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DIRECT NUMERICAL SIMULATION OF WAVE PACKETS OVER A ROUGH FLAT PLATE

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Abstract. *The turbulent flow is characterized by drag increase relative to the laminar. Thus, in aeronautical applications, the greater the region with turbulent flow, the greater the fuel consumption and, consequently, the lower its payload. In this way, the understanding of the transition phenomena means greater precision in the prediction of the aircraft drag and the possibility of surface optimization to obtain a greater laminar region. In this sense, this work proposes the study of the natural transition mechanism that occurs on real surfaces. In order to conduct this study, it is proposed the use of a DNS (Direct Numerical Simulation) code developed by this group, to simulate a flat plate immersed in an incompressible subsonic flow on which a perturbation is introduced in the form of wave packets. The choice of wave packets lies in the quest to approach the natural transition. This comes from the fact that the wave packets are composed of a large number of oscillation modes and not just by two or three as done in most boundary layer transition studies. Furthermore, some studies present that the natural transition displays wave packets that lead to turbulent spots formation.*

Keywords: *wave packets, dns, roughness*

1. INTRODUCTION

The main motivation on the study of flow transition is the prediction and control of this point to avoid, as much as possible, the turbulent flow and thus, obtain less fuel consumption. *Airbus A320* aircraft presents almost 50% of total drag composed of friction drag and the wings contribute with 25% of this number (Marec, 2001).

The transition phenomenon goes back to the Reynolds (1883) experiments in tubes. The natural transition term refers to the mechanism that occurs in nature, generated from random perturbations in several frequencies. When such perturbations reach amplitudes on the order of 1 % from free stream velocity the nonlinear phenomena rapidly lead to turbulence (Kachanov and Levchenko, 1984). Fluctuations are introduced into the flow through thermal, mechanical and acoustic disturbances, as well as turbulence of the flow and surface irregularities, among other sources. These perturbations evolve in space and time and are selected by the flow itself through frequency selection mechanisms and thus amplified until eventually lead to the transition.

In order to simulate the natural transition white noise sequences has been used to perturbate the flow. Shaikh and Gaster (1994) observed that white noise leads to transition through the generation of turbulence spots in a very similar way to that presented in uncontrolled experiments. The results obtained from the works of Shaikh (1993) showed that the first nonlinear stages of the evolution of the noise sequences involve the appearance of frequency waves smaller than the Tollmien-Schlichting, similar to the results obtained from wave packets. This suggests that wave packets may represent a part of the natural transition process (Martinez and Medeiros, 2016a).

2. DNS CODE

The code used here directly solves non-conservative form of the Navier-Stokes equations, therefore called DNS (Direct Numerical Simulation),

$$\frac{\partial \rho}{\partial t} = -\rho \frac{\partial u_i}{\partial x_i} - \frac{\partial \rho}{\partial x_i} u_i \tag{1}$$

$$\frac{\partial u_j}{\partial t} = -\frac{\partial u_j}{\partial x_i} u_i - \frac{1}{\rho}\frac{\partial p}{\partial x_j} + \frac{1}{\rho}\frac{\partial \tau_{ij}}{\partial x_i} \tag{2}$$

$$\frac{\partial e}{\partial t} = -\frac{\partial e}{\partial x_i}u_i - \frac{p}{\rho}\frac{\partial u_i}{\partial x_i} + \frac{1}{\rho}\tau_{ij}\frac{\partial u_j}{\partial x_i} - \frac{1}{\rho}\frac{\partial q_i}{\partial x_i} \tag{3}$$

where τ_{ij} is the viscous tensor and q_i the heat flux term defined as

$$\tau_{ij} = \frac{\mu(T)}{Re}\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} - \frac{2}{3}\delta_{ij}\frac{\partial u_k}{\partial x_k}\right) \tag{4}$$

$$q_i = -\frac{\mu}{(\gamma - 1)\, Re\, Pr\, M_\infty^2}\frac{\partial T}{\partial x_i}. \tag{5}$$

Assuming ideal gas and the Sutherland's law to model the viscosity term,

$$T = e\gamma(\gamma - 1)M_\infty^2, \quad p = \rho e(\gamma - 1), \quad \frac{\mu^*}{\mu_\infty} = \mu(T) = \frac{1 + C}{T + C}T^{\frac{3}{2}}, \tag{6}$$

with $C = \frac{110K}{T_\infty^*}$ and $T_\infty^* = 300K$. All variables are non-dimensionalized by the displacement thickness at the disturbance position, δ_0^*, freestream velocity, U_∞^* and density, ρ_∞. The Reynolds, Prandtl and Mach number are defined as

$$Re = \frac{\rho_\infty^* U_\infty^* \delta_0^*}{\mu_\infty^*}, \quad Pr = \frac{\mu_\infty^* c_P^*}{k^*}, \quad M_\infty = \frac{U_\infty^*}{c_\infty^*} = \frac{U_\infty^*}{\sqrt{\gamma \frac{p_\infty^*}{\rho_\infty^*}}} \tag{7}$$

The DNS code was developed by the own research group focused on the solution of transition problems in the subsonic boundary layer Martinez and Medeiros (2016a); Mathias and Medeiros (2018). Implemented in Fortran 90 and paralleled by MPI (Message Passing Interface). LAPACK library routines solve the system of linear equations for calculation of the spatial derivatives.

Spatial discretization is done through finite differences with spectral resolution based on the work of Lele (1992), allowing high precision with fewer mesh points when compared to non-compact methods. The scheme is 4th order precision and consists of a tridiagonal stencil that reduces the computational cost compared to pentadiagonal implementations. Integration in time is done through 4th order Runge-Kutta scheme.

At the inflow, uniform flow and temperature were fixed and a Neumann condition for pressure was imposed. At the outflow and upper boundary, the pressure was fixed and a Neumann condition imposed for velocities and temperature. Buffer zones are also placed at the outflow and upper boundary to avoid reflections into integration domain. Walls were modelled with no-slip and no-penetration conditions for velocity, pressure gradient was null in the normal direction and temperature fixed. At the inflow, a region with free-slip condition was included in the wall to accommodate the flow before plate.

A low pass filter is applied at each time iteration at points inside the domain to control the spurious oscillations that are present in the simulation, either from the application of boundary conditions and grid stretching. These filters are necessary to prevent the amplification of these non-physical oscillations that affect the simulation result. The code was also parallelized using the 2DECOMP&FFT library, allowing division of the computational domain into $N \times 1$ or $N \times M$ blocks. In this type of decomposition each processor stores a sub-domain that contains all the points of the axis in one direction in which the derivatives in that direction are calculated in parallel with the other sub-domains.

A good description of the code as well as validations can be found in the works produced by our research group when applied to cavity problems and boundary layer (Bergamo *et al.*, 2015; Martínez *et al.*, 2015; Martinez and Medeiros, 2016b).

3. DNS SETUP AND PRELIMINARY RESULTS

Preliminary results show the baseflow and the wave packet over the flat plate that reproduce the experiments from Medeiros and Gaster (1999b,a). The experiment considered a 1.68 m long flat plate with free-stream velocity 17.3 m/s. The disturbance was introduced using a loudspeaker connected to a small hole with 0.3 mm diameter placed at 203 mm from the plate leading edge. Previous DNS simulations that reproduced these experiments were performed and presented by Martinez (2016) and here is used as reference to compare the present simulation results. Flow parameters were $Re = 835$ Mach number was 0.2 which is considered essentially an incompressible scenario. The domain considered for integration in streamwise, height and span directions were $0 \leq x \leq 2000$, $0 \leq y \leq 20$ and $-300 \leq z \leq 300$ non-dimensionalized by δ_0^* which is the displacement thickness at the perturbation position in experiments from Medeiros and Gaster (1999b,a); Medeiros (2004). The wave packet function was applied as perturbation in the y-velocity vector at the plate surface and defined as

$$v' = A_0 \sum_{n=1}^{Nn} \sum_{k=-N_k}^{N_k} cos(\alpha_0(x - x_0) \pm k\beta_0 z)cos(n\omega_0 t), \tag{8}$$

where $A_0 = 5.4410^{-6}$ was the amplitude; $Nn = 80$ and $Nk = 40$ the number of modes in streamwise and spanwise directions, respectivelly; with $\alpha_0 = 0.1963$ and $\beta_0 = 0.126$, the respective wave numbers and $\omega_0 = 0.0013$. The perturbation was centered at $x = 284$ in the streamwise direction and $-\frac{\pi}{\beta_0} \leq z \leq \frac{\pi}{\beta_0}$ in the spanwise.

Mesh parameters are resumed in Fig. 1 in which the convergence study of baseflow is also presented. The number of points were 551, 70 and 160 in x, y and z directions respectivelly. Additional buffer zones were included in x, 50 points, and y, 10 points. The grid of the region of integration, excluding the buffer zones, is also presented in Fig. 1 every 10 points in x-direction and every 4 points in y-direction.

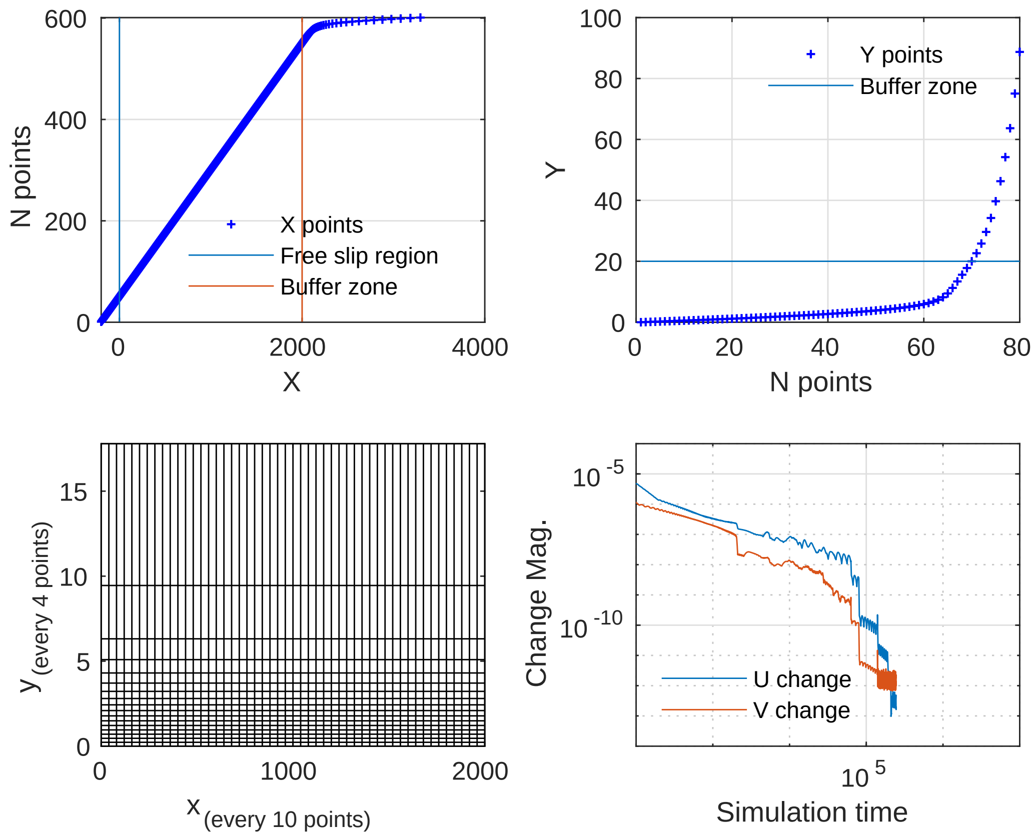


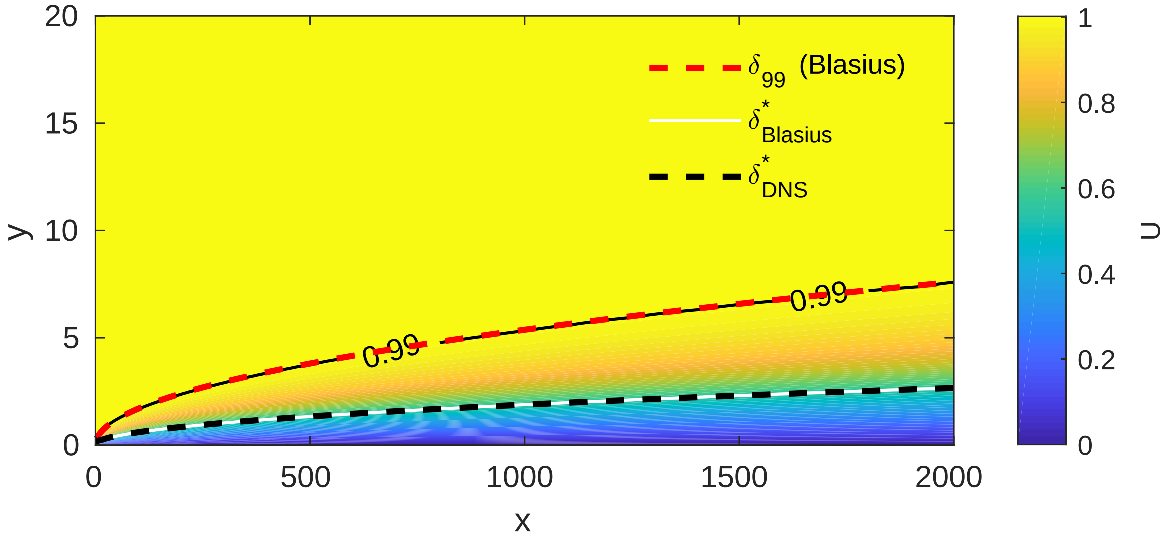
Figure 1. Mesh parameters and study of convergence of the baseflow.

Comparison between the theoretical Blasius solution for baseflow are presented in Fig. 2 and velocity profiles are compared in terms of the similarity variable, η, showing good agreement with the theory.

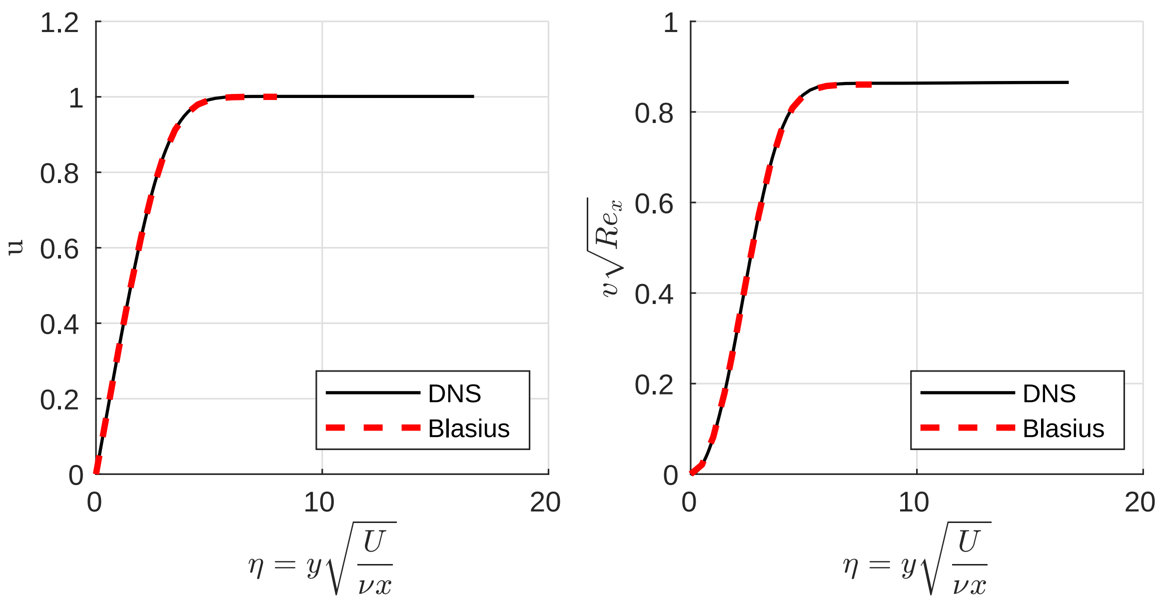
Preliminary results for wave packet evolution are presented in Fig. 3 in which the streamwise velocity fluctuation are provided at $y = 0.6\delta^*(x = 1500)$ and the linear evolution of the wave packet are observed.

Additionally to the preliminary studies, a wavetrain evolution was also simulated to reproduce the experimental results of Medeiros (2004). With these DNS simulations, we aimed to optimize the mesh parameters and also investigate the asymmetric behaviour observed in the crescents presented by the experiment and then include a roughness to analyse if this asymmetry was caused by some imperfection over the plate surface. The experiment setup is similar to the previous study on wave packet evolution. The disturbance, however, was defined mochromatic in time with $\omega = 0.0523$, and along the span covered 20 symetric modes of a fundamental wave number, $\beta_0 = 0.0226$, both non-dimensionalized. The domain had the same dimensions used for wave packet simulation except from Z direction which spanned from 0 to 348 in non-dimensional length scale. The mesh was composed by $N_X = 581$, $N_Y = 60$ and $N_Z = 101$ points.

Results comparing the contour of the velocity fluctuation along the time and span direction for DNS and experiments are showed in Fig. 4 for positions $X = 400$; 600; 900 and 1000 mm for $Y = 0.6\delta_0^*$. In this plot the numerical results are showed in the same points presented in the experiments. The comparisons are reasonable but further analysis on the spectral content and the meanflow distortion at the centreline will be provided at the conference.

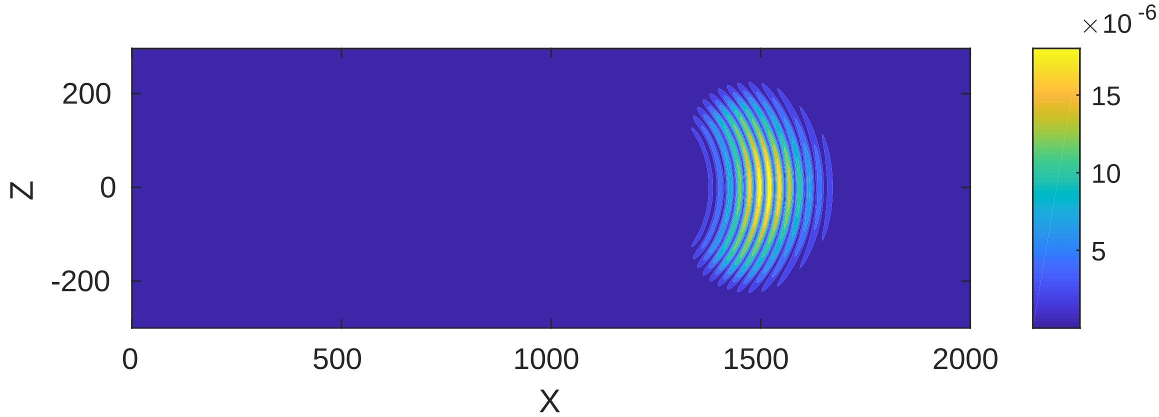


(a) a)

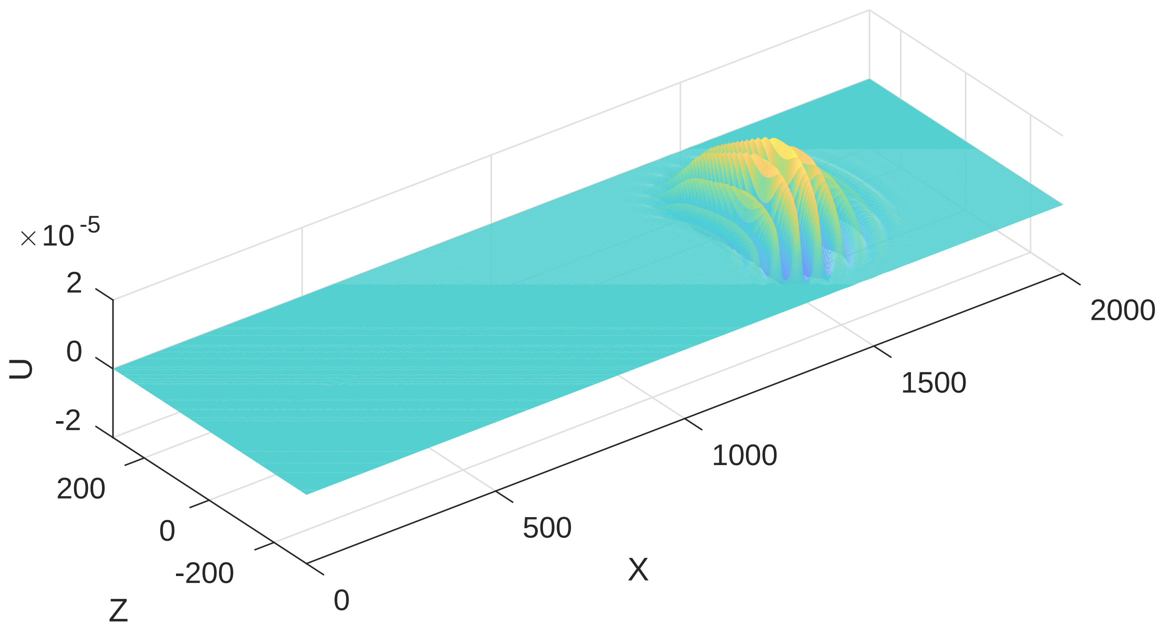


(b) b)

Figure 2. DNS baseflow solution and Blasius profiles for velocity components, u, v..



(a) a)



(b) b)

Figure 3. Wave packet evolution along the plate, U velocity fluctuation at $0.6\delta^*(x = 1500)$.

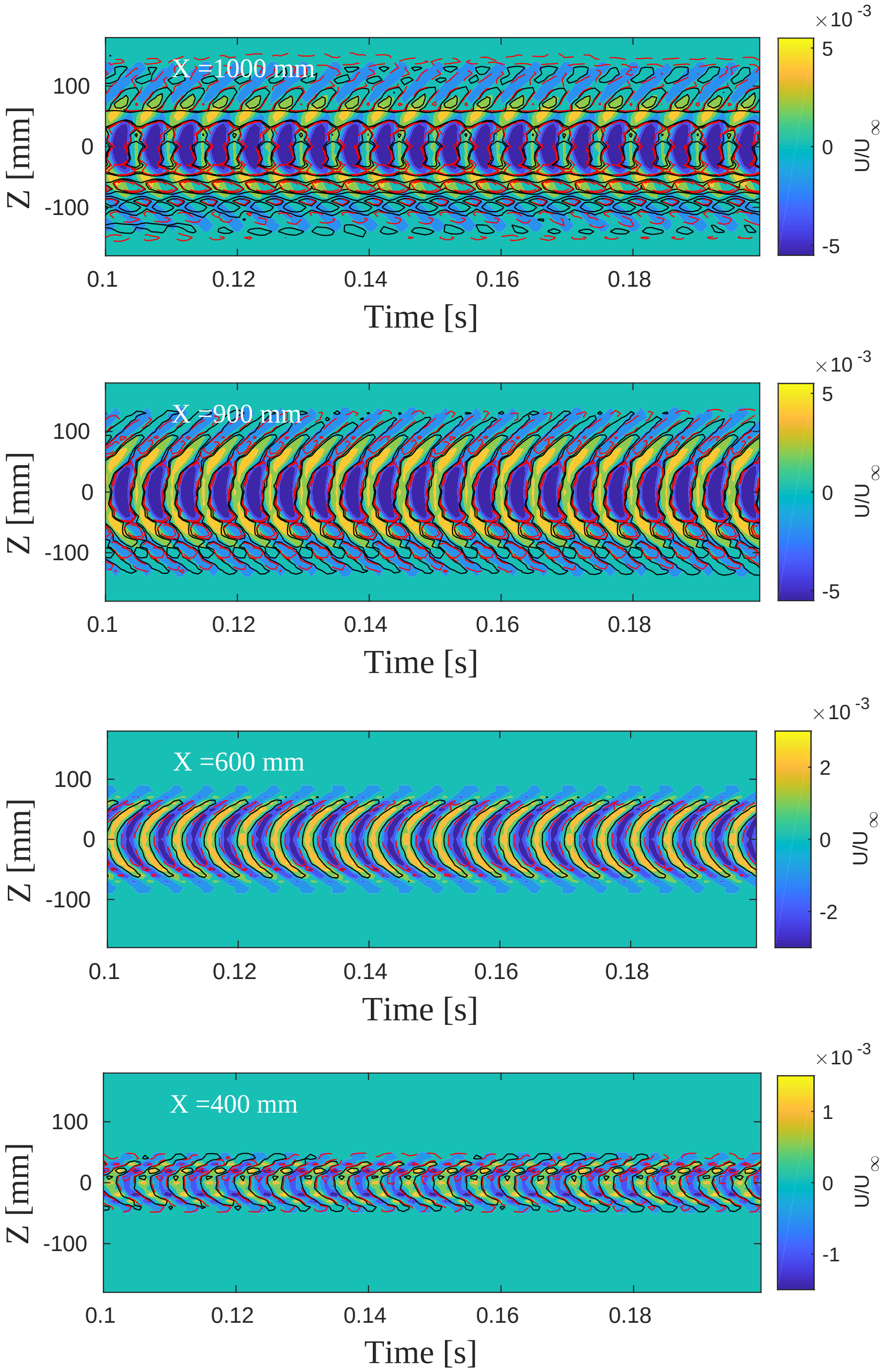


Figure 4. Comparison between DNS (filled contour) and experimental (contour levels) results from Medeiros (2004) for wavetrain evolution along the plate, U velocity fluctuation at $Y = 0.6\delta_0^*$. Solid black and dashed red represent positive and negative values for experiments.

4. CONCLUSIONS

Good agreement between the DNS solution and Blasius theory are presented. Reasonable comparisons with experiments on wavetrain evolution are also provided. Further analysis will include the pos-processing of the data, new parameters simulated and inclusion of roughness along the plate. The interaction between the roughness and the wave packet are the main interest of this work in order to study the most real situation of transition process.

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