

Effects of Random Micron-Sized Roughness on Swept-Wing Transition

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This study examines the effect of random micron-sized distributed roughness on stationary crossflow instabilities. The roughness parameters are varied by creating nanoparticle coatings of various formulations and applying them to inserts that cover approximately the first 14% of the model. In addition to the baseline configuration (no added roughness, root-mean-square (RMS) $\approx 0.42 \mu\text{m}$), panels with RMS roughness values of 4.8 and 8.6 μm were tested, with correlation lengths of 1029 and 385 μm , respectively. Despite the significant roughness levels tested, the transition location was found to be only mildly impacted by the additional roughness, and the roughness panel with lower RMS amplitude caused a larger upstream movement of transition, on average. However, the stationary crossflow amplitudes and wavelength content were found to vary substantially depending on the roughness input. In particular, the panel with higher RMS roughness amplitude resulted in significantly larger amplitudes in the 7.5–9 mm wavelength range at the farthest upstream measurement station, while the lower roughness panel resulted in mildly larger amplitudes at 10 mm and wavelengths larger than 15 mm. Nonlinear Parabolized Stability Equations (PSE) computations were performed to attempt to estimate the initial amplitudes of the stationary crossflow instabilities. Wavelength spectra were matched at the most upstream measurement location, but large discrepancies exist between the predicted and measured growth behavior farther downstream, thus, more work is required to improve confidence in initial amplitude estimates.

I. Nomenclature

A_0	=	initial amplitude of disturbance
c	=	chord length
C_p	=	pressure coefficient, $C_p = \frac{p - p_\infty}{\frac{1}{2}\rho U_\infty^2}$
k	=	wavenumber, $k = \lambda_z^{-1}$
N	=	N -factor
Re'	=	unit Reynolds number
Tu	=	turbulence intensity
u', v', w'	=	fluctuating velocity components in the x , y , and z' directions
U, V, W	=	mean velocity components in the x , y , and z' directions
U'	=	steady disturbance velocity
U'_{rms}	=	spanwise root mean square of steady disturbance velocity, U'
U_e	=	boundary-layer edge velocity
U_∞	=	freestream velocity
x	=	streamwise direction
x_{tr}	=	streamwise transition location
y	=	wall-normal direction
z	=	spanwise direction (parallel to the leading edge)
z'	=	direction normal to the streamwise direction
λ_z	=	spanwise wavelength

II. Introduction

LAMINAR to turbulent boundary-layer transition is an important flow phenomenon with far-reaching implications. Accurate transition prediction is of high importance for numerous applications. For example, laminar flow control (LFC), a promising technique for improving the fuel efficiency of aircraft, relies on the ability of transition models to accurately predict transition locations. In real-world applications, disruption of laminar flow can occur if small protuberances or surface imperfections are present on the wing surface. These imperfections can result from insect residue, rivets, bolts, steps, gaps, paint, and background surface roughness. In order for LFC to be effective in an operational environment, it is crucial that we understand how surface irregularities affect transition.

In swept-wing, low-turbulence flows, such as the environment experienced in flight, stationary crossflow instabilities are known to be the dominant transition mechanism [1, 2]. It is well known that stationary-crossflow instabilities are highly sensitive to micron-sized distributed roughness [3, 4]. Radeztsky et al. [3] noted a significant delay in transition when the model surface was polished from 3.3 μm rms (9 μm peak-to-peak) down to 0.25 μm rms. The sensitivity is ascribed to the observation that the random distributed roughness contains physical length scales that are dangerous for transition. However, it is not clear how best to quantify roughness parameters to help predict the impact on the stationary crossflow instabilities. In most studies where it is relevant, the surface roughness value is simply quoted as a single number, usually the root-mean-square or average roughness height.

The physical mechanisms that account for the impact of distributed roughness on stationary-crossflow instabilities can be divided into three categories: receptivity, altering of the instability growth, and local scattering. Receptivity refers to the process by which external disturbances (in this case, surface imperfections) are introduced into the boundary layer, essentially determining the initial amplitudes of the various stationary-crossflow modes [1, 5, 6]. This process requires that the length scales of the external disturbances and the instability modes be comparable. The receptivity process is typically most effective near the leading edge, where the lower-branch neutral curve of the crossflow eigenmodes is located. Because the boundary-layer is so thin near the leading edge, it is highly sensitive to very small roughness amplitudes. Thus, receptivity is considered to be the primary mechanism resulting in the high sensitivity of stationary-crossflow instability to surface roughness.

The present study is focused on the impact of random micron-sized roughness on the initial amplitude, wavelength content, and growth of stationary crossflow instabilities. Roughness is varied near the leading edge, thus, receptivity is the primary mechanism of interest. While most stationary-crossflow receptivity studies have focused on the impact of discrete distributed roughness elements (DREs) [7, 8], the impact of random roughness is more directly applicable to realistic problems of interest. A recent experimental and theoretical study by Borodulin et al. [9] and Crouch et al. [10] explored the impact of varying random roughness distributions and freestream turbulence. However, the impact of the roughness topology was not a primary focus of the study. For the current study, the surface roughness topologies are fabricated in a way that affords some control over certain roughness parameters. For instance, we attempt to keep the RMS constant, while varying the wavelength content. Independent control of various roughness parameters will allow us to determine the importance of these parameters.

III. Experimental Setup

The experiment was performed in the 2-Foot by 3-Foot Low Speed Boundary-Layer Channel at the NASA Langley Research Center. The tunnel is a closed circuit facility with a 0.61-m high by 0.91-m wide by 6.1-m long test section. The tunnel can reach speeds up to 45 m/s ($Re' = 2.87 \times 10^6/\text{m}$) in the test section. Freestream turbulence intensity levels, $Tu = \frac{1}{U_\infty} \sqrt{\frac{1}{3}(u'^2 + v'^2 + w'^2)}$, were measured using a crosswire in an empty test section to be less than 0.05% for the test speed of 26.5 m/s. This value represents the total energy across the spectrum, high-pass filtered at 0.25 Hz. Thus, this tunnel is considered a low-disturbance facility for purposes of conducting transition experiments [11].

The 0.0127-m thick flat plate model consists of a 0.41-m long leading edge piece, swept at 30°, and a larger downstream piece (see Fig. 2). The model is 0.91 m wide (thus, spanning the width of the test section) and 2.54 m long on the longest edge. The downstream or leading edge pieces can be adjusted relative to each other using precision shims to create either forward-facing or backward-facing 2D steps of different heights, parallel with the leading edge. For the current test, the pieces were adjusted to be flush to avoid a step. Both the leading edge and larger downstream plates have a surface finish of approximately 0.4 μm . A leading-edge contour was designed for the bottom side of the plate in order to make the suction-peak less severe and avoid separation, which could potentially cause unsteadiness in the attachment line.

A 3D pressure body along the ceiling was designed to induce a streamwise pressure gradient, which, along with the sweep, causes stationary crossflow growth. A second purpose of the ceiling liner was to simulate infinite swept-wing

flow within a midspan measurement region of width 0.3 meters. This was achieved by designing the liner such that the C_p contour levels parallel with the leading edge within the measurement region were constant. The ceiling liner was fabricated out of a hard foam using a computer-controlled milling machine. All measurements were performed at a freestream velocity of 26.5 m/s ($Re' = 1.69 \times 10^6/m$). Since no pressure taps were included in the model, pressure belts were temporarily installed to measure the surface pressure distribution. The pressure belts consisted of ribbon tubing with 20 tubes, each with an outer diameter of 1.6 mm and an inner diameter of 0.71 mm. Results from these measurements are plotted in Fig. 1. For more details of the experiment setup, refer to Eppink [12].

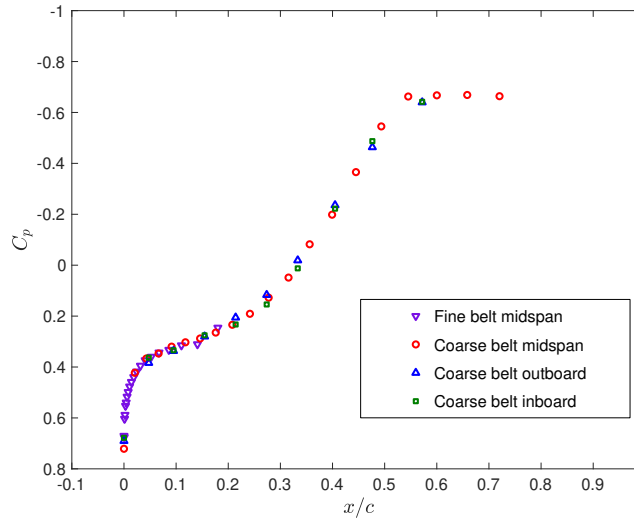


Fig. 1 C_p distribution measured using pressure belts

For the current study, the leading edge piece was designed to include an insert that could be used to study different random roughness coatings. This insert extends from approximately $x/c = 0.0175$ to 0.15 and spans a width of 457 mm (the middle half of the model). The insert can be adjusted using set screws to achieve a sufficiently flush juncture with the surrounding plate ($\lesssim 0.05$ mm). The roughness panels themselves are fabricated from 0.4-mm thick aluminum sheet metal, wire EDM cut to the shape of the insert. A one-inch perimeter around the edge of the panel is masked off before the nanoparticle roughness coating is applied to the panel surface. The panel is then taped onto the insert using thin double-sided tape and the insert is adjusted so that the edges are flush with the surrounding plate. Any remaining gaps are filled with clay and smoothed. Due to the masking of the panel edges, the roughness extends from approximately $x/c = 0.0185$ to 0.14.

IV. Experimental Procedure

A. Naphthalene Surface Flow Visualization

Sublimating chemicals have been used for many years as a tool to document transition location in a variety of flow conditions [13]. The sublimating chemical (in this case naphthalene) is mixed with a solvent and sprayed onto the model surface. Since the sublimation rate of naphthalene is sensitive to shear stress, the chemical will sublime faster in turbulent regions of the flow. It is often even possible to view the tracks of the stationary crossflow vortices with this technique. For this test, the naphthalene was dissolved in the solvent at a ratio of 10:1 (solvent to solute), and a pressure-fed spray gun with a 1-m extension was used for an in situ application of the coating due to the limited space between the model and the ceiling liner. Only the region downstream of the roughness insert was sprayed to avoid contaminating the roughness or the leading edge of the model with any additional roughness from the naphthalene.

A camera located above the test section was used to document the naphthalene flow-visualization results. Due to the ceiling liner, optical access is limited to a window located upstream of the leading edge of the liner, and the model surface is visible from just upstream of the leading edge-model juncture to approximately 1.4 m downstream of the leading edge. Before testing, a grid was drawn on the model as a spatial reference, and a baseline picture was acquired. The pixels of the grid were extracted and overlaid on subsequent pictures to provide spatial information. The

naphthalene images presented herein have been unswept and undistorted to aid in visual interpretation of the results.

B. Particle-Image Velocimetry Measurements

A high-speed double-pulsed Nd:YLF laser provided the laser sheet for the particle image velocimetry (PIV) measurements (see Fig. 2). In previous tests, the laser sheet was set up parallel with the leading edge, with two high-speed 4-megapixel cameras acquiring the time-resolved PIV (TRPIV) measurements in a stereo configuration. However, this configuration only allowed limited movement in the streamwise direction, due to the required camera angles. Thus, for the current setup, the laser sheet is now oriented in the streamwise (x) direction, and two cameras are used in a 2D-PIV configuration. This setup allows measurements to be performed over most of the laminar-flow portion of the model. To achieve the laser setup, a mirror was placed downstream of the test section, mounted through the gap between the test section and diffuser section of the tunnel. In order to acquire measurements of the stationary crossflow amplitude, multiple streamwise planes of data must be acquired in the spanwise direction and then compiled together to obtain the spanwise planes. The downstream mirror is mounted on a traversing system, which allows motion in the spanwise direction, so that multiple planes of data can be acquired across the span. Likewise, the cameras are mounted on a traversing system that allows motion in all three directions, and this system is aligned to move precisely with the mirror traversing system in the spanwise direction.

Two cameras were used for this setup, each with 300 mm lenses, achieving a total field of view of approximately 50 mm by 25 mm, and allowing measurement of the u - and v -velocity components. The two cameras were separated in the streamwise direction by approximately 10 cm and were used to simultaneously acquire data, primarily to reduce the required acquisition time. The data presented in this paper consist of multiple streamwise-oriented planes covering a spanwise measurement region. Eight to nine such regions were acquired for each case, covering a large portion of the laminar flow region from approximately $x/c = 0.16$ to $x/c = 0.5$. For each streamwise location, 120 planes of data were acquired, separated by approximately 0.866 mm in the z -direction and spanning a total region of approximately 100 mm. Five hundred image pairs were acquired at each location, and these image pairs were processed using a 16x16 pixel interrogation size, with 50% overlap. These processing parameters resulted in an in-plane spatial resolution of approximately 0.15 mm. For ease of data processing, the system was traversed parallel with the leading edge, which allowed reconstruction of planes parallel with the leading edge without any interpolation required. The resulting measurement volume covered approximately 10 wavelengths of the primary stationary-crossflow mode. An oil-based fog machine generated the seeding, which was introduced downstream of the test section.

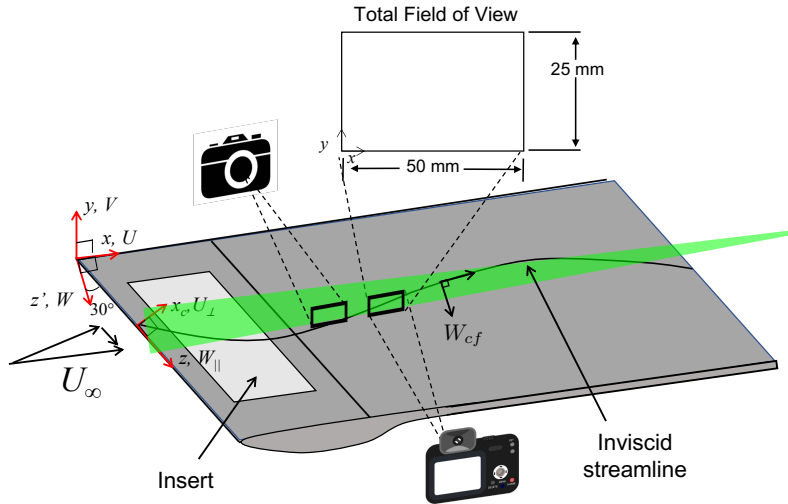


Fig. 2 Sketch of model coordinate system and TRPIV setup.

Table 1 Roughness Panel Parameters.

Panel	RMS (μm)	Peak-to-peak (μm)	Correlation length (μm)	Mean x_{tr}/c^a
Baseline	0.42	1.79	153	0.5/0.5
TP 1	8.64	39.36	385	0.498/0.474
TP 2	4.78	20.68	1029	0.48/0.471

^a The first value given for x_{tr}/c is averaged across the full measurement region from $y/c = -0.06$ to 0.06 . The second value is averaged across just the PIV measurement region.

V. Results and Discussion

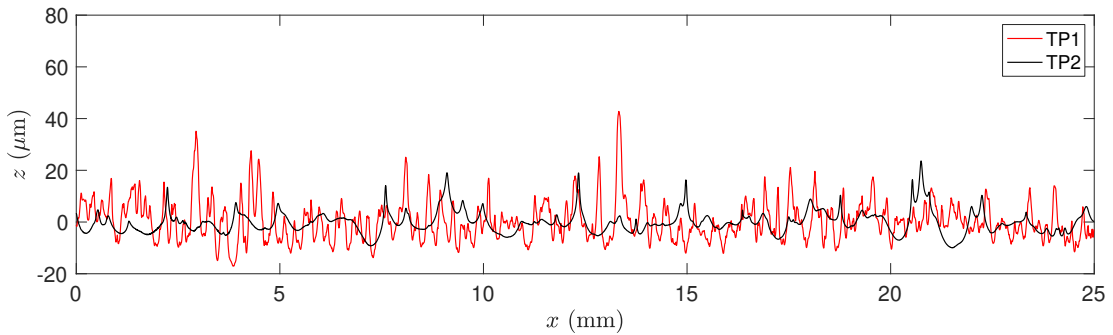
A. Surface Roughness Inserts

The roughness panels were fabricated by spraying the panel surface with nanoparticle coatings of varying formulations. The size and weight ratio of the the nanoparticles were varied to obtain different roughness parameters. The goal has been to generate roughness panels of similar RMS levels, but with varying wavelength content. Initial tests were promising, but recreating the panels with the desired roughness properties has proven to be more difficult than expected. Thus, on-going work is presented in this paper, consisting of results from a baseline (no-added roughness) panel and two panels with different roughness formulations. Both formulations use an epoxy-based coating with nanoparticles of different sizes and weight percentages. Test Panel (TP) 1 was formulated with 5 weight percent fumed silica particles, while TP2 was formulated using $70\ \mu\text{m}$ diameter glass spheres at 7.5 weight percent.

Throughout this paper, the baseline configuration refers to the case with no additional roughness. For this case, a blank aluminum panel (i.e., before any roughness coating is applied) was installed onto the insert in the leading edge. The root-mean-square (RMS) values, peak-to-peak values, and correlation lengths obtained from contact profilometry scans of each surface are given in Table 1. These values were computed by averaging the measurements obtained from six 25-mm long scans, three of which were obtained in the streamwise direction, and three of which were obtained in the spanwise direction, at various streamwise and spanwise locations on the panel.

Example traces from the surface profilometer are given in Fig. 3 for TP1 and 2. It is clear from the roughness traces that the topologies of these two panels are quite different, particularly in terms of the correlation length. As mentioned previously, the goal with these two formulations was to match the RMS level, but this clearly was not achieved, as TP2 has a substantially lower RMS amplitude, by almost a factor of 2.

The wavelength content of the two panels is examined by plotting the power spectral density (PSD) of the roughness measurements. Again, these PSDs are averaged from the six profilometer traces. The wavenumber ($k = \lambda_z^{-1}$) PSDs are shown in Fig. 4 for the two roughness panels, as well as the baseline panel. The energy content is quite similar between TP1 and TP2 for the larger wavelengths ($\lambda_z > 1\ \text{mm}$). TP1 has significantly more energy than TP2 at all wavelengths smaller than $1\ \text{mm}$. Both roughness panels contain significantly more energy than the baseline panel across the wavelength spectrum.

**Fig. 3 Roughness traces of TP1 and TP2.**

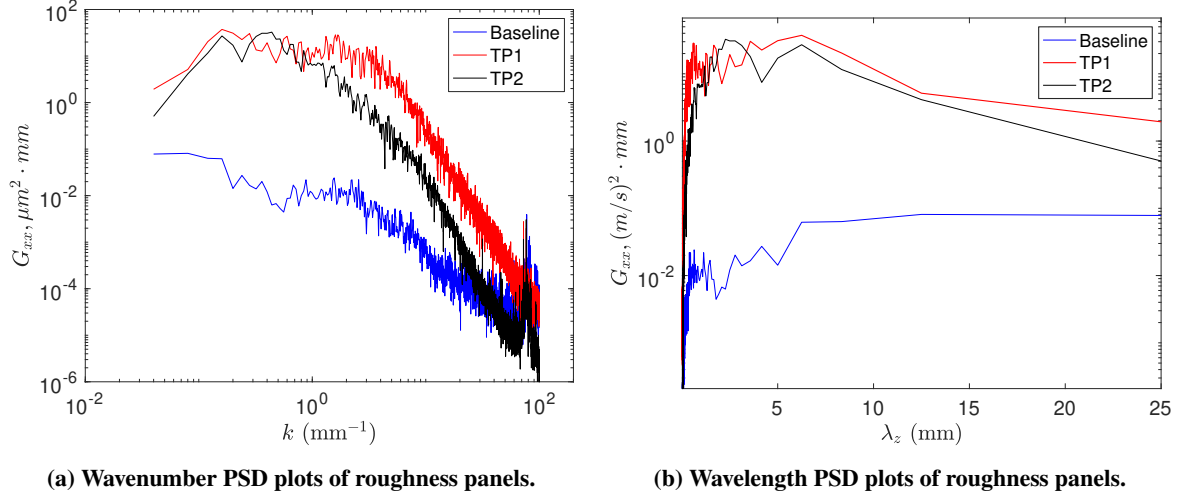


Fig. 4 Wavenumber and wavelength PSD plots of roughness panels.

B. Transition Location Measurements

For each panel, naphthalene flow-visualization was performed to determine the impact of the additional roughness on the transition location. The results are shown in Fig. 5 for each of the three cases. The flow is from bottom to top, and the white regions in these images correspond to regions of laminar flow, while the darker regions near the top of the image indicate turbulent flow. The green rectangles illustrate the area that was covered by the PIV measurements for each case. The saw-tooth transition pattern seen in these images is indicative of stationary-crossflow dominated transition. Interestingly, the elevated roughness from the panels only seems to have had a small effect on the transition front. The first transition locations reported in Table 1 were obtained by finding the location of maximum slope in the image intensity ($\partial I / \partial x$) at each y/c location, and averaging that across the full measurement region of $-0.06 < y/c < 0.06$. Additionally, the transition locations were averaged only across the spanwise extent of the PIV measurement region, and these are the second x_{tr}/c numbers reported in Table 1. It is surprising that the panel with the largest roughness (TP1) appears to have only moved the average transition location by $x/c \approx 0.002$, while TP2 resulted in an upstream movement of $x/c \approx 0.02$. However, when looking only at the PIV measurement regions, the transition locations were slightly farther upstream and more comparable between the two roughness panels. Given the larger increase in roughness levels provided by the panels, this minimal change in the transition front location is somewhat surprising. This is especially true when one considers the significant change in transition location ($> 0.2x/c$) observed by Radeztsky et al. [3] when the roughness level was increased from 0.5 to $3.3 \mu\text{m}$ rms, at similar Re_c compared to the present experiment. This difference in behavior illustrates the fact that the impact of surface roughness on the transition location is very configuration dependent.

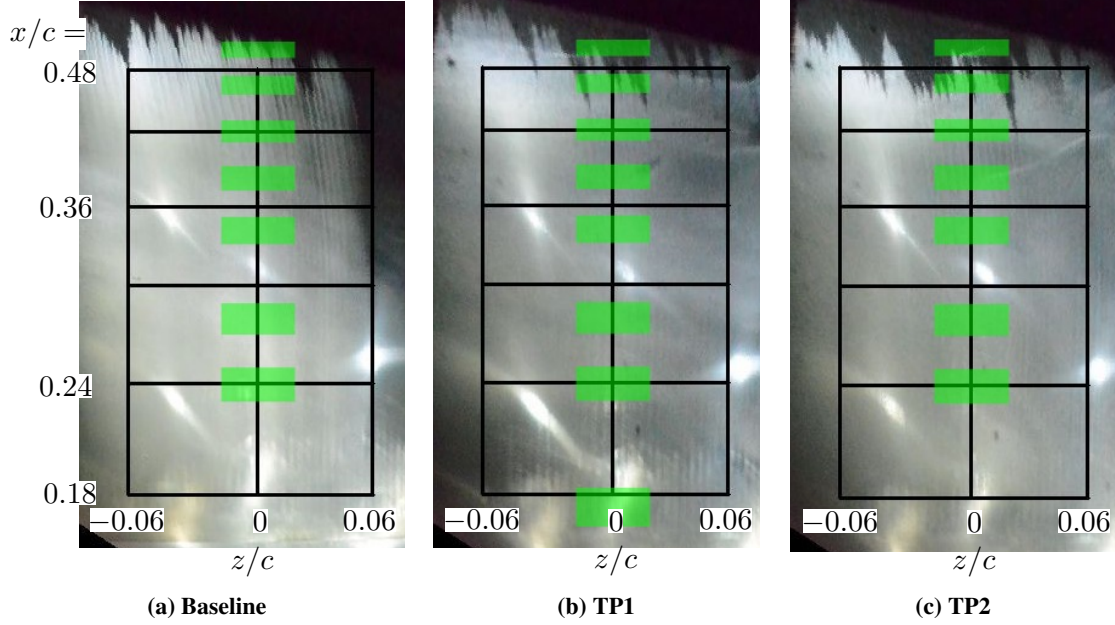


Fig. 5 Naphthalene flow-visualization of transition front. Green rectangles indicate regions measured using PIV [Source: NASA].

C. Boundary-Layer Measurements

For most cases, data were acquired at 7 streamwise stations, ranging from $x/c = 0.23$ to $x/c = 0.51$, as illustrated in Fig. 5. An additional set of planes were acquired for TP1 at $x/c \approx 0.16$. Several reconstructed spanwise planes are shown in Fig. 6. These planes were constructed by taking the first profile from each $x - y$ measurement plane and plotting them vs. z . At the farthest upstream measurement location of $x/c = 0.23$, the mean flow distortion caused by the stationary crossflow instabilities is just barely evident for the baseline case. The distortion is more evident at this location for the two roughness panel cases. By $x/c = 0.37$, the mean flow distortion is clearly evident for all three cases. Since there is no controlled roughness input for the baseline case, the stationary crossflow amplitude and wavelength is somewhat nonuniform across the measurement region. The mean flow distortion resulting from the two roughness panels appears somewhat more uniform, particularly for TP1. By the last station shown, $x/c = 0.455$, the stationary crossflow vortices are at or near saturation, and there are localized regions of very high spanwise shear.

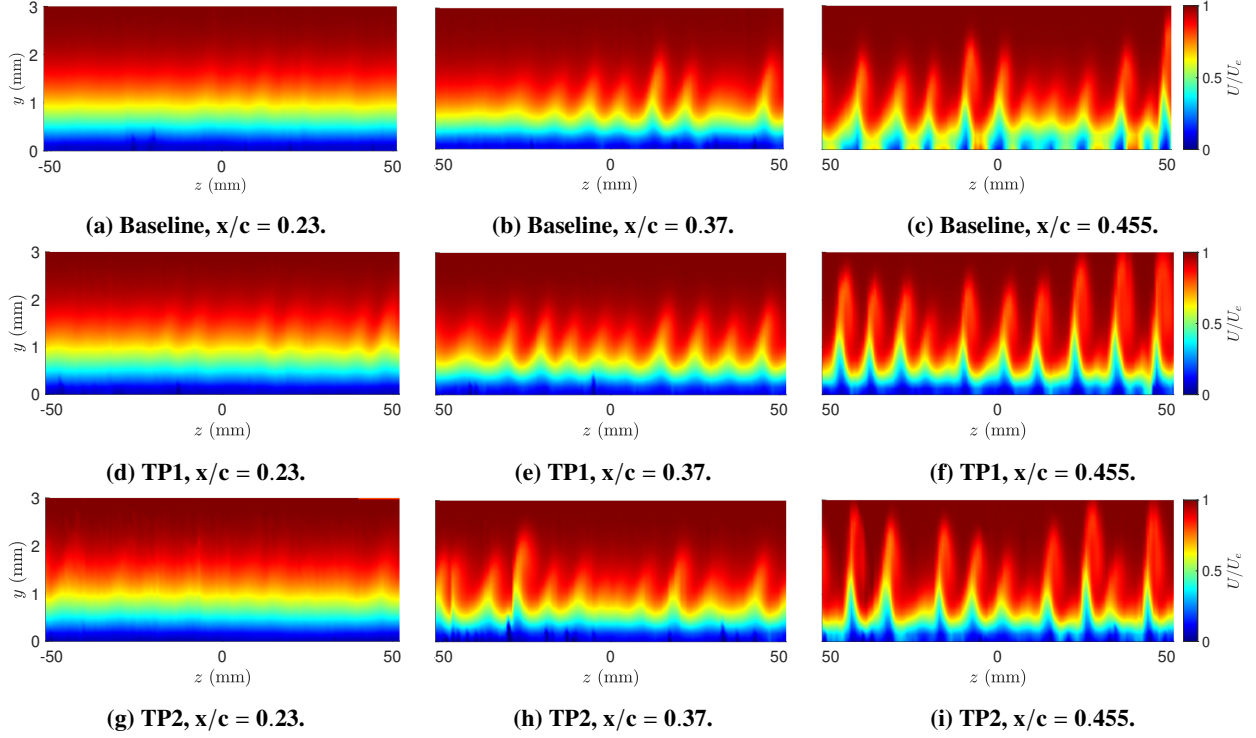


Fig. 6 U -velocity profiles for all cases at selected streamwise locations.

The development of the stationary crossflow instability amplitude vs. x/c is plotted in Fig. 7. To obtain these amplitude values, the wavelength spectra are computed at each y -location for a given x/c plane and integrated from $\lambda_z = 5$ to 20 mm. These values are then plotted vs. y to visualize the mode shape, and the maximum amplitude (in y) is chosen as the amplitude of the mode at that streamwise location. The U'_{rms} amplitudes (normalized by U_e) are plotted in Fig. 7a. The wavelength filtering is performed primarily in order to filter out any larger or smaller wavelength noise that exists in the measurement. Results are plotted for the first and last x -locations within each $x - y$ measurement plane that was obtained, thus, 14 to 16 locations are included in the plot.

The amplitudes at the farthest upstream measurement locations (from $x/c = 0.23$ to 0.29) are quite similar between the baseline and TP2 cases, near $U'_{rms}/U_e = 0.01$. The amplitudes at these upstream locations are noticeably larger for the TP1 case, ranging from $U'_{rms}/U_e = 0.015$ to 0.02. Beyond $x/c = 0.3$, the amplitude grows significantly for all three cases, until it saturates near $x/c = 0.475$. It is interesting that the saturation location remains the same for all three cases, within the limited spatial resolution, even though the TP1 case results in a larger saturation amplitude of $U'_{rms}/U_e = 0.15$, compared to $U'_{rms}/U_e = 0.125$ for the baseline and TP2 cases. It is also interesting that, despite the larger amplitudes acquired with TP1 in place, the transition location was not farther upstream compared to TP2. It is possible that traveling crossflow instabilities could be playing a factor in the saturation behavior, as traveling instabilities are known to impact the saturation amplitude of stationary crossflow vortices [1]. The current measurements do not indicate significant increases in u' -fluctuation levels, when looking solely at RMS levels. Since these measurements were aimed primarily at quantifying the stationary crossflow vortices, the frame rate and number of images acquired was too low to adequately capture the appearance of traveling waves. Future measurements will include some time-resolved measurements to determine whether traveling crossflow instabilities are a factor.

In Fig. 7b the U'_{rms} amplitudes are normalized by the amplitude at $x/c = 0.23$ to compare the relative growth for each case. Initially, from $x/c = 0.23$ to 0.29, the relative amplitudes collapse onto the same curve, indicating that the initial growth rate is similar between all three cases. However, downstream of $x/c = 0.29$, all three curves diverge. Initially, the TP2 cases seems to be growing at a higher rate, but only for a short extent before the baseline case becomes larger near $x/c = 0.35$. The growth is consistently slowest for the TP1 case.

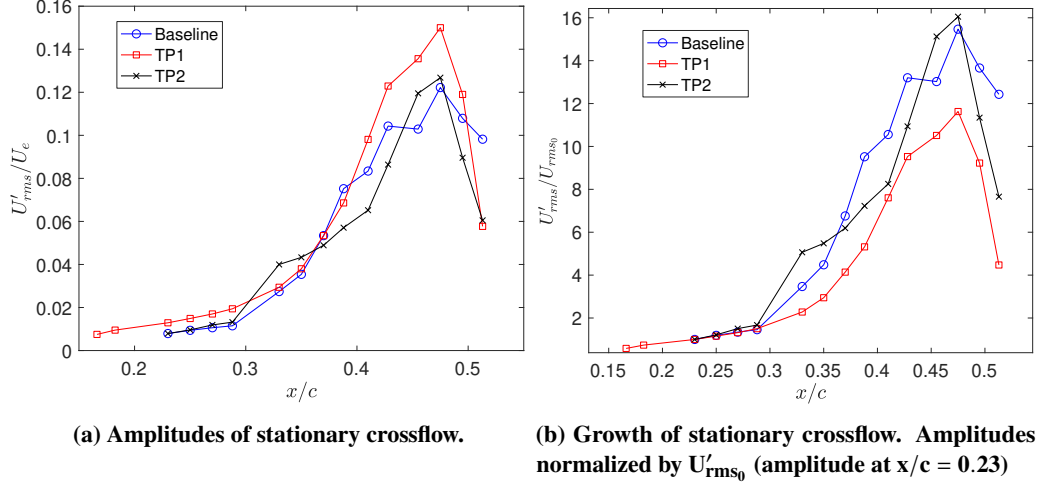


Fig. 7 Stationary crossflow growth for all three cases, wavelength spectra integrated from $\lambda_z = 5$ to 20 mm.

Next, we examine the wavelength spectra to attempt to gain more insight into the impacts of the different roughness topologies on the initial amplitudes of the various stationary crossflow modes. Figure 8a compares wavelength spectra for all three cases at the most upstream measurement station of $x/c = 0.23$. The wavelength spectrum for TP1 contains a large and narrow peak centered at $\lambda_z = 8.25$ mm. The spectra for the other two cases also contain peaks near 7.5 to 8.25 mm, but of significantly lower amplitude, as is also reflected in the lower U'_{rms}/U_e amplitudes plotted in Fig. 7a. The spectrum for TP2 also contains a peak of similar amplitude centered at $\lambda_z = 10$ mm, while the other two cases contain almost no energy at that wavelength.

Figure 8b contains wavelength spectra for all three cases at two locations, $x/c = 0.29$ and $x/c = 0.33$. Since there is a significant difference in the growth rate of the three cases between these two streamwise stations, it is interesting to compare the spectra at these two locations. Starting with the baseline case (blue lines), the spectrum illustrates two broad peaks of similar amplitude starting at $x/c = 0.29$, centered around $\lambda_z \approx 8$ and 12 mm. Moving to $x/c = 0.33$, the peak at 8 mm grows substantially, while there is only a small amount of growth that occurs at the larger wavelengths. Next, TP1 starts out with a large amplitude narrow peak near $\lambda_z = 8$ mm, and a smaller peak near 12 mm, similar to the wavelength spectrum at $x/c = 0.23$. At $x/c = 0.33$, the peak near 8 mm has increased, but at a smaller rate compared to the growth of the same peak for the baseline case. Meanwhile, two more peaks are clearly evident, though at smaller amplitudes: one at $\lambda_z = 10$ mm, and another near 13 mm. Finally, the spectra for the TP2 case illustrates substantial growth of both peaks that were initially evident at $x/c = 0.23$. The peak at 8 mm grows to about twice the amplitude of the peak at 10 mm by $x/c = 0.33$.

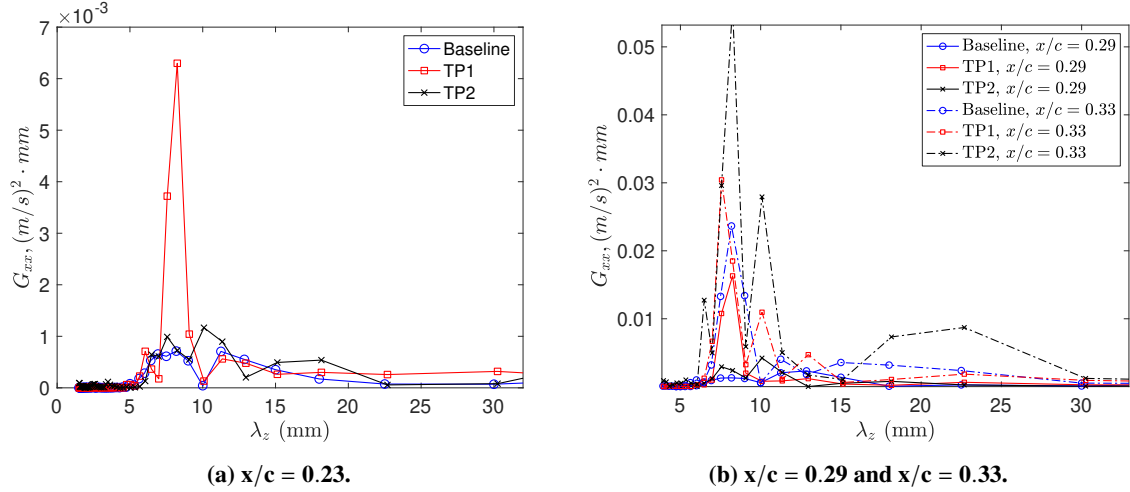


Fig. 8 Wavelength spectra compared at three streamwise locations.

D. Computations

It is clear that the roughness panels result in substantially different stationary crossflow initial conditions, despite the relatively mild change in the transition front location observed for these cases. It is possible that this particular pressure distribution is somewhat robust in terms of the impact that different initial stationary crossflow amplitudes and wavelength distributions have on the transition location. The quantity that would be of most value to the transition community is the initial amplitudes of the stationary crossflow vortices that result from the different roughness topologies. While the differences can be somewhat inferred from the wavelength spectra shown at the most upstream location where measurements were performed for all three cases (see Fig. 8a), this location was, unfortunately, a relatively long distance downstream of the roughness panels and the branch I location. The main reason that measurements were not performed farther upstream is the fact that the amplitudes were already so low at $x/c = 0.23$, it was believed that the uncertainty would be too large to obtain reliable stationary crossflow amplitude results. Since the TP1 case resulted in larger amplitudes, it was possible to obtain quality measurements of the stationary crossflow amplitudes farther upstream ($x/c \approx 0.16$). However, to go any farther upstream would require measurements above the roughness panels, which would likely be impossible given the surface flare that would occur from the laser hitting the rough surface.

Therefore, to estimate initial amplitudes, nonlinear PSE computations were performed. The computations were performed using a smoothed and interpolated version of the experimentally measured midspan C_p distribution as input for the boundary-layer code, BLSTA [14], which was used to compute the laminar basic state under the assumption of an infinite-span swept airfoil. Then, LASTRAC [15] was used to perform the stability computations. Results from the boundary-layer computations are shown in Fig. 9, where computed U -velocity profiles are compared with spanwise-averaged profiles that were measured at three different streamwise locations. Overall, the agreement is fairly good, although there is some discrepancy between $y=1.5$ -2 mm, particularly for the most upstream measurement location of $x/c = 0.23$. The agreement improves farther downstream. Linear stability results from the computations are shown in Fig. 10 for several different wavelengths across the range of amplified modes. Wavelengths in the range of 9–11 mm are the most amplified, but some smaller wavelengths are amplified farther upstream.

There are many possible approaches to the problem of estimating the initial amplitudes, and as an initial pass, an attempt was made to manually tune the initial modal amplitudes so as to match the experimental wavelength spectra at $x/c = 0.23$ within the wavelength range of $\lambda_z = 5$ to 20 mm. Fifty modes were initialized at the branch-I location ($x/c = 0.0214$), with the fundamental wavelength set to 200 mm. The measured and computed wavelength spectra for each case are plotted in Fig. 11. This process is currently being performed manually, though it would likely benefit from the implementation of an optimization routine, which is left for future work. Even so, relatively good matches are obtained at $x/c = 0.23$ for all three cases.

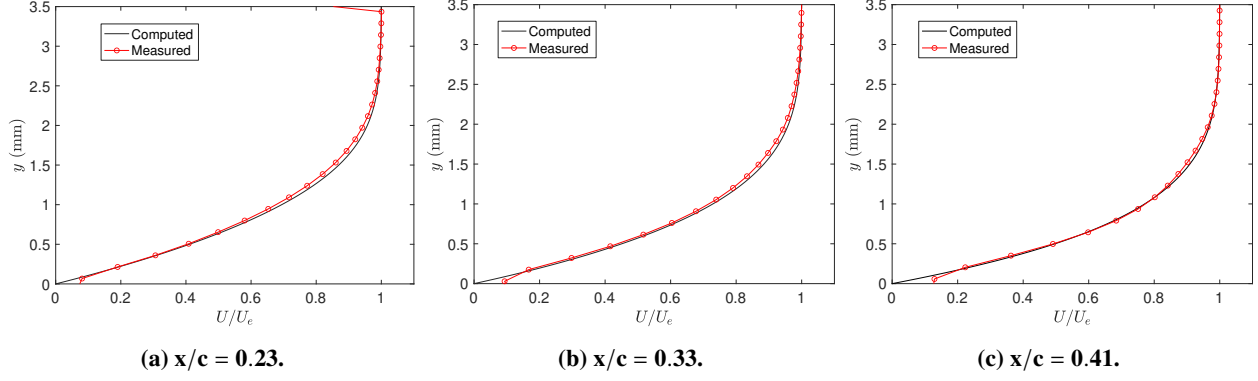


Fig. 9 Comparison of computed and spanwise-averaged boundary layer profiles at various streamwise locations.

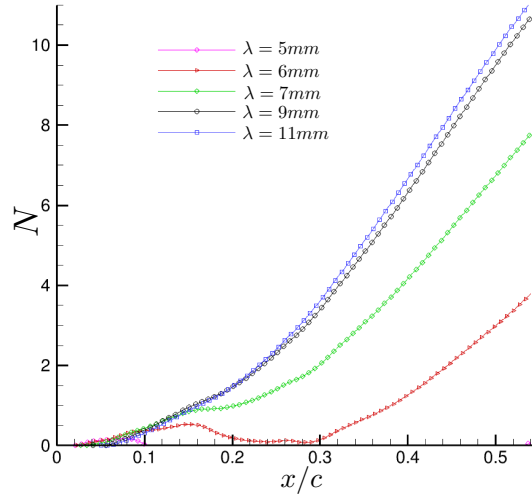


Fig. 10 Linear N -factor results.

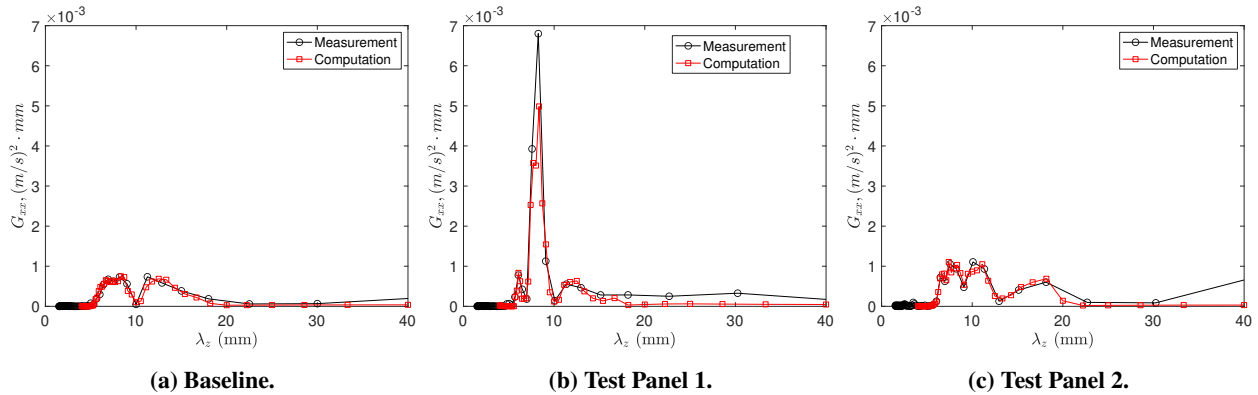


Fig. 11 Measured and computed wavelength spectra compared at $x/c = 0.23$ for each case.

The computed modal growth downstream of $x/c = 0.23$ is compared with the measured amplitudes in Fig. 12. Given the limited wavenumber resolution for the experimental results, it is difficult to directly compare individual (computed) modal amplitudes to those obtained experimentally. This is further complicated by the fact that the wavenumbers of

the peak amplitudes tend to shift slightly as the flow travels downstream. Therefore, it was decided to integrate the experimental results over two wavelength ranges, one to capture the larger wavelengths from 9–20 mm, and the other to capture the smaller wavelengths, from 5–9 mm. Likewise, the total computed amplitude for each wavelength range was obtained by taking the root-mean-square of all the modes falling within that wavelength range. Since the initial amplitudes were chosen such that the wavelength spectra match at $x/c = 0.23$, the integrated amplitudes should match well at this location as well. This is indeed true for all three cases, as can be seen in Fig. 12. For most of the cases, the initial growth ($x/c = 0.23$ to 0.29) is matched pretty well between the experiment and computation, but beyond that, the computations typically predict much stronger growth than was observed experimentally. For the baseline case, the smaller wavelength growth (red squares) matches fairly well, but the computations predict a much larger growth of the larger wavelength modes (blue circles). For TP1, the smaller wavelength growth and saturation amplitude are over-predicted, while the growth of the larger wavelength modes matches a little better with the experiment, even though the saturation amplitude is also over-predicted. Finally, the TP2 results provide the worst comparison. In the experiment, the smaller wavelength modes grow faster early on. However, the computations predict the growth of the larger wavelength modes, followed by a later growth of the smaller wavelength modes. Incidentally, the predicted growth of the smaller wavelength modes appears to match quite well with the growth of the larger wavelengths from the experiment. Meanwhile, the predicted growth of the larger wavelength modes increases to levels well beyond what was measured in the experiment.

As a second attempt, the initial amplitudes were chosen in such a way as to try to match the growth farther downstream, rather than matching the amplitudes and wavelength content at $x/c = 0.23$. However, the manual approach to this method was found to be prohibitively time consuming, given the large number of inputs and the sensitivity of the results to small changes. Rather than initializing a broad range of wavelengths, this approach was also attempted by initializing two primary wavelengths (corresponding to $\lambda_z = 8$ and 10 mm). However, this approach did not produce any better match than was found using the previous method. Once again, potential future work includes the implementation of an optimization routine to better match the computed modal growths to the experimental results.

While it may be possible to obtain a better comparison, there are numerous potential sources of error that can complicate this process. First of all, it is difficult to directly compare the experimental results, which are relatively non-uniform, particularly for the baseline and TP2 cases, to the computations, which are inherently uniform in span. Additionally, the measurements are performed over only a limited spanwise extent of the model and therefore do not consistently track the same vortices, since the streamlines are curved in and out of the measurement region. Due to this limited spanwise measurement extent, our wavelength resolution is limited as well. Finally, since the C_p measurements on which the computations are based were obtained using pressure belts, these pressure belts may have impacted the flow significantly enough to impact the computed stability results. There are clearly some differences between the measured and computed results, as illustrated in Fig. 9, but it is not known if this impact could affect the results this significantly.

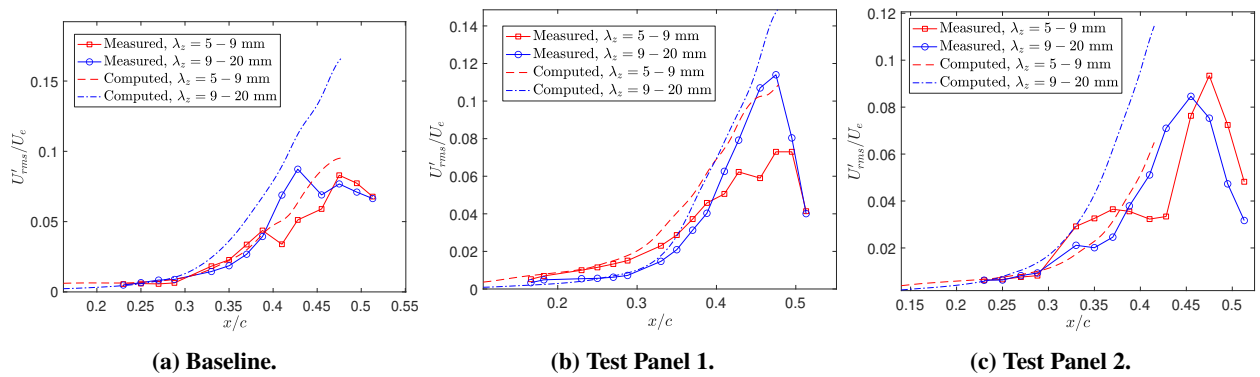


Fig. 12 Stationary crossflow growth for two different wavelength ranges, compared with nonlinear PSE computations. The initial amplitude input is from Fig. 13a

Given the consistent behavior at the farthest upstream measurement locations (i.e., the collapse of the growth rates of all cases in Fig. 7b from $x/c = 0.23$ to 0.29), it seems feasible that matching the amplitudes and wavelength content of the modes at $x/c = 0.23$ would result in a reasonable approximation of the initial amplitudes introduced by the roughness panels. To that end, the initial amplitudes (A_0) that were required to match the experimental amplitudes

at $x/c = 0.23$ are plotted in Fig. 13a for all three cases. Overall, the estimated initial amplitudes generally follow the trends we observe from the wavelength spectra at $x/c = 0.23$ (Fig. 8a). For instance, at wavelengths ranging from 7.5–9 mm, TP1 resulted in a significant increase in initial amplitude, while the initial amplitudes predicted for TP2 and the baseline panel are very similar and about half the magnitude compared to TP1. Conversely, TP2 resulted in larger initial amplitudes than TP1 and the baseline panel for wavelengths between 10–12 mm, as well as larger wavelength modes above approximately 15 mm. The very large values of initial amplitude predicted for the 10 mm mode for all cases, but especially for TP2, is somewhat surprising, as that amplitude was not significantly larger than similar wavelengths (i.e., 9.5 and 10.5 mm) at $x/c = 0.23$. This mode is observed to initially decay, and grow at a slower rate than the 9.5 and 10.5 mm modes in the computation. It is unclear why this particular mode behaves this way, but this large difference in initial amplitude is likely an unphysical result. Additionally, the initial amplitudes predicted at the smaller wavelengths ($\lambda_z \leq 6.5$ mm) do not follow the expected behavior, as the baseline panel is not expected to result in significantly larger amplitudes at those wavelengths, and this behavior is also not reflected in the wavelength spectra at $x/c = 0.23$ (see Fig. 8a).

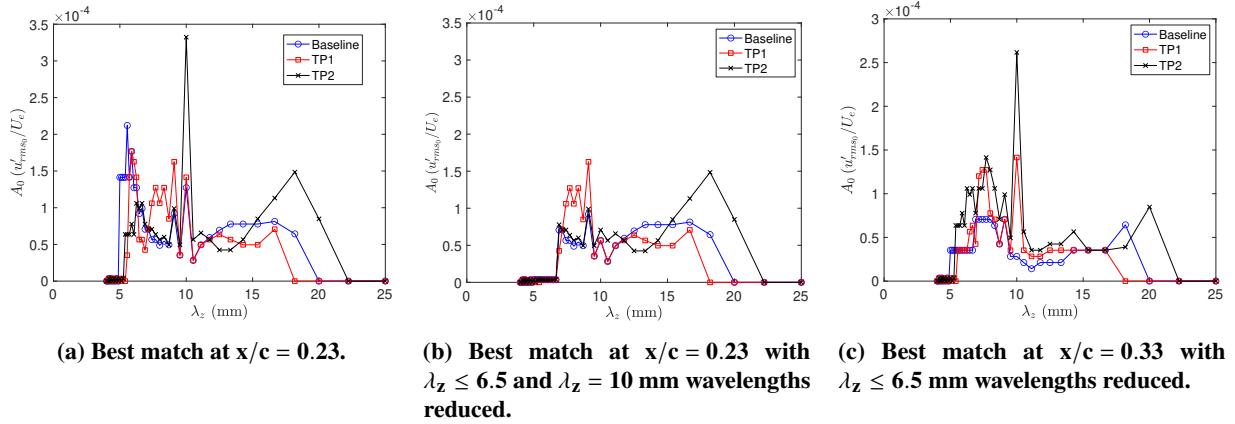


Fig. 13 Comparison of initial amplitudes ($x/c = 0.0214$).

Because of the slower growth of the smaller wavelength modes ($\lambda_z \leq 6.5$ mm), as well as the 10 mm mode, near the leading edge, large initial amplitudes are required for those modes in order to match the relatively small amplitudes that were measured at these wavelengths at $x/c = 0.23$. However, these modes appear to be rather inconsequential in terms of matching the overall growth behavior of the instabilities, since they do not initially result in much growth. In other words, the system is not very sensitive to the inputs in this wavelength range, and this may be contributing to erroneously large initial amplitudes. The insensitivity to these wavelengths is illustrated by substantially reducing the initial amplitude of any wavelength with $\lambda_z \leq 6.5$ mm, and $\lambda_z = 10$ mm, and rerunning the computation. This new initial amplitude input is illustrated in Fig. 13b, and the results from these computations are shown in Fig. 14. In general, the reduction in initial amplitude of these wavelengths has resulted in very little change, and in some cases, slightly better agreement with the measured results.

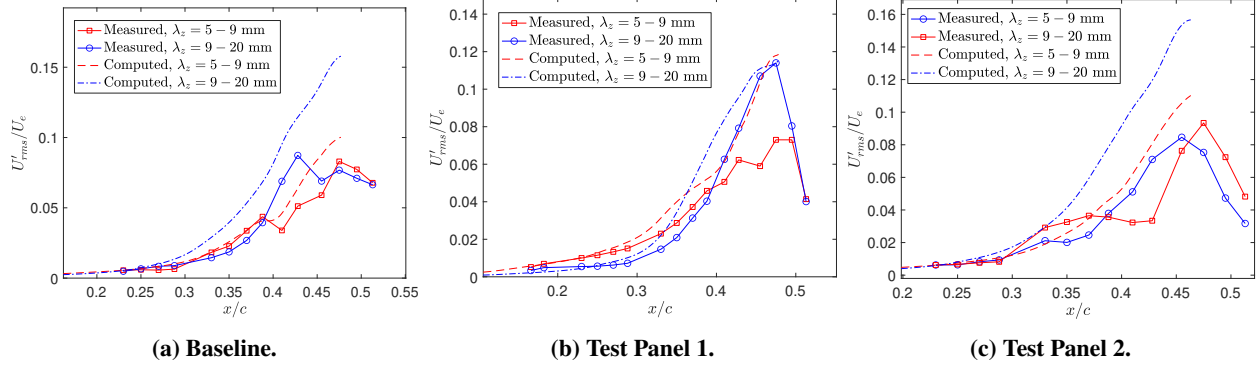


Fig. 14 Stationary crossflow growth for two different wavelength ranges, compared with nonlinear PSE computations. The initial amplitude input is from Fig. 13b.

These results highlight an often overlooked problem involved in experimentally determining the impact of surface roughness on stationary crossflow instabilities in a way that is meaningful for the broader community. The small amplitudes of the stationary crossflow vortices at the upstream measurement locations (and thus, the noise introduced into the spectral results), combined with the limited wavelength resolution, make direct comparisons with computations difficult. Additionally, some modes may be introduced with very large relative initial amplitudes based on the roughness topology, but if those modes quickly decay or do not exhibit substantial growth due to the stability characteristics of the flow, they will not be measured adequately. This behavior is illustrated by the insensitivity of the overall growth of the instability modes to a very large change in initial amplitude of the smaller wavelength modes. A large initial amplitude is required to match the amplitude at the farthest upstream measurement location, however, the measured amplitude at that location is relatively small and appears to be resulting in erroneously large initial amplitude estimates for those modes. The N -factors shown in Fig. 10 for the 5 and 6 mm wavelengths also illustrate this behavior. While the 6 mm mode does exhibit some substantial growth near the leading edge, by the first measurement location of $x/c = 0.23$, the mode has decayed substantially. It does exhibit some linear growth farther downstream, but by that point, nonlinear effects are expected to be substantial. The 5 mm mode, on the other hand, only grows somewhat near the leading edge, but decays by $x/c = 0.1$.

To avoid the problem of small amplitudes and potentially obtain a better match in terms of overall growth rate behavior and downstream development of the modes, it may be advantageous to match the modal amplitudes at a farther downstream location, which is attempted next. However, this does not address the problem of how to identify the modes that are potentially introduced initially at large amplitudes, but that never reach a measurable amplitude and do not have a substantial impact on the growth of other modes due to the stability characteristics of that particular flow. Of course, for a given flow field, one does not care much about the initial amplitudes of the modes that do not grow substantially. However, with the goal of predicting the impact of a given roughness topology on a range of conditions and geometries, it becomes important to quantify the impact of the roughness on all modes that could potentially be of interest in other flow fields, otherwise, the results are really only valid for the flow field in which the measurements were performed.

Next, we attempt to match the wavelength spectra at $x/c = 0.33$, to see if the downstream growth of the stationary crossflow modes will be better captured with this approach. Comparisons of the experimental and computed wavelength spectra at $x/c = 0.33$ are provided in Fig. 15. In the case of TP2, the smaller wavelength content ($\lambda \leq 6.5$ mm) is ignored, for the reasons given previously, while the $\lambda_z = 10$ mm content is maintained, since there are substantial peaks at this wavelength for both roughness panels. The smaller wavelengths in this case are primarily only an issue for TP2, which exhibits a small peak near $\lambda = 6.5$ mm. Relatively good matches were easily obtained for all three cases. The results for the growth of both broader wavelength bands are shown in Fig. 16. For the baseline and TP1 cases, the overall growth matches much better between the experimental and computational results than was previously shown. In most cases, the saturation amplitude is still significantly overpredicted. In the case of TP2, the computed results do not appear to have improved significantly in comparison to the experimental results. The initial amplitudes that resulted from the present analysis are plotted in Fig. 13c. Now, both roughness panels TP1 and TP2 exhibit larger amplitudes for wavelengths in the range of approximately 7 to 9 mm, compared to the baseline case. Once again, a large initial amplitude was estimated for the 10 mm mode, this time only for both roughness panels, since they both exhibited a peak at that wavelength at $x/c = 0.33$. However, the amplitude still appears to be erroneously large compared to

that predicted for similar wavelengths. Given the poor match between the computed and experimental results for TP2, both upstream and downstream of $x/c = 0.33$, it is difficult to trust the initial amplitudes predicted for that case. Thus, repeat measurements are planned to determine the repeatability of the experimental results. The other cases, however, appear more reliable, and may be able to provide a better estimate of the initial stationary crossflow amplitudes, keeping the previously mentioned caveats in mind. In general, the initial amplitudes estimated in the range of 7–9 mm for the baseline and TP1 cases were fairly consistent between the two approaches of matching the wavelength spectra at $x/c = 0.23$ (Fig. 13b) and at $x/c = 0.33$ (Fig. 13c).

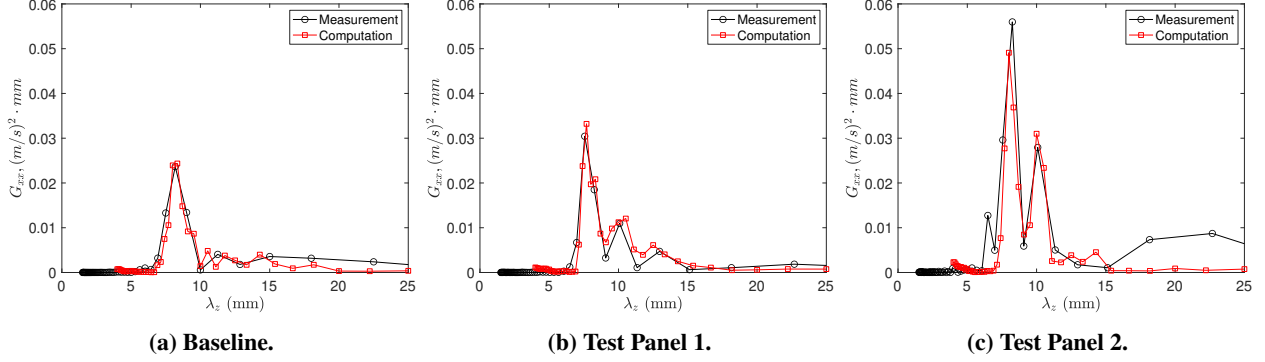


Fig. 15 Measured and computed wavelength spectra compared at $x/c = 0.33$ for each case.

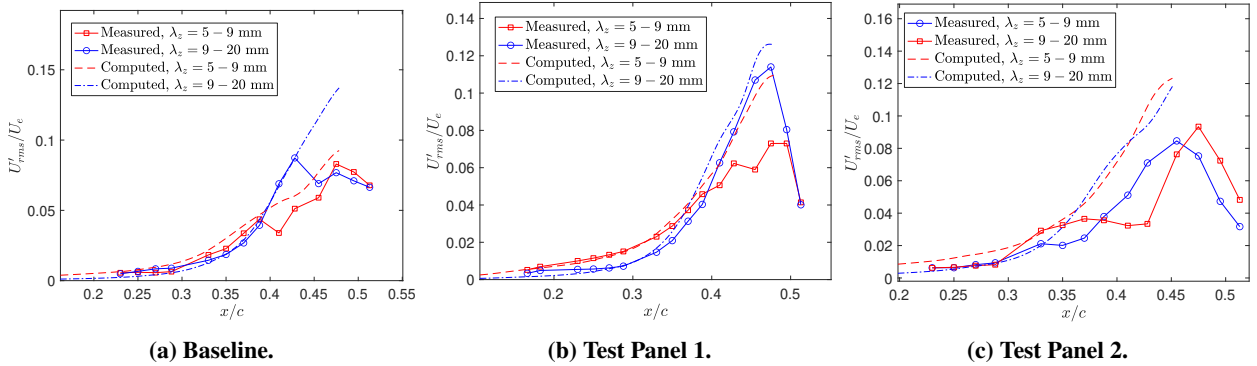


Fig. 16 Stationary crossflow growth for two different wavelength ranges, compared with nonlinear PSE computations. The initial amplitude input is from Fig. 13c.

VI. Conclusion

The results presented in this paper illustrate the complexity of studying the impact of random roughness on stationary crossflow dominated transition. While it is well-known that stationary crossflow instabilities are sensitive to surface roughness input, it is not well understood exactly how to best quantify that input. In the present case, significant roughness levels were introduced at the leading edge of a swept-wing model ($4\text{--}8\text{ }\mu\text{m}$ RMS), yet, the transition location was not significantly impacted. At most, the transition location moved upstream by approximately $x/c = 0.02$, however, this movement occurred for the lower amplitude roughness panel (TP2), and the higher amplitude roughness panel (TP1) had almost no impact on the average transition location. At the same time, the initial amplitudes of the stationary crossflow instabilities were substantially impacted by the addition of the roughness, particularly for TP1. Thus, it is unclear why this did not translate into a larger impact on the transition location. Perhaps this particular pressure distribution results in a system that is rather insensitive to initial disturbance amplitude variations. Given these observations, a meaningful and useful quantification of the impact of surface roughness needs to include initial amplitude and wavelength content of the stationary crossflow instabilities.

Using nonlinear PSE, the initial amplitudes of the stationary crossflow instabilities were estimated by matching

the PSE results to the experimentally measured wavelength spectra at the farthest upstream measurement location for all three cases, $x/c = 0.23$, and additionally at $x/c = 0.33$. While it was relatively easy to obtain a good match at the upstream location, the growth that occurred significantly farther downstream ($x/c > 0.3$) did not match very well between the experiment and computations. Matching the amplitudes at $x/c = 0.33$ resulted in better matches in overall growth behavior for both the baseline case and TP1. However, the results were not much improved for TP2. Thus, further work is required to obtain the best possible match and will likely require the implementation of an optimization routine. The initial amplitude estimates indicated that TP1 resulted in substantially higher amplitudes in the wavelength range of $\lambda_z \approx 7 - 9$ mm, while the results for TP2 are somewhat inconclusive, since the two different approaches resulted in very different results. It remains to be determined how exactly the different roughness topologies lead to the varying stationary crossflow wavelength content. The repeatability of these results are planned to be tested in upcoming entries, in which the same roughness panels will be tested, but rotated 180° in order to test a slightly different roughness layout, but with the same average parameters. This should help to illuminate the sensitivity of the resulting initial amplitudes to the specific localized roughness that is encountered on a panel with the same average roughness parameters. Time-resolved measurements will also be performed to determine if traveling crossflow plays any role in the transition process. Additionally, panels with higher RMS roughness levels are being fabricated and will be tested in future entries.

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