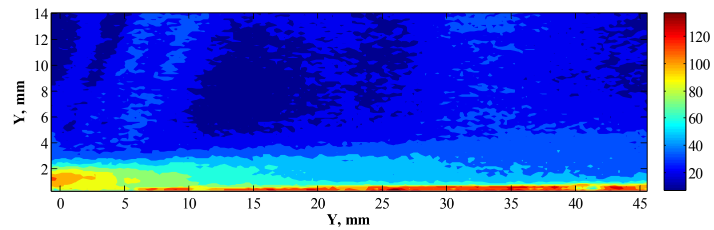
Flow in a wake



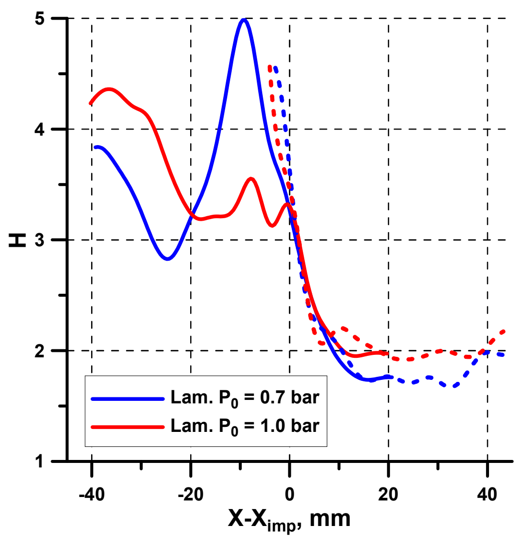
Momentum thickness



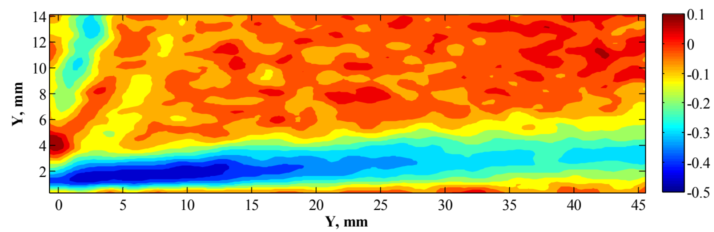
Mean velocity



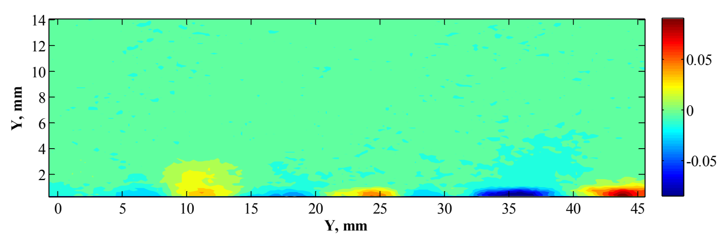
RMS of longitudinal velocity



Shape factor



Correlation coef. R_{UV}



Example of POD

The velocity and velocity fluctuations distributions in the boundary layer at the end of the measuring area become closer to the equilibrium turbulent boundary layer.

Since the momentum thickness in this wake varies weakly it can be assumed that the evolution of the boundary layer occurs only by redistribution of the energy accumulated in the zone of SWBLI. And the exchange of energy with the inviscid flow in the wake is weak. POD analysis shows weak damping of structures in the boundary layer in the wake.

Conclusions

- It was found that the evolution of the turbulent boundary layer in the wake strongly depends on the state of the boundary layer upstream of SWBLI.

- It is shown that the effect of the angle of the incident shock wave on the flow depends on the state of the incoming boundary layer.

- It was found that for the laminar case the turbulent boundary layer generated in the zone of interaction quickly takes energy from the flow.

- The optimal is to provide SWBLI in the area of laminar-turbulent transition.

Thank you for your attention

Question?