COBEM 2021 26th International Congress of Mechanical Engineering
ABCM Associação Brasileira de Engenharia e Ciências Mecânicas
November 22-26, 2021, Virtual Congress, Brazil

COB-2021-0582
Numerical Simulation of the boundary layer laminar-turbulent transition caused by a small gap

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Abstract. *Aerodynamic surfaces in aircraft often have imperfections that might influence the location of the transition from a laminar to a turbulent flow and, therefore, impact the overall drag. Among such imperfections are small gaps, which have been observed to cause transition at an order of magnitude lower Reynolds number based on displacement thickness when compared to a smooth surface. The type of transition depends on the gap: more unstable gaps may cause greater oscillations and lead to a bypass transition; while more stable gaps may enhance Tollmien-Schlichting waves that will, then, lead to the transition. Previous studies by our group demonstrated that, contrary to smooth surfaces, gaps and cavities may become more unstable as the Mach number is increased due to Rossiter modes, causing the transition to move further upstream at higher Mach numbers. In this work, we simulate a boundary layer on a flat plate with a small rectangular gap. The free stream Mach number is 0.5 and the Reynolds number based on displacement thickness is 693 and 775 at the gap. The simulation is carried out by high fidelity 3D DNS. No artificial disturbance is used to force the transition, representing a quiet enviroment. At the time of this writing, the simulation is ongoing and is monitored by several probes at different stream-wise positions. The amplitude of the span-wise velocity component at the probes downstream to the gap is steadily growing, indicating an increasing tridimensionality of the flow. After the transient phase dissipates and a limit-cycle is reached, we intend to use the mean flow profiles to verify whether the flow has transitioned to turbulence. A DNS that can be used to simulate the transition to turbulence caused by a gap is a powerful tool in gaining a better understanding of this complex phenomenon and can be used to better explain experimental results.*

Keywords: *boundary layer, flow instability, transition to turbulence, DNS, open cavity*

1. INTRODUCTION

All the surfaces in aircrafts have some kind of roughness, steps and cavities. In this study, the gap was analyzed, since it is present in all plate joints, being present both in the fuselage and in the wings of the plane. The gap is nothing more than a small cavity, and previous studies have shown that gaps can collaborate in some way in the boundary layer transition (Crouch and Kosorygin, 2020).

The importance of this study comes from the fact that if it is possible to delay the transition, keeping the laminar flow for as long as possible, there is a decrease in drag, causing a decrease in fuel consumption. With the reduction in consumption, it is possible not only to increase reach, but also to reduce the emission of pollutants, a goal that has been intensely pursued by engineers over the years.

The cavities cause different types of instabilities, from instabilities due to Tollmien–Schlichting waves, to instabilities due to centrifugal modes and Rossiter modes. (Crouch and Kosorygin, 2020; Garicano-Mena *et al.*, 2018; Sun *et al.*, 2017a) It was observed that in gaps the instability mechanism due to TS waves, result in anticipation of the boundary layer transition.(Crouch and Kosorygin, 2020; Garicano-Mena *et al.*, 2018) An interesting effect obtained for cavities is that the temporal spectrum is sensitive to depth in relation to displacement thickness (Garicano-Mena *et al.*, 2018), and also the relevance of Mach number, for stabilization or destabilization of the boundary layer. (Sun *et al.*, 2017a) For the case where a turbulent boundary layer passes through a cavity, for small Ma, there is sound generation starting from the forward step.(Hao *et al.*, 2013)

For cavities, it is also possible to observe instabilities in the wake mode (Sun *et al.*, 2017a), where it was possible to observe two-dimensional Rossiter modes. However, wake modes are much more difficult to be observed in experiments, being found more in numerical results. Having an idea of what was found for the cavities, we need to return to our main focus of studies, the gaps.

As previously mentioned, the gaps have very small dimensions, being of the order of magnitude of the boundary layer, for the gaps we have interactions a little different from those found in the cavities, as well as a smaller experimental sampling. To overcome this deficiency, articles based on numerical simulations were used.

For the gaps, unlike the cavities, where transitions were found in wake mode, the transition occurred in the shear layer, with the presence of self-sustaining oscillations. (Rowley *et al.*, 2002) Again, different from the cavities, where the independence of Ma was observed in the oscillation frequencies, that is, where purely hydrodynamic instabilities existed, (Rowley *et al.*, 2002)in the gaps, one can observe the sound generation, present in low Mach numbers, as well as the dominance of the acoustic generation located in the forward step. (Hao *et al.*, 2013)

For gaps, the existence of three-dimensional modes, such as centrifugal modes and Rossiter modes present inside the gap, was documented.(Citro *et al.*, 2015; Bres and Colonius, 2008) Furthermore, it was possible to relate a modulation of the low frequency shear layer with the centrifugal mode contained in the cavity. (Bres and Colonius, 2008)

Moreover, as stated earlier, wake modes are difficult to observe in experiments. With everything in numerical experiments, it can be noticed that the frequency of wake mode is very close to that of Rossiter modes.(Sun *et al.*, 2017b) While for two-dimensional simulations, Rossiter modes go towards the shear layer, and different from that reported for larger cavities, where stabilization and destabilization is closely related to Mach number, three-dimensional instabilities, or centrifugal instabilities, are stabilized with the increase in Mach. (Sun *et al.*, 2017b)

It is important to emphasize that for different geometries, that is, gaps/cavities with shapes other than rectangular, such as Gaussian cavities for example, the same general characteristics could be found. (Thomas *et al.*, 2018)

Considering smaller cavities, the gaps, the purpose of this study was to seek how the presence of a gap with a length-to-depth ratio (L/D) equal to two interferes with the flow, with the interest of finding a region where Reynolds number based on displacement thickness, causes the boundary layer to transition.

2. METHODOLOGY

For the present study, a marginally unstable case was initially chosen. This case was chosen based on previous studies of the group, where a parameter sweep was performed (Mathias and Medeiros, 2019). All the case in question was non-dimensionalized by the displacement thickness of the boundary layer at the cavity's landing edge (δ_0^*), and by the free-flow velocity. Also follows the following definitions: length-depth ratio (L/D) equal to 2, as well as a depth of 5.77 δ^*. The cavity is situated at a Red* of 693, with Mach equal to 0.5 .

After preliminary results, it was decided to analyze a second case in parallel, an even more unstable case. For this case, the following characteristics were chosen: length-depth ratio (L/D) equal to 2, as well as a depth of 6.45 δ^*. The cavity is situated at a Red* of 775, with Mach equal to 0.5 .

Both situations were simulated using DNS. The DNS was developed by the group and written in Fortran 90, and it solves Navier Stokes' compressible equations. For the spatial resolution, the sixth order Compact Finite Difference Schemes with Spectral-like method was used, and for the bufferzones, the explicit fourth order method was used. For the temporal resolution, the fourth order Runge-Kutta method was used. A Fig. 1 contains a section of the X Y plane, to exemplify the operation of the mesh

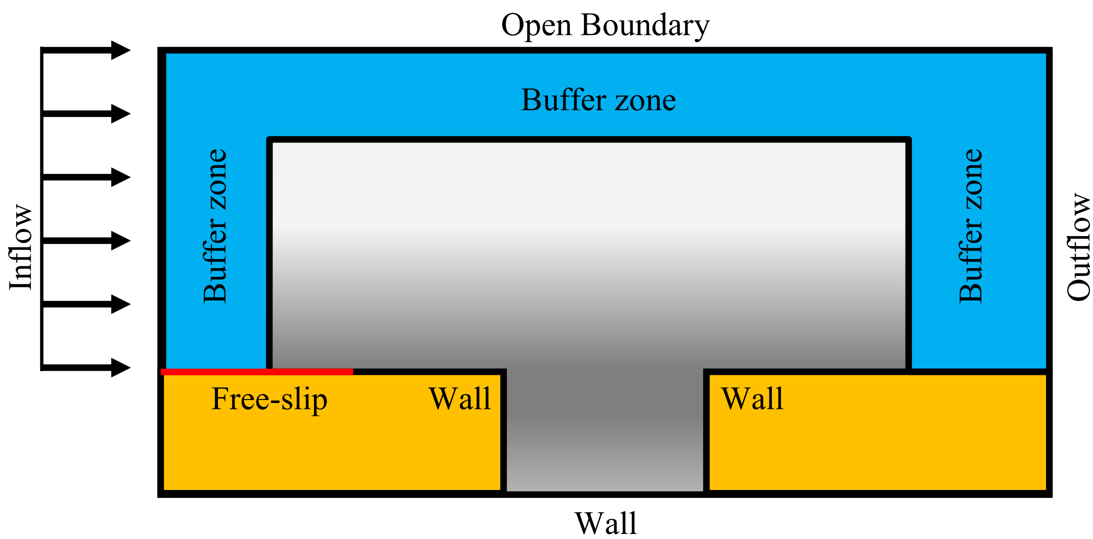

Figure 1. Illustrative image of the computational domain, the bufferzones are in blue.

For the stability analysis, the instability calculation code also developed by the group was used (Mathias and Medeiros, 2018).

For the first case, a perturbation was used only at instant zero, in the order of 10^{-6}, in the form of white noise in the entire domain, in all variables. This disturbance is needed to trigger the flow instabilities, which may eventually evolve into turbulence.

As can be seen in the results of the first case, the order of magnitude of the initial disturbance and the location turned out not to be the best choice, therefore, for the second case, the initial disturbance chosen was a white noise, with a Gaussian distribution with the value maximum being defined as 10^{-4}, and perturbation being centered in the center of the gap.

The preliminary results obtained were post-processed and the cross sections of the planes plotted in order to better understand the effects occurring in the simulation. The friction profiles on the wall were also plotted for different time points.

For both cases, the mesh N_x x N_y x N_z was defined from the initial two-dimensional simulation, and after the instability analysis, the domain in Z was defined to contain multiple frequency pairs in the most mode unstable. Thus having the best conditions to find the transition caused by the gap. For the second case, however, due to the oscillation amplitude found in the results, it was necessary to reduce the number of points in the Z domain by half, since to correct the divergence problems of the results, it was necessary to significantly increase the refinement in X (increase in 70 %), and in Y (increase in 30 %).

We also measured the friction, were also the friction means along the Z axis, for a better analysis of the mean flow behavior, therefore, all friction analyzes in the present work were made for the spatial mean of frictions.

3. RESULTS

3.1 CASE 1

For the first case, the $Re_{\delta^*} = 693$, and for this case, the mesh used was $N_x = 1075$, $N_y = 236$ and finally $N_z = 64$. For the first case, the X mesh has different spacing, with the largest number of points present in the gap and the gap's downstream. For the Y mesh, the greatest refinement was maintained in the region of the blend layer and in the regions from $-D$ to $+D$, with the objective of having the greatest possible refinement in the boundary layer. Finally, for the Z mesh, it was done with constant spacing, since the objective was to see the global effects of the gap. The Z-domain was defined as going from -12 to 12, to have 8 wavelengths of the most unstable mode inside the cavity.

For the results that will be presented, the cuts are in the XZ plane, in the position of $Y \approx \delta^*$.

As for this case, it was defined that a snapshot of the flow results would be saved every 100 time units of simulation, for the first flow saved, we have the U component of the velocity with the distribution present in Fig. 2.

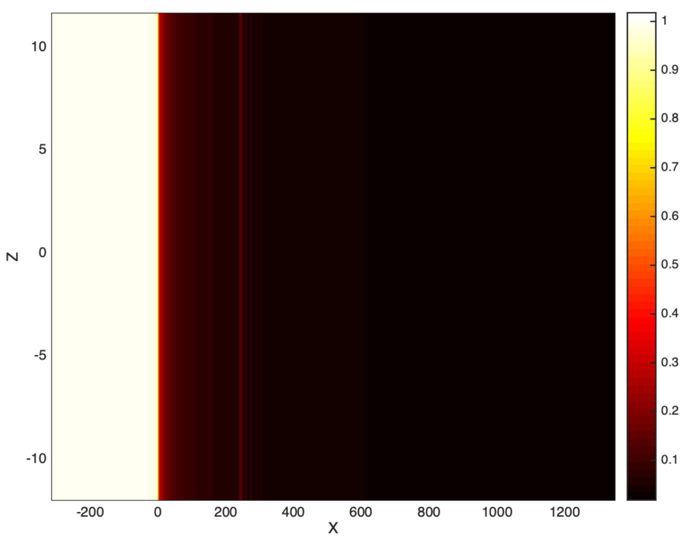

Figure 2. Colormap of the U component of the velocity for the instant t =100, in the first snapshot of the simulation.

Later, with the evolution of the system over time, the perturbation placed at the beginning of the simulation is amplified, generating visible modes inside the cavity, as can be seen in Fig. 3. To facilitate visualization, the X component of velocity was chosen for this figure, clearly showing the presence of structures along a line, where the cavity is located.

After a few more moments of evolution, the structures present in the cavity begin to leave through leaving the gap, propagating downstream of the gap. It is possible to visualize the U and W components, in order to show that the

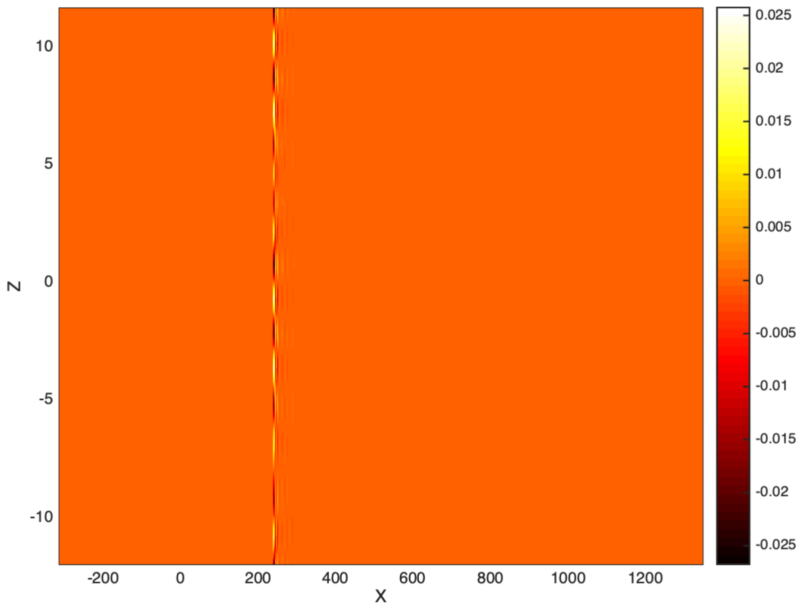

Figure 3. Colormap of the W component of the velocity for the instant t =1300, where we can see a line containing structures, where the cavity is located.

oscillations are not only present in one or another component. For the U and W components respectively, the cuts are available in Fig. 4, respectively.

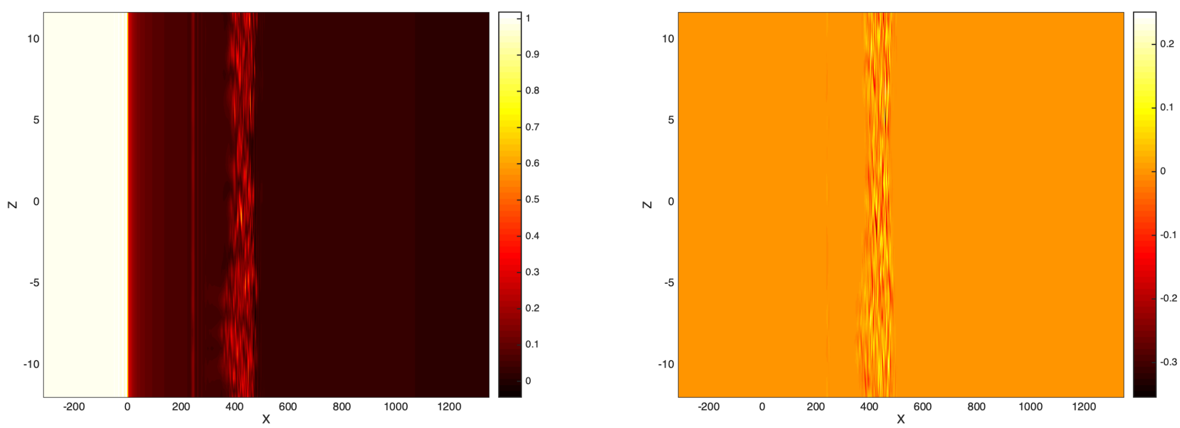

Figure 4. Colormap of the U and W components of the velocity for the instant t =1800, we can observe the oscillations in the entire XZ plane in both components.

In Fig. 5, it can be seen that there is a turbulent spot propagating downstream, however, it appears to stabilize again when outside the spot, showing an intermittent result, not showing a complete transition in the boundary layer.

Turning now to the analysis of friction on the wall, we can initially see how the friction was behaving, for that we can see in Fig. 6, that the region with the greatest friction is the cavity, due to the mixing layer.

With the evolution of time, and the appearance of the spot, we can see that wherever the spot passes, it considerably increases the friction of the region, being clear in Fig. 7, where the friction on the wall for two different instants, where the spot is in different positions.

It is then possible to see a first indication of a boundary layer transition. As this is a preliminary study, it is necessary to carry out a new study with a more refined mesh, such as the one needed for the second case. However, this first spot is an important result, showing that it is possible to see transitions, even if for this case it is not a complete transition, with the appearance of the spot, we see that using DNS, despite the difficulties of convergence and computational cost, also we can study transition.

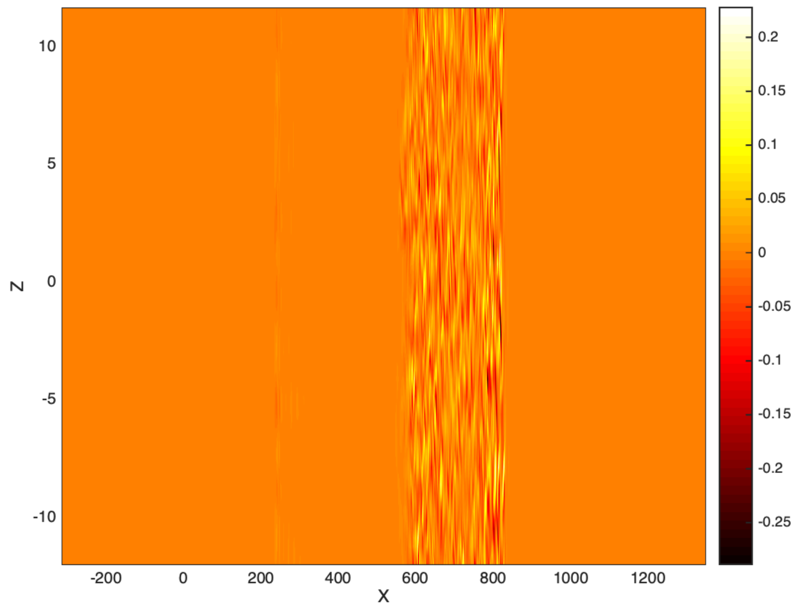

Figure 5. Colormap of the U and W components of the velocity for the instant t =2200, we can see that the oscillations are propagating further and further away from the cavity, with the fluid appearing to be more stable as the spot moves out of the domain.

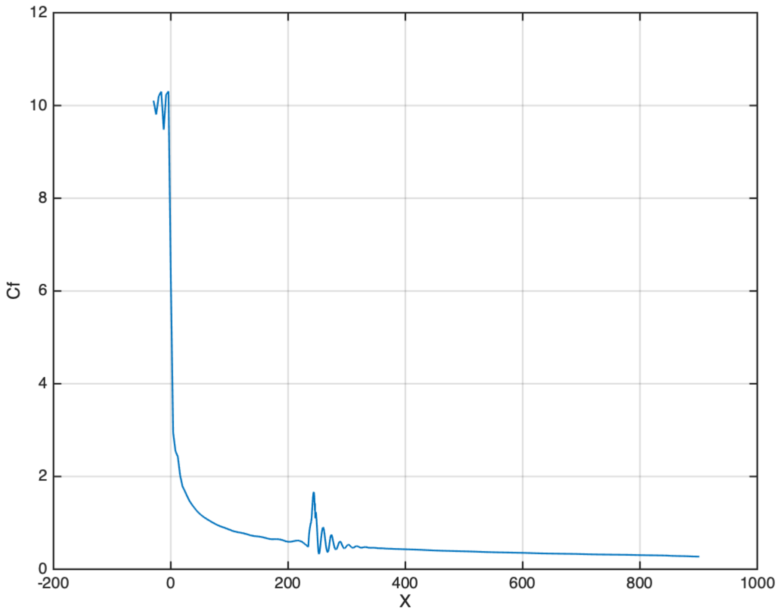

Figure 6. Friction on the wall, for the first stream saved, at time t=100, where the flux is laminar.

3.2 CASE 2

For the second case, the $Re_{\delta^*} = 775$, and for this case, the mesh used was $N_x = 1768$, $N_y = 306$ and finally $N_z = 32$. For the first case, the X mesh has different spacing, with the largest number of points present in the gap and the gap's downstream. For the Y mesh, the greatest refinement was maintained in the region of the blend layer and in the regions from $-D$ to $+2D$, with the objective of having the greatest possible refinement in the boundary layer. Finally, for the Z mesh, it was done with constant spacing, since the objective was to see the global effects of the gap. The Z-domain was defined as going from -4 to 4, to have 4 most unstable wavelengths inside the cavity.

Again, a Y was chosen for the cuts, with the cuts in the XZ plane, in the position of $Y\delta^*$. Thinking to better observe

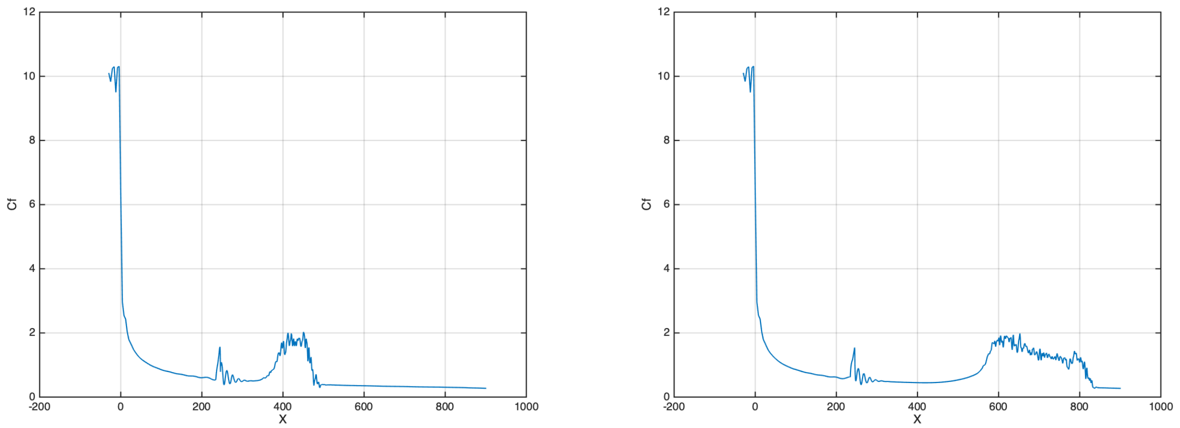

Figure 7. Friction on the wall, to move the spot, at time t=1800, and the time t = 2000, respectively.

the evolution of the system, for this case, it was chosen that every 25 time units of simulation a snapshot would be saved, so, again taking into account the first snapshot, we have in Fig. 8, placing the U and W components of the velocity side by side, realize that the system starts laminar, without three-dimensionality, and with the perturbation centered in the cavity, according to the Gaussian chosen initially.

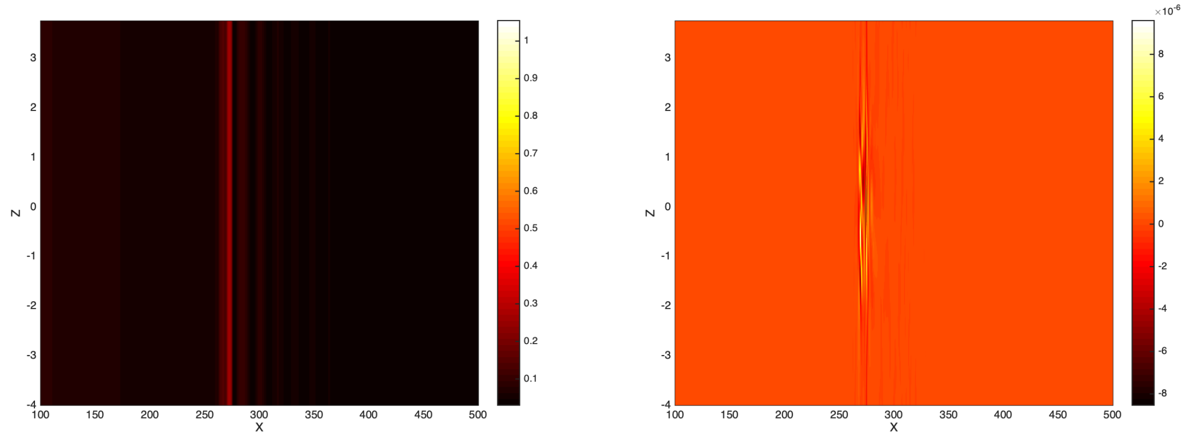

Figure 8. Velocity components for the instant t= 25, where we have a laminar flow for the U component, and is possible to observe the initial perturbation placed on the W component of the system respectively.

As in the previous case, according to temporal evolution, we have structures leaving the cavity, as well as amplification of the structures inside the cavity. These structures can be visualized in the velocity components, for better visualization, the U and W components were chosen again, contained in Fig. 9, it is possible to see some small structures downstream of the cavity. Phenomenon relatively similar to the one observed in the previous case. It is important to mention that much smaller structures left the cavity at times before this one, however, as the order of magnitude of the oscillations was very small, it was decided to present them only from the time t = 500.

However, unlike what was observed in the previous case, the oscillations, in addition to propagating, are self-sustainable, as well as amplified up to a limit, where they remain over time. We can observe, in Fig. 10, that the oscillations and structures are present in the domain after the gap. It is important to emphasize that oscillations start in the cavity and propagate downstream, where they amplify and increase in value, as well as with spatial evolution.

It can also be noticed that the oscillations fill almost the entire domain after the cavity, however, there is a small region, where there are not so many structures and oscillations. This region before the oscillations is located immediately after the cavity and is about twice the size of the cavity, that is, about 25 δ^* in length.

We can also make a comparison between the friction on the walls at the beginning of the simulation, at t=25 and at t=750, where it is expected to recover something similar to what was observed in the previous case inside the spot. For this, in Fig. 11, the Cf were placed side by side, where a lower friction is expected for t=25, where we have a laminar flow, in turn, it is expected a friction growth, as we expect non-laminar flow.

As previously mentioned, it is possible to notice a large increase in the average friction, which is really an indication

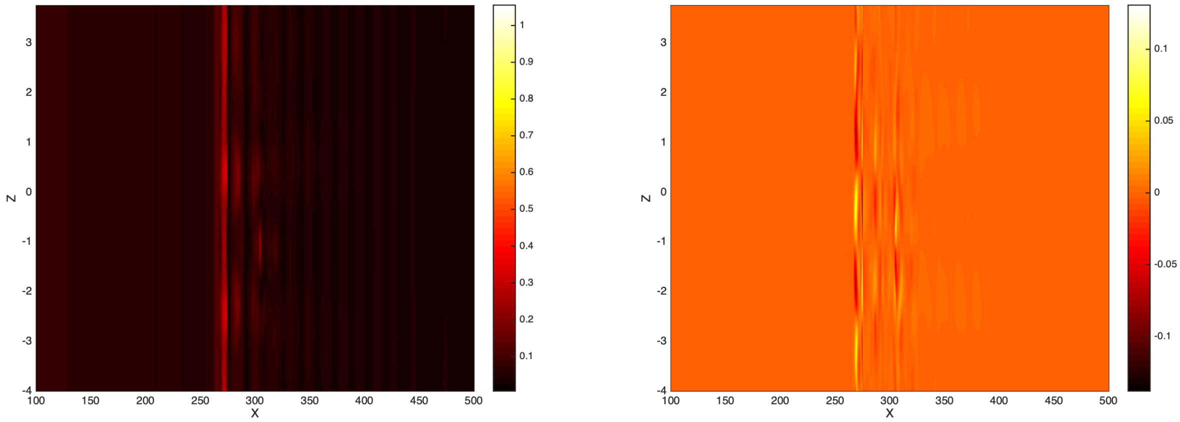

Figure 9. Velocity components for the instant t= 500, in this figure it is possible to see some structures in both the U component and the W component, respectively.

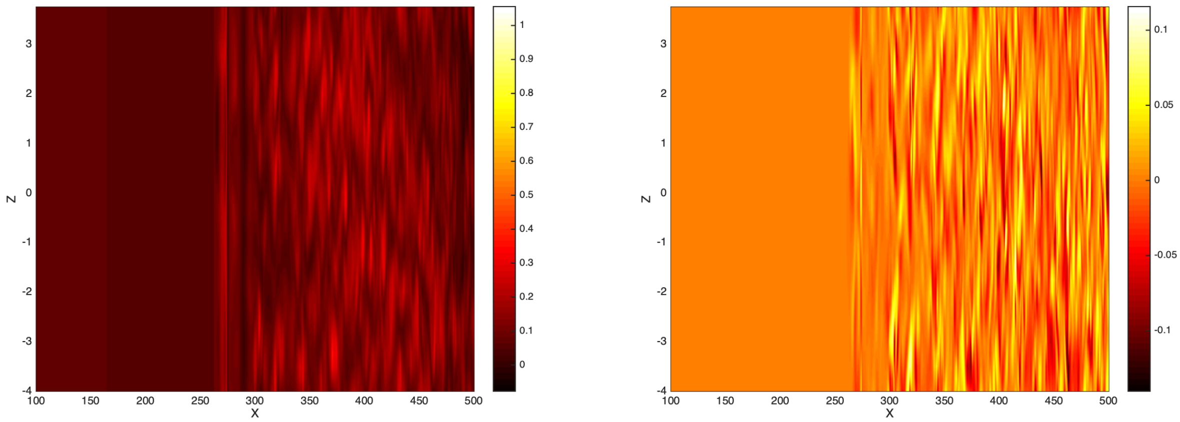

Figure 10. Velocity components for the instant t= 750, in this figure it is possible to see some structures in both the U component and the W component, respectively.

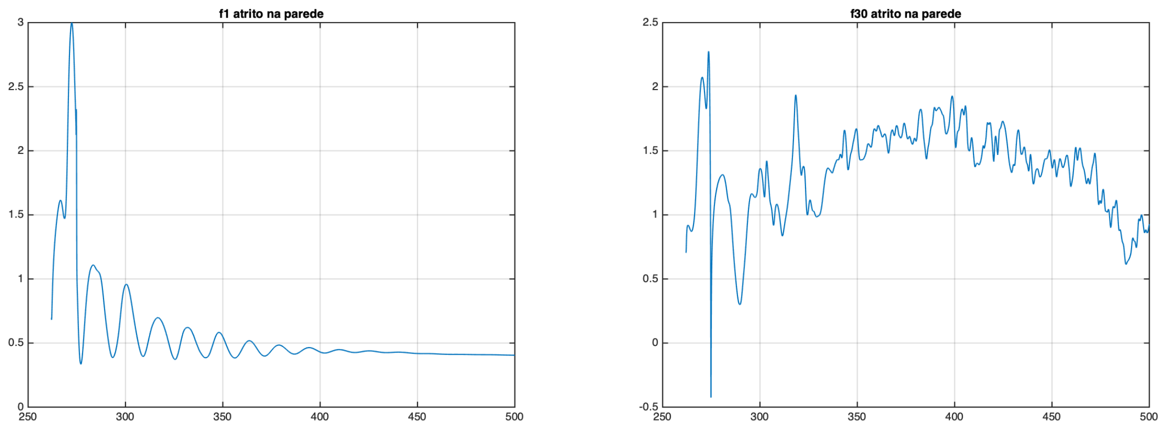

Figure 11. The friction on the wall for the instant t=25 and t=750 respectively, where an increase in friction can be observed, an indication of transition in the boundary layer.

that there is a possibility of a transition in the boundary layer. Again, different from the first case, evolving in time even more, we have again the presence of structures, in the downstream region of the cavity, the difference occurs, since the structures are maintained as time evolves. As seen in the previous case, a spot appeared that propagated downstream the cavity to the bufferzone. However, in the present case, the oscillations keep occupying the regions as time evolves.

It can be seen in Fig. 12 and Fig. 13, that even over time we keep the oscillations in the flow, as well as the region between the cavity and the larger oscillations. For Fig. 12, the instant t=1000 was chosen, placing again the components U and W of the velocity. For Fig. 13, the instant t =1250 was chosen, having the components U and W side by side.

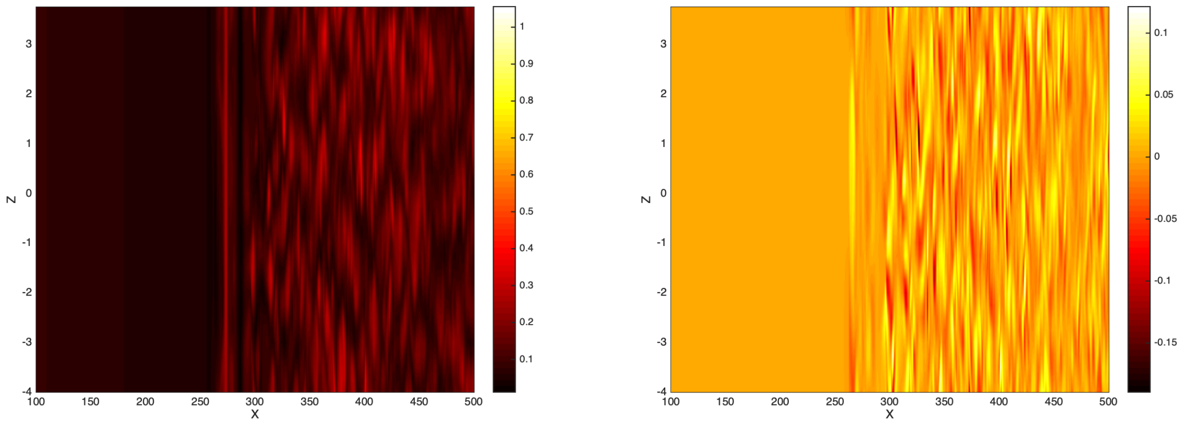

Figure 12. Velocity components for the instant t= 1000, in this figure it is possible to see some structures in both the U component and the W component, respectively.

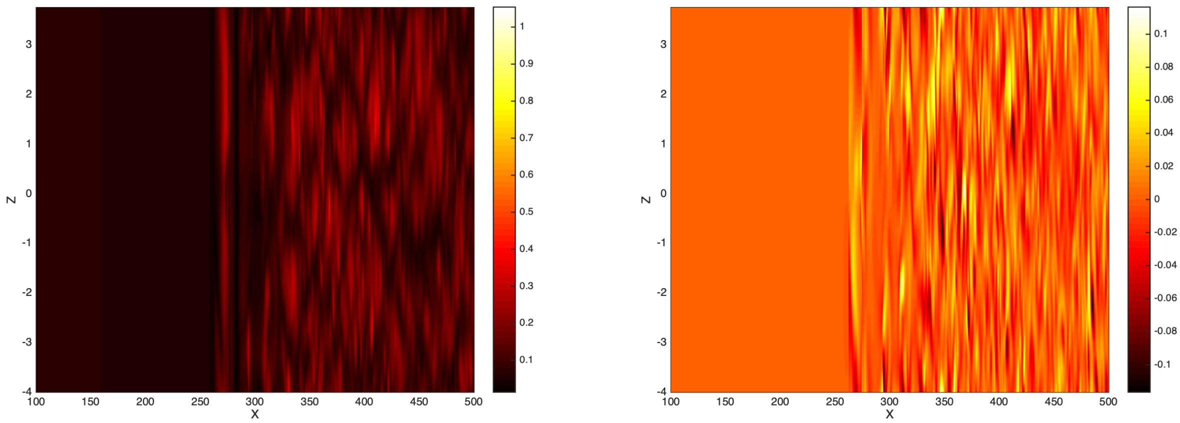

Figure 13. Velocity components for the instant t= 1250, in this figure it is possible to see some structures in both the U component and the W component, respectively.

In both instants of time, we can observe that the region between the cavity and the oscillating structures maintains approximately the same size as in instants. Therefore, we hope that over time, the simulation will maintain the limit cycle and the observed characteristics. Regarding the friction on the wall, we can observe that the increase in friction was maintained over time, in Fig. 14, we have the average friction on the wall for the instants t = 1000 and t = 1250 respectively, we can note, that despite the increase in friction, it is not exactly the same for different times. However, it is interesting to note that, as well as the structures and oscillations present in this case, the friction profile remains similar over time, different from that observed in the first case, where the change in friction follows the spot along its spread to the end of the domain.

For the continuation of the studies, simulations are being carried out in order to increase the amount of data, in order to have a better statistical sampling. Having a larger statistical sampling of this second case, it will be possible to determine if it really presented a transition, starting to have a purely turbulent flow.

3.3 DISCUSSION AND STUDIES IN PROGRESS

After the results obtained above, the focus of the present studies is focused on the use of the mesh of the second case, which mesh manages to capture with greater resolution the structures present in the DNS simulations. Three cases are being worked on simultaneously, the first case presented in this project is being re-studied with the new mesh as well as using a new domain. For the second case, the simulation is running in order to increase the sampling and increase the

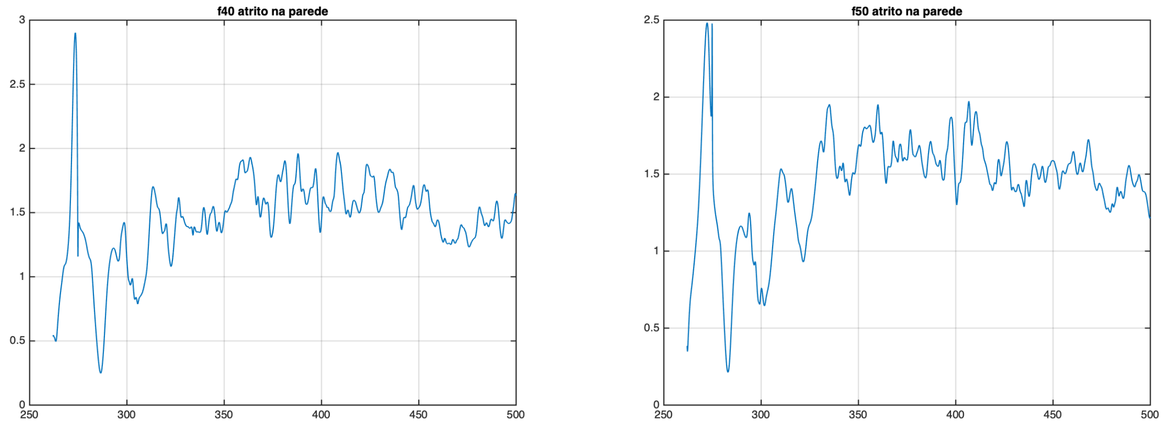

Figure 14. The friction on the wall for the instant t=1000 and t=1250 respectively, where where we can see that the friction characteristics are being maintained over time and space.

number of data, with this it is expected that in the future it will be possible to carry out a precise statistical analysis and better capture the flow behavior over time. Finally, a third intermediate case is being studied, with a Reynolds number $Re_{\delta^*} = 734$, for this case, we seek to know what the behavior is, if we will see intermittent spots, or if we will see a behavior continuous.

Finally, after the studies mentioned, we intend to study cases where the oscillations may be greater, increasing the Re_{δ^*}, since, as seen, it is expected that with this increase, the instability of the system will increase. We still cannot guarantee that the transition occurred, but with the evidence obtained so far, and presented in this work, we can see that there are signs that we are on the way to find and perhaps map the laminar-turbulent transition using DNS.

4. CONCLUSION

Numerical studies in boundary layer are extremely important for aerodynamics, since knowing where and how the laminar-turbulent transition occurs, one can try to avoid the transition, causing drag reduction, thus reducing fuel consumption and pollutant emission. Within this study, numerical simulations of the DNS type were employed using high numerical precision, in order to try to find cases where this transition could occur.

Although preliminary, the present study analyzed 2 cases, the first is marginally unstable, and the second is comparatively more unstable case. For both cases, three-dimensional DNS was used, simulations with more than 1.5×10^6 points, demanding intensive use of computers. The preliminary results obtained showed for the first case, a turbulence spot being generated by the cavity, however, it was the only indication obtained in this case. We conclude from this first case that more studies are needed, using more refined meshes, as was done in the second study, to find out if the spot was generated due to the mesh or if it is really an intermittent effect. It is also necessary for the DNS to run longer, in order to acquire much more data, so that we have statistical results with much more relevance, and thus having quantitative results. In the meantime, what we have are just qualitative results that have shown us ways to follow, better directing the studies of the second case.

For the second case analyzed, it was necessary to reduce the domain, as well as further refine the mesh, due to several divergence problems in the DNS solution. Resulting in a mesh, with a much greater refinement, indicating that there is a possibility of loss of structures in the first case due to the mesh size. Using the initial perturbation of the second case, it was also possible to obtain self-sustainable amplifications with less simulation time, needing to be tested also in the first case, to confirm the results. The importance of the second case comes from the evidence obtained of a possible transition to a turbulent regime. The still preliminary indices need an extensive simulation time to obtain a much larger amount of data, making possible a much more rigorous statistical analysis, and obtaining quantitative results

However, despite the qualitative results, we were able to see that despite being at the beginning of the studies, apparently the research is going on the right path. Preliminary results also show us where the problems may lie, thus knowing where we should focus our efforts, avoiding problems and increasing the efficiency in the use of resources available for research.

5. ACKNOWLEDGEMENTS

M.S.M is sponsored by FAPESP (grant no. 2018/04584-0). M.A.F.M. is sponsored by CNPq/Brazil (grant no. 307956/2019-9), sponsored by FAPESP (grant no. 2019/15336-7) and the US Air Force Office of Scientific Research

(AFOSR) for grant FA9550-18-1-0112, managed by Dr. Geoff Andersen from SOARD; the University of Liverpool for the access to the Barkla cluster, provided by Prof. Vassilios Theofilis; and the Center for Mathematical Sciences Applied to Industry (CeMEAI) funded by São Paulo Research Foundation (FAPESP/Brazil), grant 2013/07375-0, for access to the Euler cluster, led by Prof. José Alberto Cuminato.

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