Mitigation of roughness-induced boundary layer transition for engineering applications

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Boundary layer transition to turbulence caused by surface roughness can significantly increase skin friction in different engineering applications. Recent studies at the University of Texas have shown that such a roughness-induced transition (RIT) can be delayed using control strips and other surface textures, for a parameter regime relevant to insect impacts on low-speed aircraft wing leading edges. This project examines a range of other engineering scenarios, such as racing yacht hydrofoils, automotive applications, helicopter blades, gas turbine blades, and wind turbine blades where roughness-induced transition could be a potential issue. These applications have different operating conditions, such as much higher free-stream turbulence intensity compared to aircraft applications. This project thus involves an extensive literature review, estimation of parameters, and computation of relevant dimensionless numbers such as roughness Reynolds numbers and turbulence intensities across the different applications. To validate the possibility of a new application, preliminary computer simulations were executed to examine the challenges in transition mitigation for the wind turbine application.

Applications

In order to identify markets in which roughness-induced transition is an issue, identifying parameters that are comparable to those that exist for aircraft provide an insight into whether or not the strips would be of benefit to the application. Five low-speed aerodynamic applications were considered at the beginning of the study—racing yacht hydrofoils, automotive applications, helicopter blades, gas turbine blades, and wind turbine blades. To get an overview of all the applications and identify which are most applicable, a table with characterizing parameters such as those listed below helped in answering the big question of whether or not the application has a market.

Characterizing parameters and questions: Re_δ on Re_c, Re_{kk}, Tu (U'_{RMS}/U_∞, $X_{transition}/c$, $\frac{dp}{dx}$, c, multielement?, U_∞, υ, $X_{transition}$, evidence of RIT (e.g. wedges), Roughness source? Where does it accumulate? Roughness height, K?, U'_{RMS}, flow separation? When? How Big?, and amount of harm by roughness element.

Racing Yacht Hydrofoils and Racing Car Wings

The first applications investigated were the racing yacht hydrofoil and racing car wings. In an attempt to identify some of the characterizing parameters, a paper written by Luke S. Roberts, Mark V. Finnis, and Kevin Knowles titled Characteristics of *Boundary-Layer Transition and Reynolds-Number Sensitivity of Three-Dimensional Wings of Varying Complexity Operating in Ground Effect* and *Effect of the laminar separation bubble induced transition on the hydrodynamic performance of a hydrofoil* by P.L. Delafin, F. Deniset, and J.A. Astolfi were read. In the hydrofoil application, the paper focused on running a computational fluid dynamics study on the effect of a laminar separation bubble on a smooth hydrofoil. While reading this paper, it became apparent that the parameters identified were not relevant to the question at hand. Although many parameters were of no use, it is important to note that the simulation was tested at conditions such that the Reynolds number was equivalent to $7.5x10^5$. Similarly, the research conducted by Roberts et al. on the racing wing also did not include key information that contributed to a better understanding of whether racing car wings could be a marketable application. The wind tunnel experiments executed had the purpose of looking at downforce as a function of ground clearance and Reynolds number. The experiments were executed at Reynolds numbers ranging from $1.63x10^5$ to $2.85x10^5$. Considering that both the hydrofoil and racing car wing application executed experiments using Reynolds numbers in the range that is applicable for aircraft, it is possible that other parameters of both of these applications are comparable to the case in which the University of Texas at Austin has already studied where strips work to mitigate roughness induced transition—airplane wings. However, the decision of not pursuing these applications was made in the interest of time.

Helicopter Blades

Helicopter designers are wanting to use the amount of laminar flow to reduce drag thus making transition position an important aspect of design. As helicopters are used for defense, medical, entertainment, and many more purposes, the source of damage to the blades comes from a range of elements. Roughness elements include, but are not limited to, insect contamination, metallic erosion, dust, and dirt. The effect of surface roughness effects a helicopter's thrust and power coefficients. Found in Richter and Schulen's experiments , the minimal drag coefficient is

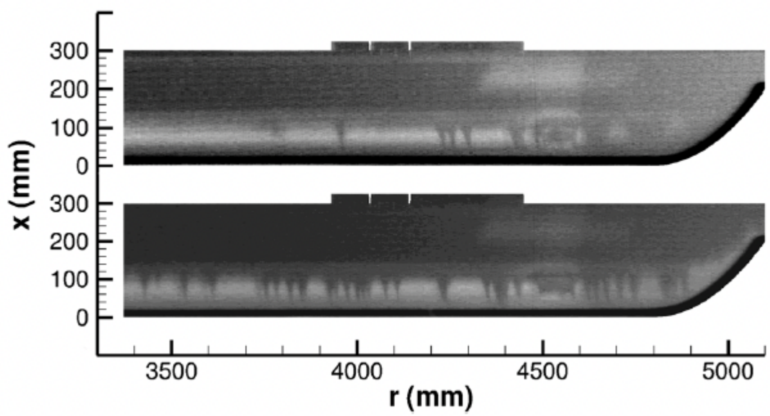


Figure 1. Clean and contaminated full-scale EC135 rotor blade tip (top and bottom, respectively)

lowest when a helicopter blade has a smooth surface. An increase in surface roughness results in a rise in drag coefficient. This same pattern is seen in the thrust-to-power ratio. From Richter and Schulen, Figure 1 shows proof of roughness induced transition. Turbulent wedges can be seen in a clean and contaminated comparison image of a full-scale EC135 rotor blade tip. In addition, Richter and Schulen show another contaminated helicopter blade section of a BO105 with turbulent wedges (Figure 2). This goes to show that RIT presents an impact on this application and the performance of helicopters has the potential to improve once a mechanism is developed to

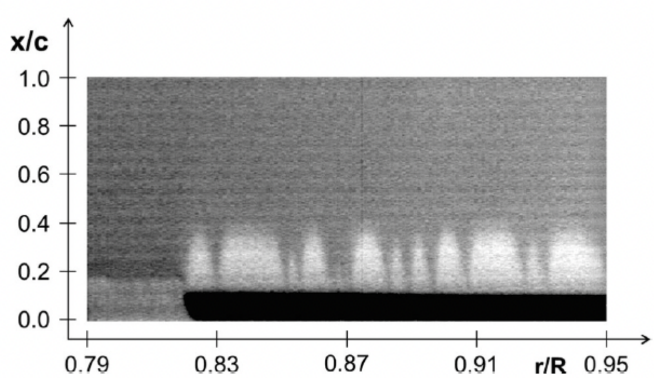
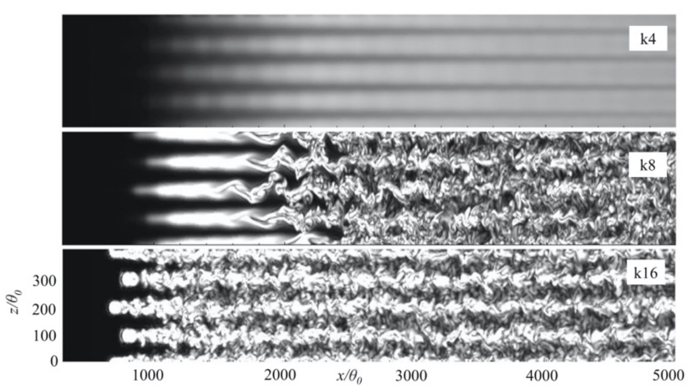


Figure 2. Contaminated BO105 rotor blade section

mitigate RIT. Although this seems like a feasible application to pursue, there are critical parameters needed in order to compare the environments of an aircraft with that of a helicopter. Considering the timeline of the study, the only parameter identified as to be within range of the airplane application is the Reynolds number. The Re_c of a helicopter is found to be between $Re_c = 1.24x10^6$ and $1.3x10^6$. Although Re_c is comparable, it is important to gather information on the average roughness height, *k*, roughness Reynolds number, Re_{kk}, and freestream disturbance a helicopter experiences.

Low Pressure Gas Turbine Blades

Gas turbines are used to power most modern aircrafts and for electrical power generation. Low pressure turbines drive the fan of the engine and produces 80% of the thrust (Sengupta). There is a direct correlation between the efficiency of a low pressure turbine and fuel consumption. Any improvements on efficiency can save money as well. Since these blades experience a vast range of environmental conditions, roughness elements such as corrosion, erosion, combustion products, dust, and dirt (Sengupta). Figure 3 shows a simulation carried out by Vadlamani et al. where multiple roughness element heights were tested, turbulent wedges can be seen. Re_{kk} is set to be 150, 400, and 800, for test case k4, k8, and k16, respectfully. When $Re_c = 2.5x10^4$,the free stream turbulence intensity (FSTI) is found to range from less than 1% to about 3% in between the wakes. When in the wakes, the FSTI increases around 8% (Volino).

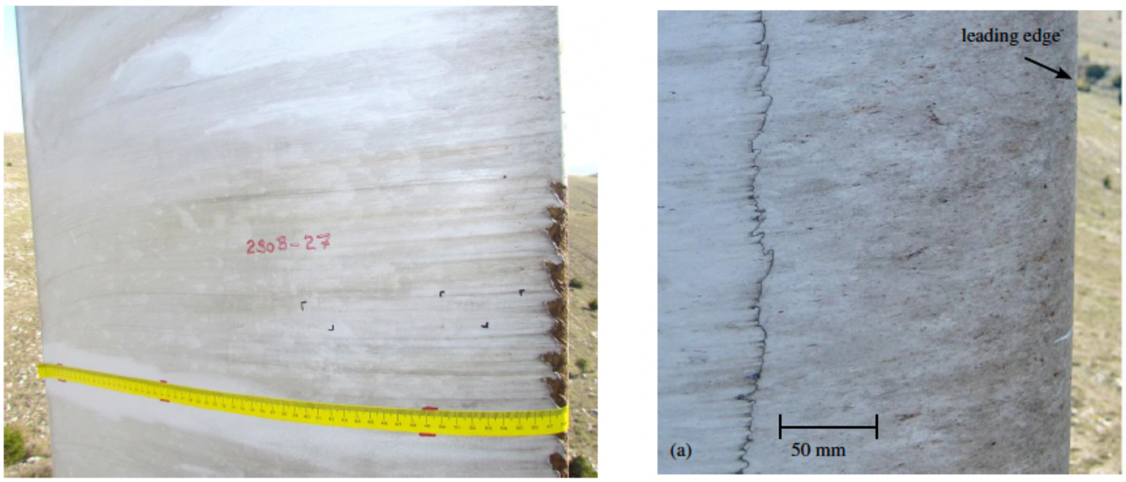


(a) On a wall normal height of $y/\theta_0 = 20$.

Figure 3. Turbulent wedges for different Re_{kk} values (Vadlamani)

Wind Turbine Blades

It's estimated that 20% of the world's energy will be harnessed from wind by 2030 (energy.gov). It is important to ensure that the rotors are able to produce maximum power without any loss due to roughness on the leading edge. Sources of leading edge roughness include insects (k = 100 μm-140 μm), erosion and chipped paint (k = 1.0+/-0.1 mm), icing, dust, and dirt (Ehrmann and White). The erosion (Figure 4a) causes micrometer scale deviations in the smoothness of the wind turbine. Similarly, chipped paint (Figure 4b) creates a small roughness element step and deviates the wind from its original path. The difference between erosion and chipped paint is that erosion causes pits and gouges in the wind turbine blade, while the chipped



a. **b.**

Figure 4. ***a.*** *leading edge erosion* ***b.*** *paint chipping near the leading edge (Ehrrmann and White)*

paint strips off layers. For simplicity, a deeper evaluation of paint chipping on the leading edge is executed to identify if there is a market for RIT mitigation. To prove if this application is applicable, it is critical to understand the detrimental effects of the paint chipping to the trajectory of wind passing over the wind turbine, and at what point the roughness of the leading edge becomes too severe.

In an IR image from Ehrmann and White, bypass transition occurs once roughness becomes critical and forms turbulent wedges. Effects of this turbulence show that as roughness height and density increase, lift-curve slope, $C_{l\,max}$, and drag decrease. Ultimately, these charateristics need to be optimized to maintain a steady-energy-produciing wind turbine. The turbulent wedges are proof that RIT occurs and the idea that wind turbine performance can be enhanced through RIT mitigation. In order to do so, being able to understand an analysis of a wavy forward facing steps with a z-normal height, κ, wavelength, λ, and wave height, H will aid in the steps to improving wind turbine capabilities.

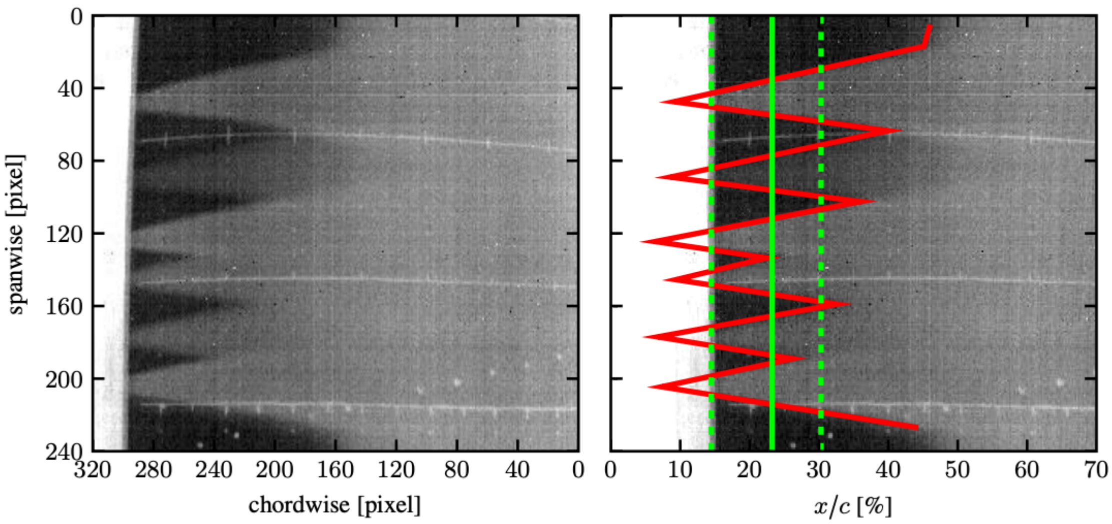
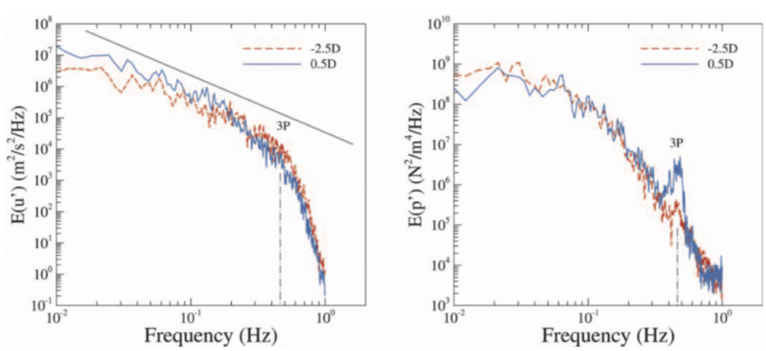


Figure 5. Turbulent wedges produced after bypass transition occurs

Comparable parameters have been identified for the case of chipped paint. The roughness height was found to be K = 157 ± 6 μm. The roughness Reynolds number is equivalent to Re_{kk} = 246 ± 27 @ Rec= 2.4E6 (Ehrmann and White). The Free stream disturbance frequency is concentrated in Hz as depicted in Figure 6—emphasis on the fact that it is not in the order of kHz (Churchfield). Re_{kk} is in the order of hundreds, the free stream disturbance is mostly concentrated in low frequency, the case is comparable to an airplane that experiences RIT. If any of the aforementioned parameters are found to be out of range in comparison to the airplane case, adjustments would have to be made to the in-house direct numerical simulation solver.

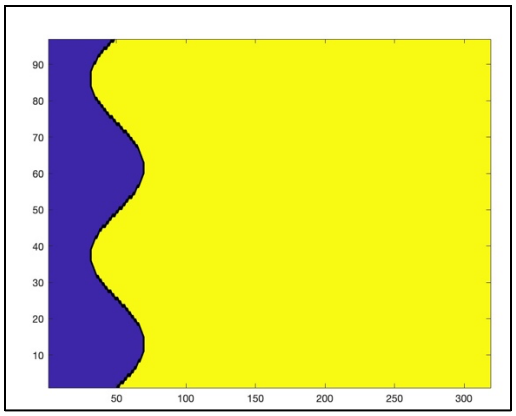


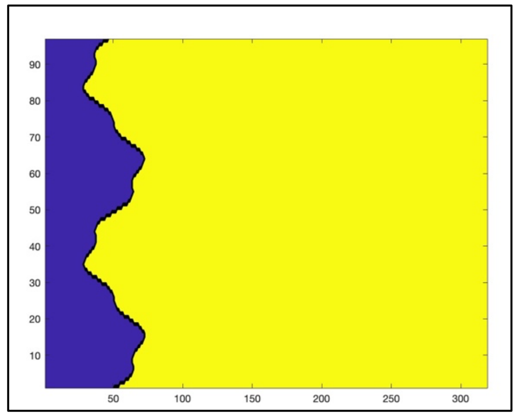
a. **b.**

Figure 6. Spectra of (a) the streamwise velocity fluctuation and (b) the pressure fluctuations sampled at 50 Hz and 2.5 rotor diameters upstream (red) and 0.5 rotor diameter downstream (blue) of the turbine center line at a height equal to the top of the rotor disk from the high-roughness neutral case

Computation

As an initial step prior to running the DNS code, a mesh had to be generated. Figure 7 shows a topographic plot of the different meshes used to run the DNS code. Figure 7a shows a single sinusoid for comparison to the other cases. Figure 7b shows a double sinusoid that was calculated based on the following equation: $xs = @(z)\, x0 + (A * sin(N * (2\prod z)/Lz) + A2 * sin(N2 * (2\prod z)/Lz))$. Where x_0 is somewhere in the middle of the domain, A is the amplitude of the wave, z is the z location, and Lz is the spanwise direction of the test section.





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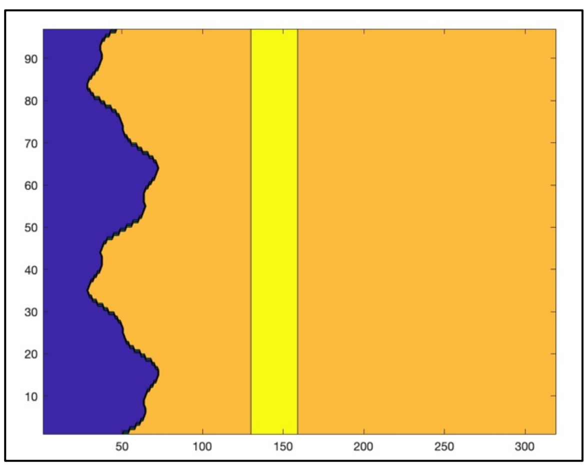
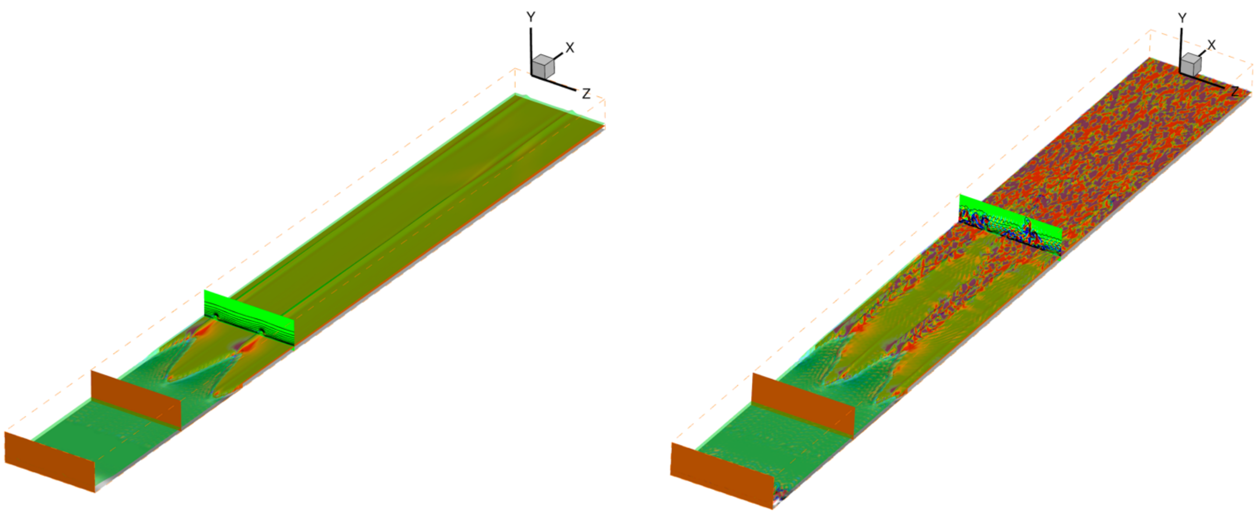


c.

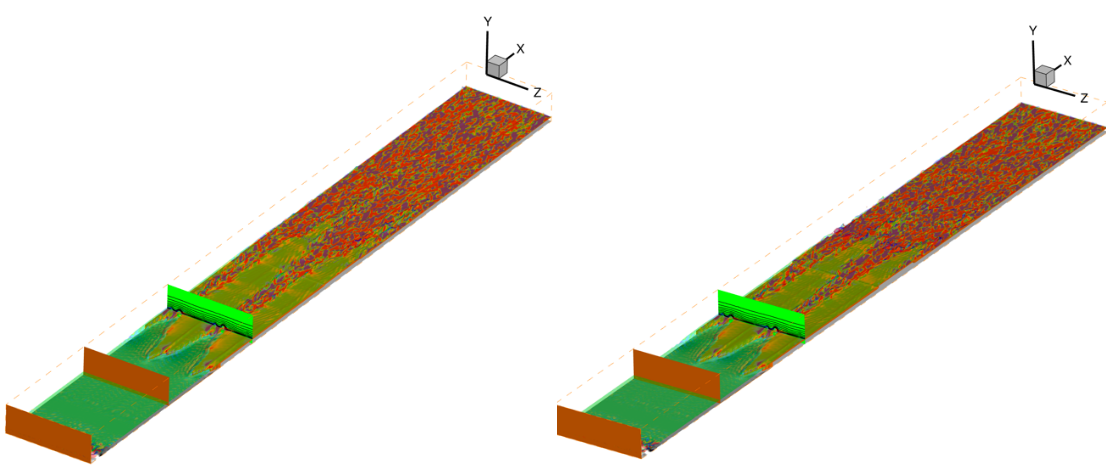
Figure 7. a Single sinusoid with wave frequency = 2, A =1, step height =0 .07 ***b.*** *Double sinusoid with wave frequency = 2 and 8, A = 1 and 0.2 step height = 0.07* ***c.*** *Double sinusoid with wave frequency = 2 and 8, A = 1 and 0.2 step height = 0.07 and strip with step height = 0.2*

After running the DNS code, Tecplot 360 was used to visualize the data. The plots in Figure 8 do not contain a strip to attempt RIT mitigation. However, the plots in Figure 9 contain a 0.2 and 0.5 height strip that spans across the entire domain of z. The plots are colored by ω_x and the freestream velocity. It's worth noting the visual difference in Figure 8a and Figure 8b. By changing the wave to represent a double sinusoid, turbulence is seen. Few among many reasons why this could be happening is because Figure 8a has not been run for long enough and/or the step height needs to change. From Figure 9a, there is not much of a difference when



a. **b.**

*Figure 8. **a.** Single sinusoid with wave frequency = 2, A =1, height = .07 **b.** Double sinusoid with wave frequency = 2 and 8, A = 1 and 0.2*



a. **b.**

*Figure 9. **a.** double sinusoid with same parameters as Figure 4b **a.** strip with height 0.2 **b.** strip with height 0.5*

the strip height is 0.02 or 0.05. Further investigation needs to be completed to draw a conclusion on the possibility of a wind turbine blade having a RIT mitigation market. All simulations were ran at a low resolution, therefore may be missing key data. In the next iteration of this simulation, the simulations should be run at a higher resolution in addition to extending the runtime. With these changes, more conclusion information can identify if strips would be sufficient and marketable for wind turbine blades that experience roughness induced transition.

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