

Effects of Forward-Facing Step Shape on Stationary Crossflow Instability Growth and Breakdown

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The effect of forward-facing step shape on stationary-crossflow growth was studied downstream of a two-dimensional step in a swept-wing flow. The step height was set at 81% of the local unperturbed boundary layer thickness at the step location, and the shape was varied by placing two ramps of differing slopes upstream of the step: 30° and 45° . The ramps were successful at delaying transition, with increasing success as the slope was decreased. The ramps significantly altered the mean flow, reducing or eliminating the separation region and crossflow-reversal region downstream of the step, which reduced the amplification of the stationary crossflow modes shortly downstream of the step. The mean flow modification induced by the step also had destabilizing effects that persisted farther downstream as the flow recovered from the near-step region. The downstream growth of the stationary crossflow instabilities was also mitigated by the introduction of the ramps upstream of the step. The presence of harmonics beginning near this region confirms previous findings that there are nonlinear interactions contributing to the growth of the instability.

Nomenclature

H	boundary-layer shape factor, with $H = \frac{\delta^*}{\theta}$
Re'	Unit Reynolds number
Tu	turbulence intensity
U	streamwise velocity component
u'	fluctuating components of velocity
U', V'	steady disturbance velocity
u'_{rms}	temporal root mean square of u'
U'_{rms}, V'_{rms}	spanwise root mean square of steady disturbance velocity, U', V'
U_e	boundary layer edge velocity
U_∞	freestream velocity
$U_\perp$	velocity component normal to the step
V	wall-normal velocity component
$W_\parallel$	velocity component parallel to the step
W_{cf}	velocity component normal to the local inviscid streamline
x	streamwise direction
x_c	direction normal to the leading edge
x_s	streamwise location of step
x_{sh}	number of step heights downstream of step
y	wall-normal direction
z	spanwise direction (parallel to the leading edge)

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Symbols

δ	boundary-layer thickness, location where $U=0.99U_e$
δ^*	boundary-layer displacement thickness
λ	spanwise wavelength
θ	boundary-layer momentum thickness

I. Introduction

IN the ongoing quest for improved fuel efficiency of aircraft, laminar flow control remains a promising technique. Laminar flow control (LFC) techniques can work quite well in theory and in the laboratory. However, real-world applications result in additional difficulties that can be detrimental if not well-managed. 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 other sources. In order for LFC to be effective in an operational environment, it is crucial that we understand how surface irregularities affect transition. This is important so that more reasonable manufacturing tolerances can be specified.

In order to develop better prediction models for acceptable roughness levels, we need to understand the mechanisms that cause transition when the surface imperfections are present. The transition mechanisms will vary depending on the type of surface imperfection. The effect of 2D steps on swept-wing transition has been studied recently. This work has generally been limited to observing the behavior of the transition front as the step height is increased,^{1,2} but more recently, researchers have begun to study the flow in more detail. Duncan et al.³ performed hotwire measurements downstream of forward- and backward-facing steps to determine the effect of the steps on stationary crossflow instabilities. They found that the steps caused an increase in the growth of the stationary crossflow vortices. The forward-facing step (FFS) caused a larger growth of the stationary crossflow than the backward-facing step (BFS). Tufts et al.⁴ performed computations to study the interaction between stationary crossflow instabilities and a two-dimensional step excrescence. The forward-facing step, above a critical height, was found to substantially increase the growth of the stationary crossflow mode. They suggest that the mechanism for this increased growth involves a constructive interaction between the incoming stationary crossflow vortex and the helical flow region just downstream of the step. Thus, if one can predict the height of the center of the incoming crossflow vortex from the baseline state, then this should be close to the critical step height, since this is the height at which the crossflow vortex and helical flow region would begin to interact constructively.

Eppink⁵ experimentally studied the effect of forward-facing steps on stationary crossflow growth by performing stereo particle image velocimetry (SPIV) measurements. The steps above the critical height caused a large increase in the growth of the stationary crossflow instability just downstream of the step, resulting in earlier transition. The results agreed qualitatively with the computational results of Tufts et al.⁴ Additionally, it was found that increasing the initial stationary crossflow amplitude resulted in premature transition for a previously subcritical step height. More recently, Ruis Vidales et al.⁶ performed a parametric study and found that the limit between the subcritical and critical step height regime agreed well with the method proposed by Tufts et al.⁴ The work thus far has focused on square steps. However, it is common wind tunnel practice to mitigate the effect of steps by fairing them in. Thus, it is well-known that, compared to a step, a ramp of the same height should have less of an effect on the flow, and, by extension, less of an effect on transition. Additionally, it has been shown in previous experiments in two-dimensional (unswept) flows, that one can delay transition, or decrease the critical step height, by shaping the step. Holmes et al.⁷ discussed flight test results showing that rounded steps and ramped steps could increase the critical step-height Reynolds number significantly compared to square steps at the same step height. While this knowledge is useful, it is also beneficial to perform detailed experiments to better understand the mechanisms that occur when a ramp or step is introduced into the flow. The hope is that with improved knowledge, we will be able to better define manufacturing tolerances for laminar-flow aircraft. The current work extends the previous work of Eppink⁵ by exploring the effect of ramped forward-facing steps on stationary-crossflow dominated transition.

II. 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 0.06% for the entire speed range of the tunnel, and 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.⁸

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. 1). 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. The leading edge piece was polished to a surface finish of $0.2 \mu\text{m}$, and the larger downstream plate had a surface finish of $0.4 \mu\text{m}$. A leading-edge contour was designed for the bottom side of the plate in order to make the suction-peak less severe, and therefore, 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 contours were parallel with the leading edge within the measurement region. The ceiling liner was fabricated out of a hard foam using a computer-controlled milling machine.

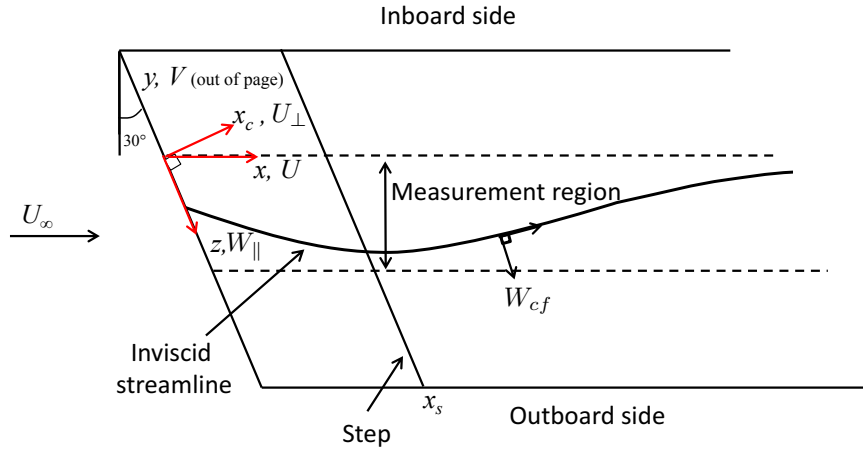


Figure 1: Model sketch and coordinate system.

All measurements were performed at a freestream velocity of 26.5 m/s ($Re' = 1.69 \times 10^6/\text{m}$). The current experiment utilized a single leading-edge roughness configuration consisting of discrete roughness elements (DREs) with a diameter of 4.4 mm. The DREs were applied with a spanwise spacing, λ_z , of 11 mm and were approximately $20 \mu\text{m}$ thick. The spacing of the DREs (11 mm) corresponds to the most amplified stationary crossflow wavelength calculated for the baseline case with no step. For more details of the experiment setup, refer to Eppink.⁹

A high-speed double-pulsed Nd:YLF laser provided the laser sheet for the particle image velocimetry (PIV) measurements (see Fig. 2). The laser sheet was set up parallel with the leading edge and the forward-facing step. Two high-speed 4-megapixel cameras were used to acquire the time-resolved PIV (TRPIV) measurements and were placed downstream of the step. One was placed on the outboard side of the test section at approximately 30° to the laser sheet, and the second camera was placed on the inboard side (in backward scattering) at an angle of approximately 45° to the laser sheet (Fig. 2). To achieve the desired

field of view and resolution, 300 mm lenses were utilized, resulting in a total possible measurement area of approximately 60 mm x 30 mm. For the majority of the measurements, the area of interest was reduced to approximately 60 mm x 8 mm to obtain an acquisition rate of 2 kHz. This area allowed acquisition of approximately five wavelengths of the stationary crossflow instability in a single frame, while still acquiring approximately 30 points (using 75% overlap and 16x16 pixel interrogation size) inside the boundary layer. For the mean flow measurements, data were acquired starting at the step and moving downstream at approximately 1 mm increments. Five hundred image pairs were acquired at each location. The cameras and laser were all mounted on the same traversing system, which allowed measurements at multiple locations with relative ease. An oil-based fog machine generated the seeding, which was introduced downstream of the test section.

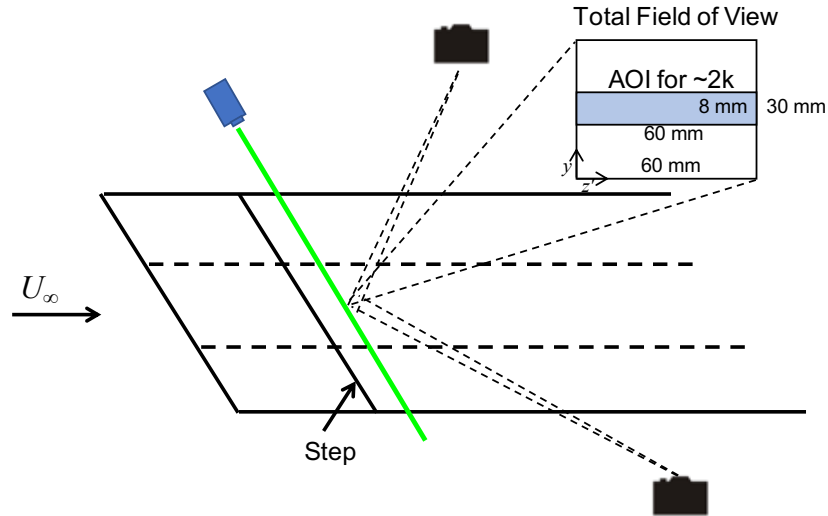


Figure 2: Top view of PIV setup.

A single forward-facing step height of 1.95 mm was studied, including a square step, along with two ramps of nominally 30° and 45°, as depicted in Fig. 3. The square step was achieved using the method described above, by inserting precision shims underneath the downstream plate. Ramps were added in front of the square step to create the ramped steps. The ramps were created using a mold, which was machined to the desired dimensions into a piece of aluminum, and the ramps were formed using a fast curing two-part silicon rubber compound. The step height of 1.95 mm was chosen due to the molding process of the ramps, which resulted in slightly larger ramps than intended. A step height of 1.7 mm was initially targeted, but this was increased to 1.95 mm to account for the larger ramps.

Measurements were performed of the step and ramp geometries across the measurement region using an in-house profilometer that utilizes an optical distance sensor mounted on linear traversing stages to allow measurements of a two-dimensional area. The scans were performed approximately perpendicular to the step at spanwise intervals of 1 mm. Throughout the paper, the ramp angles will be referred to as their nominal values of 30° and 45°, though the average measured values were slightly different: 29° and 42°, respectively. The spanwise-averaged mean profiles of the step geometries are shown in Fig. 4.

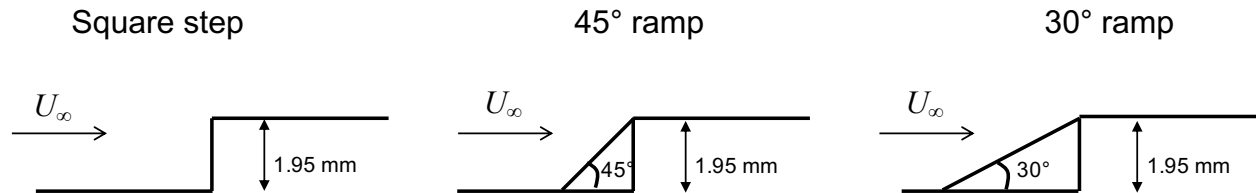


Figure 3: Sketch of step geometries studied.

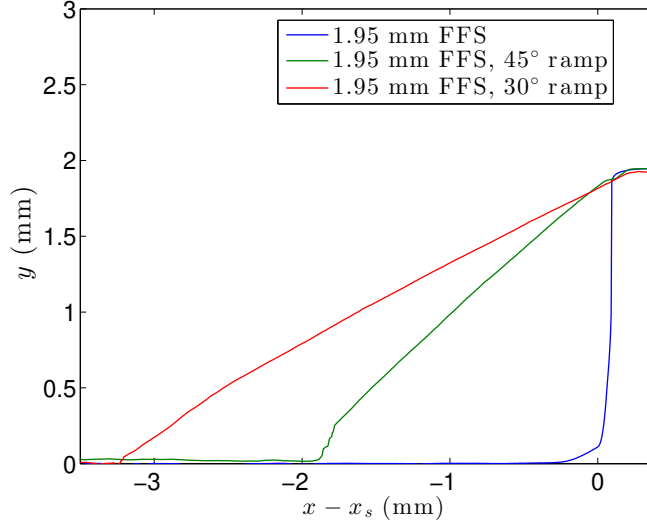


Figure 4: Averaged measurements of step geometries.

III. Results and Discussion

In the previous study,⁵ step heights ranging from 1.27 mm to 1.7 mm were examined in detail. An additional case was studied for the 1.4 mm step case, which included additional layers of DREs to increase the initial stationary crossflow amplitude. The critical step height was found to be 1.6 mm, meaning that at or above this step height, transition moved upstream relative to the no-step case. The 1.5 mm case was found to be subcritical since transition did not move upstream. However, the stationary crossflow amplitudes near the step were significantly impacted, though they eventually decayed back to the baseline amplitudes. The 1.4 mm case resulted in slight increased growth of the stationary crossflow vortex near the step, but again did not result in premature transition. However, the 1.4 mm step height with the increased stationary crossflow amplitude resulted in transition shortly downstream of the step, showing that the incoming stationary crossflow vortex amplitude plays a role in the interaction. The step causes major changes to the mean flow, which are believed to play important roles in the interaction and destabilization of the stationary crossflow vortices. Contouring or shaping the steps should reduce the impact on the mean flow, and thus should mitigate the effect of the step on the stationary crossflow vortices. The current study was undertaken to study this effect. Results have been acquired for a square step, and for ramps with nominal angles of 30 and 45°.

A. Mean Flow Effects

The effect of the step and ramps on the mean flow are shown in Fig. 5. Note that the 1.95 mm square FFS is supercritical and results in an early transition beginning approximately 15 mm downstream of the step. This transitional behavior is evident from the broadening and increased shear stress of the $U_{\perp}$ profiles downstream of $x - x_s \approx 15$ mm in Fig. 5a. As expected, the ramps do successfully mitigate the effect of the step on the mean flow, as is evident from Figs. 5d and 5g. Both ramps delay transition, with increasing success as the ramp angle is decreased. The 45° ramp u'_{rms} results, which will be shown later, indicate the existence of some high-frequency secondary instabilities beginning to grow by approximately $x - x_s = 30$ mm. In fact, some localized turbulent bursts are evident at the farthest downstream measurement location of $x - x_s = 46$ mm, indicating that the flow has begun to breakdown and will become fully turbulent shortly downstream. However, no such secondary instabilities or turbulent bursts are evident downstream of the 30° ramp, as far downstream as $x - x_s = 100$ mm.

As discussed in a previous paper,⁵ the step creates a strong and abrupt, but very short, region of positive V -velocity starting shortly upstream of the step. There is also visible, at the same location, a small kink in the $U_{\perp}$ profiles. This behavior was explained through continuity, and is evident for the plain step and for both ramps. Downstream of this small kink, the results are quite different between the step and ramp

cases. For the square step, the boundary layer begins to exhibit reversed flow starting approximately 3 mm downstream of the step. The white contour lines included on Fig. 5a indicate the region of negative $U_\perp$ velocity that was measured. This is likely the helical-flow region that was identified by Tufts et al.⁴ The boundary-layer profiles thicken as this separated region is encountered, and then the boundary-layer starts to recover. However, by this point, transition has been triggered. For the ramp cases, no reversed flow was measured. Instead, the profiles gradually recover from the sudden appearance of the step, thickening to a fairly constant boundary-layer thickness.

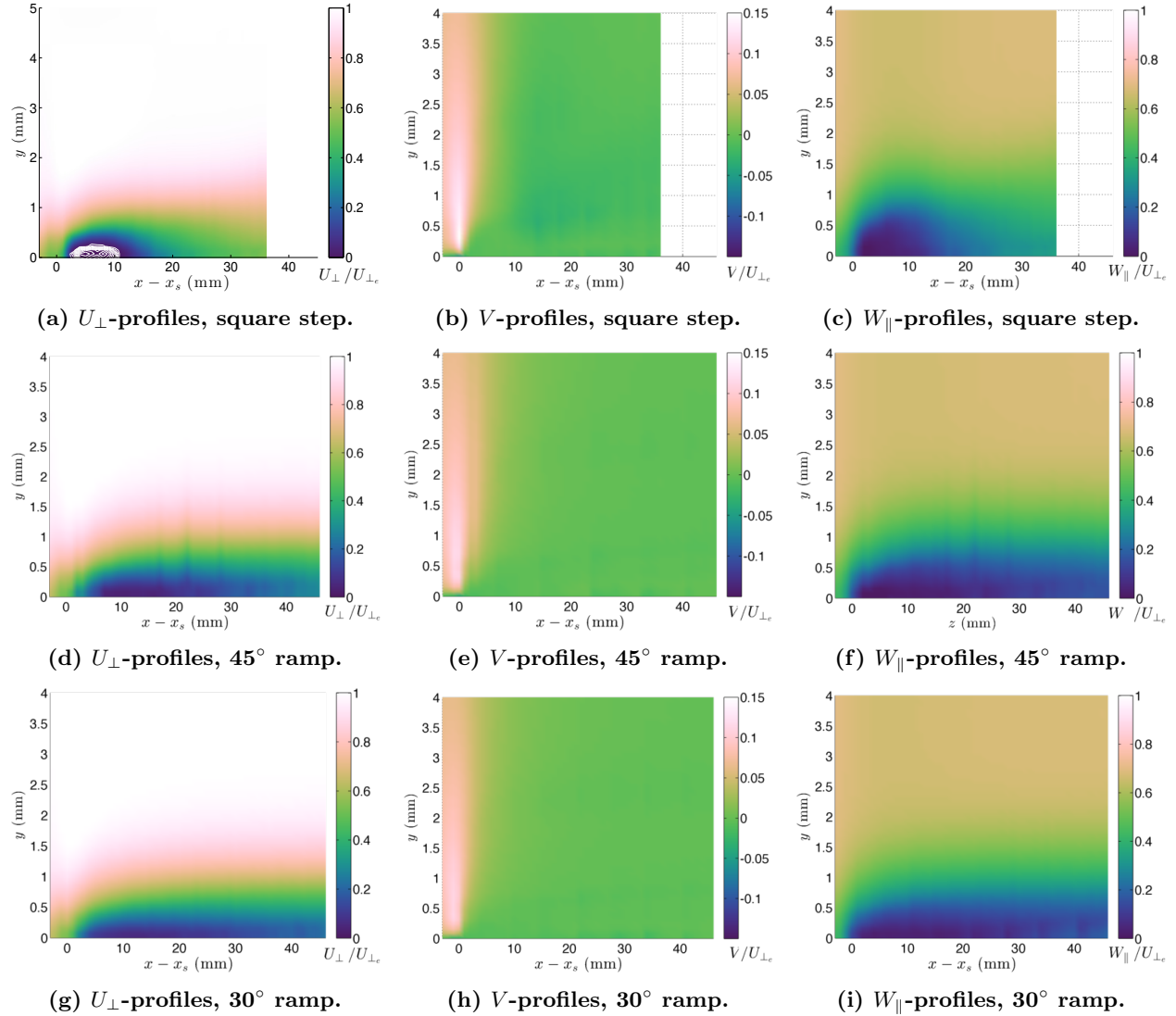


Figure 5: Spanwise-averaged velocity profiles downstream of each step. White contour lines indicate the reversed flow region.

It is somewhat difficult to compare the shapes of the boundary-layer from the contour plots, so we plot the shape-factor ($H = \frac{\delta^*}{\theta^+}$) computed from the $U_\perp$ velocity profiles. Figure 6 shows the development of the shape factor downstream of the step for all three cases. There is a drastic increase in shape factor beginning at the step for the square step case, as the boundary layer undergoes separation. Starting at $x - x_s = 6$ mm, the shape factor begins to decrease as the flow begins to recover. The two ramp cases undergo a much less dramatic increase in H downstream of the step. Initially, the shape factors for both cases are similar, until $x - x_s = 6$, where they begin to diverge. These boundary layers undergo a much slower change in H downstream of $x - x_s \approx 10$ mm as the boundary layer begins to recover from the step.

The effect that the step has on the crossflow component inside the boundary layer is illustrated in Fig. 7

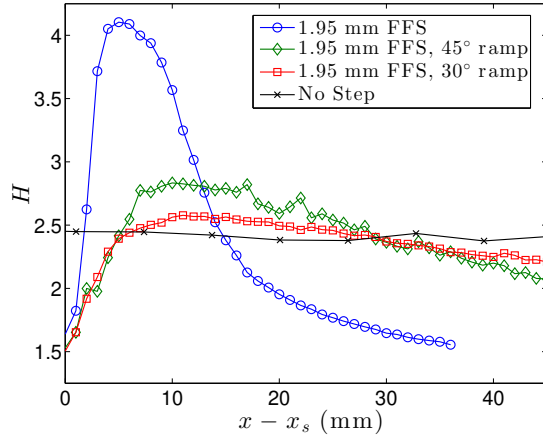


Figure 6: H -factor of $U_{\perp}$ -velocity profiles vs $x - x_s$.

for all three cases. This is the velocity component inside the boundary layer that is normal to the external inviscid streamline. As seen for some of the smaller step heights,⁵ the 1.95 mm square step results in a very strong negative crossflow component at the step, which then lifts up and gives way to a small but strongly inflectional region of positive crossflow near the wall. This positive crossflow region corresponds very closely to the region of reversed flow that was measured for this case, though it extends about 5 mm farther downstream of where separation ends. Hosseini and Fasel¹⁰ performed a computational study of swept laminar separation bubbles and showed that crossflow reversal occurs starting near the wall at the beginning of separation. The separation and crossflow reversal are both caused by the adverse pressure gradient downstream of the step. Crossflow reversal can cause the destabilization of stationary crossflow vortices that are rotating in the direction opposite to the initial primary vortices. Note that, except for the 1.7 mm FFS, for which very little reversed flow was measured, there was no measured reversed flow for the smaller step heights.⁵ However, there was measured crossflow reversal for most of the cases, excluding the 1.27 mm FFS. In those cases, the flow may have also been separated, but the separation was so weak and the separation bubble so small that we were not able to measure it.

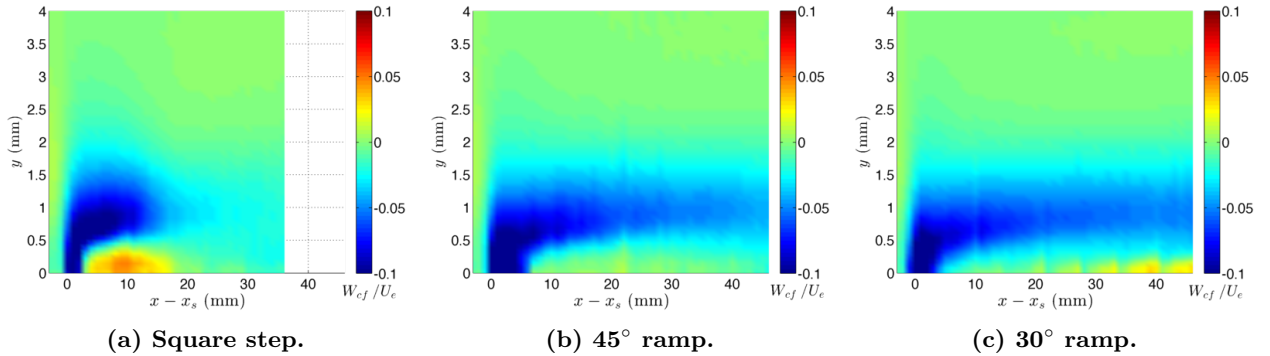


Figure 7: Spanwise-averaged crossflow velocity (W_{cf}) downstream of each step.

B. Stationary Crossflow Growth

The effect of the step on the stationary crossflow instability is examined in Figs. 8 and 9. The U -perturbation profiles are calculated from the RMS of the steady disturbance velocity (U') across the span (integrated across a wavelength range of 5 to 20 mm). The steady disturbance velocity (U') is the time-averaged velocity at each location minus the spanwise-averaged velocity at the same wall-normal location. The V -perturbation profiles are computed similarly, using the V -velocity component. As seen in the previous work,⁵ the square step results in a strong initial growth in the U'_{rms} amplitude near the wall before it decays and then grows

again starting at approximately 15 mm downstream of the step (Fig. 8a). Additionally, for this case, there is an upper lobe evident in the U -perturbation profile close to the step, which lifts up and then decays by about 8 mm downstream of the step. The ramps are very successful at limiting the growth of the stationary crossflow near the step. Again, the ramp becomes more successful as the ramp angle is decreased. The 45° ramp (Fig. 8b) results in only a small increase in stationary crossflow amplitude near the wall before the second region of growth begins approximately 15 mm downstream of the step. For this case, there is a weak upper lobe evident near the step, but instead of lifting up and decaying as in the square step case, the upper and lower lobes appear to merge right as the second region of growth begins. Contrary to the previous two cases, the stationary crossflow mode downstream of the 30° ramp (Fig. 8c) does not exhibit a near wall peak or an upper lobe near the step, nor does it undergo a region of growth, decay, and second growth. Instead, the mode shape exhibits a single broad peak that monotonically increases starting just downstream of the step.

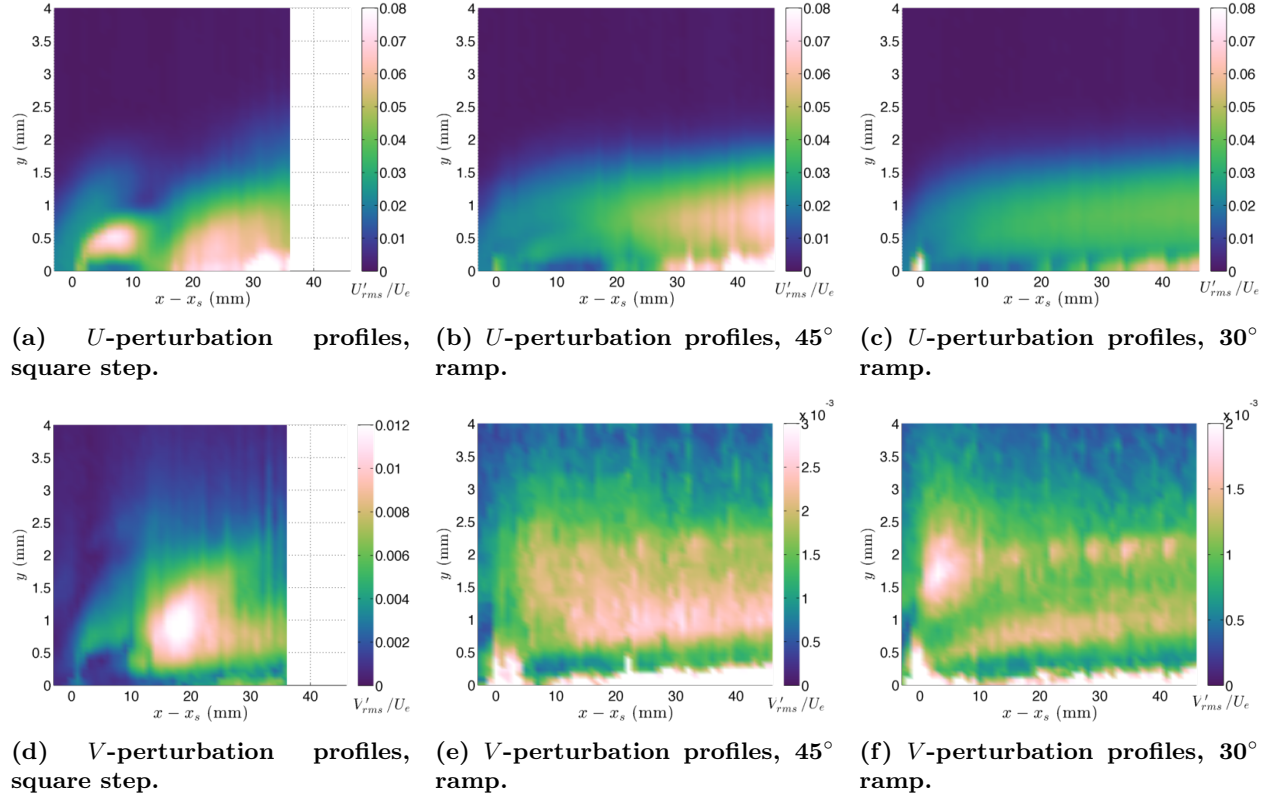


Figure 8: Spanwise-averaged velocity profiles downstream of each step.

Notice that the initial peak near the wall for the square step case (Fig. 8a) corresponds very well to both the crossflow-reversal and separated regions, identified in the previous section (see Figs. 5a and 7a). This indicates that the initial growth and decay of U'_{rms} is caused by this crossflow-reversal and separated flow region. Since both effects (separation and crossflow reversal) occur at similar locations, it is not clear if one or both are primarily responsible for the growth of the stationary crossflow vortices. In previous results,⁵ there were cases that caused increased U'_{rms} growth near the wall for which no separation was measured, but there was crossflow reversal present, and it was hypothesized that the increased growth near the wall was due to this crossflow reversal region. However, it is known that both of these effects result in an inflection point occurring either in the streamwise velocity (U) profile or the crossflow (W_{cf}) profile, which makes the profiles inviscidly unstable. The results of Hosseini and Fasel¹⁰ show that the stationary crossflow instability is highly destabilized by the separation bubble. Thus, the observation made by Tufts et al.⁴ that the helical flow region plays an important part in the amplification of the stationary-crossflow vortices near the step may be partially correct, however, there is no evidence to suggest that there is a constructive interaction between the helical flow region and the incoming vortices. Additionally, since the rotation direction of the vortices

that are destabilized near the wall would be opposite that of the incoming vortices due to the crossflow reversal, this explanation doesn't seem plausible. Separation is simply a destabilizing influence on its own because of the inviscidly unstable nature of the profiles and will cause stationary crossflow growth regardless of the height of the center of the incoming vortex. Of course, this effect will increase as the separation becomes stronger. Interestingly, even though there is a small region of growth in U'_{rms} near the wall for the 45° ramp case, there was no crossflow-reversal or reversed flow measured for that case. However, as is evident in Fig. 7b, the negative peak in the crossflow profile is lifted up coming over the step, and there is, in fact, an inflection point in both the W_{cf} -profile and U -profile, which may be just enough to destabilize the mode near the wall, even if no crossflow reversal or separation is present. In other words, perhaps separation or crossflow-reversal is not completely necessary to destabilize the flow near the wall, but the inflection points from the nearly-separated profile are enough to slightly amplify the stationary crossflow mode.

The maximum amplitudes of the U - and V -perturbation profiles shown in Fig. 8 are plotted vs. $x - x_s$ in Fig. 9. Again, the region of growth near the step, followed by decay and a second region of growth, is evident for the square step case. As seen before,⁵ the V'_{rms} amplitude follows a similar growth and decay pattern near the step, but the second region of growth begins sooner than for U'_{rms} . This behavior is also evident for U'_{rms} in the 45° ramp case, though the initial growth and decay is much less dramatic. In fact, the initial growth of the stationary crossflow mode downstream of the 45° ramp is only slightly larger than for the 30° ramp. The largest difference comes after the second region of growth, starting at $x - x_s \approx 15$ mm, where the amplitude begins to grow sharply for the 45° ramp case, while the amplitude for the 30° ramp case continues to grow at a much slower rate. The V'_{rms} amplitude for both of the ramp cases goes through an initial region of growth and decay, and then stays fairly constant beyond $x - x_s = 5$ to 10 mm. Results for the no step case are also included on this figure, and illustrate that despite the obvious success of the 30° ramp at slowing the growth of the stationary crossflow instability, the effect of the step is not completely mitigated, and the instability still grows to a larger amplitude, approximately twice that of the no-step case.

In Fig. 10, the same U'_{rms} amplitude results are plotted along with several other step heights that were studied. The initial growth rates are fairly similar between the 1.7 and 1.95 mm FFS cases, but the amplitude for the 1.95 mm step height reaches a larger value near the step before decaying initially. The amplitude grows at about the same rate initially for the two ramp cases. This growth rate is larger than that of the 1.27 mm case, and smaller than that of the 1.4 mm step case. Due to the decay in amplitude of U'_{rms} for the 1.4 mm FFS case, the amplitude for the 30° ramp case ends up being higher than the amplitude for the 1.4 mm FFS case at the farthest downstream measurement station. For the 45° ramp case, the growth rate downstream of $x - x_s \approx 20$ mm is very similar to the 1.52 mm FFS case, but the amplitudes are larger than for the 1.52 mm step due to the larger initial decay of U'_{rms} for that case.

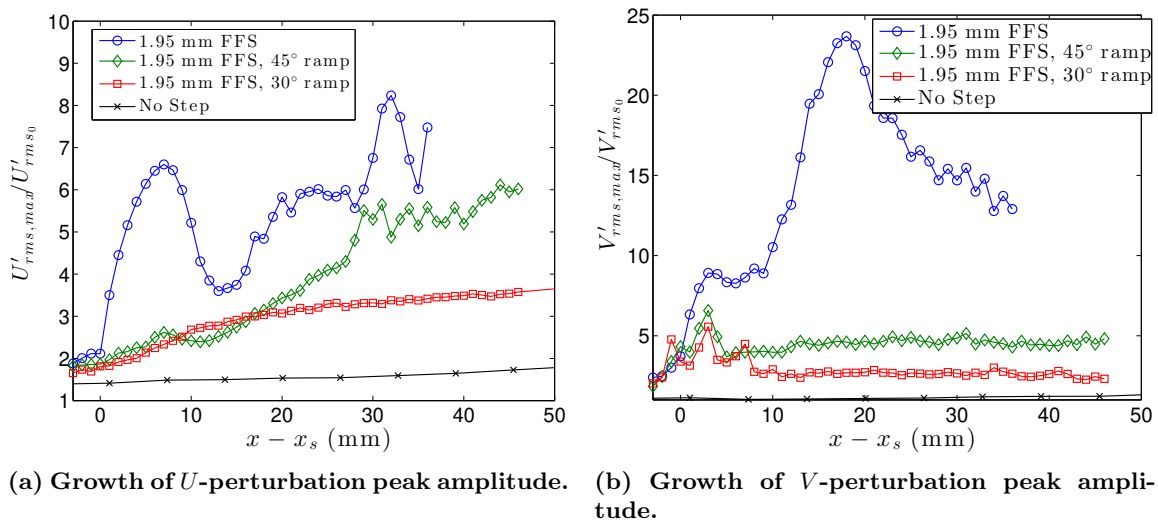


Figure 9: Growth of peak U - and V -perturbation profile.

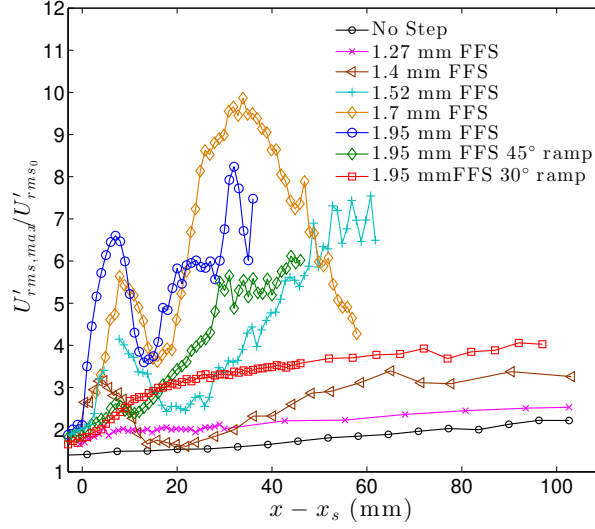


Figure 10: U'_{rms} growth rates compared with other step heights.

It was shown previously⁵ that the second region of growth of the stationary crossflow vortices is likely nonlinear due to the fact that different initial stationary crossflow amplitudes resulted in different growth rates after the initial growth and decay of the disturbance. The U' wavenumber spectra are shown in Fig. 11 for each case at a wall-normal location of $y=0.5$ mm. There are several interesting observations to make from these figures. There are quite a few harmonics present starting near $x - x_s=15$ mm, particularly for the square step and the 45° ramp. Notice that the location where the harmonics become apparent is near and sometimes slightly upstream of where the primary mode begins to grow for a second time. For the two ramp cases, some of the harmonics appear to be growing beginning at the step or shortly downstream of the step. Another interesting observation is that the primary mode near the step appears to shift to a slightly longer wavelength after the initial growth and decay near the step. This is particularly evident for the 45° ramp, but also appears to occur for the 30° ramp.

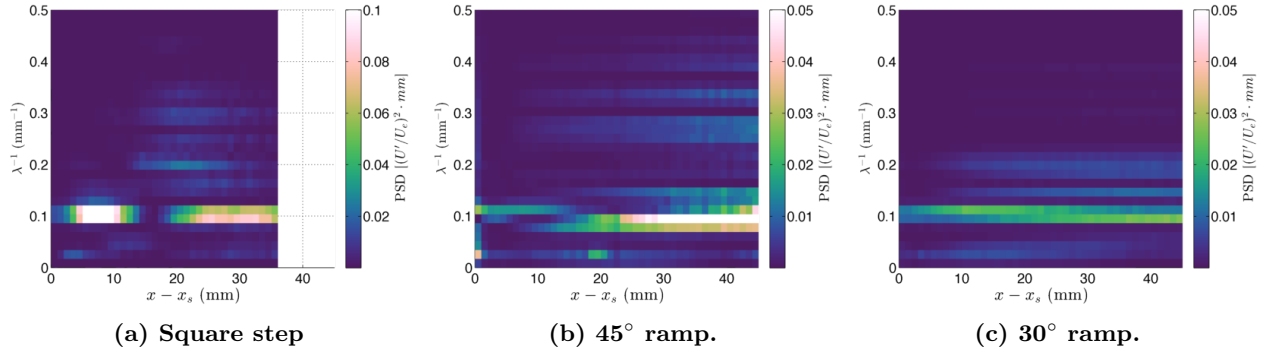


Figure 11: Wavenumber spectra at $y=0.5$ mm.

Since these spectra are taken at a single y -location, they do not give a full picture of the modal development downstream of the step. To give a better picture of the modal growth, we choose the most obvious peaks from the spectra shown in Fig. 11, and for each wavenumber of interest, we find the peak amplitude of U'_{rms} at each streamwise location. These results (Fig. 12) are similar to those shown in Fig. 9a, but are taken only at a single wavenumber and are normalized by the local edge velocity rather than the initial amplitude. For the square step case, the results for the two wavenumbers closest to the primary mode (0.086 and 0.104 mm^{-1}) are very similar, showing the initial growth, decay and second growth. Some of the harmonics (0.155 and 0.190 mm^{-1}) also experience a similar growth and decay near the step, but it is much weaker. These

modes begin to grow rapidly starting at $x - x_s = 10$ mm. This occurs about 5 mm before the second growth of the primary mode. The smaller wavelength harmonics (0.242 and 0.293 mm⁻¹) do not appear to be affected strongly near the step, but also begin to grow at around 10 mm downstream of the step.

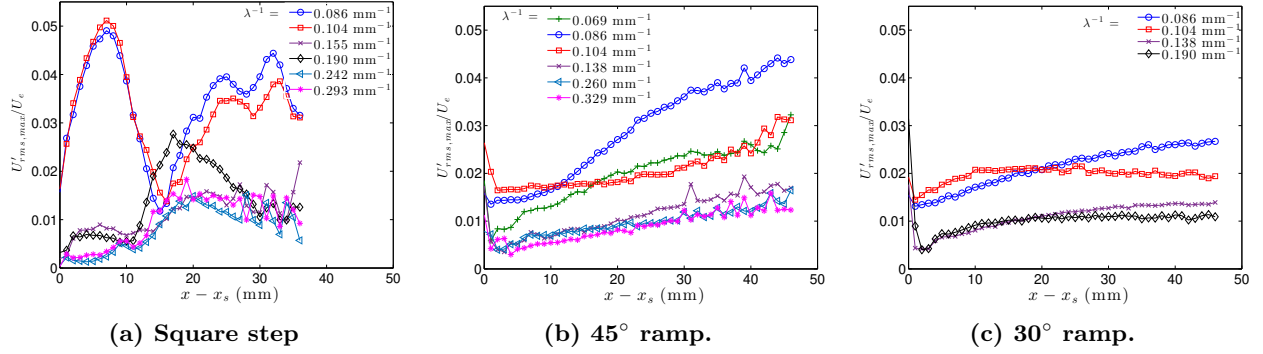


Figure 12: Peak U'_{rms} amplitudes for several different modes.

The two ramp cases are also quite interesting. Note that the mode closest to the primary excited wavenumber, which is $\lambda^{-1} = 0.086$, does not have the most energy near the step, but it is the slightly shorter wavelength mode, with $\lambda^{-1} = 0.104$, that is larger near the step. Downstream of the 45° ramp, this mode stays fairly steady until it starts to grow at around $x - x_s = 30$ mm. For the 30° ramp case, this mode grows slightly until about 10 mm downstream of the step, and then decays very slowly downstream. On the other hand, the $\lambda^{-1} = 0.086$ mm⁻¹ mode grows pretty steadily for this case, overtaking the peak amplitude of the 0.104 mm⁻¹ mode by approximately $x - x_s = 20$ mm. For the 45° ramp case, this mode stays fairly constant until about 7 mm downstream of the step, at which point it begins to grow fairly rapidly. It is clear that there are quite a few stationary crossflow modes that are destabilized by the step, and the destabilizing effect that the mean flow has on the stationary crossflow modes varies greatly for each mode. Some are affected by the separated region near the step, and some are affected more strongly as the flow recovers from the separation. The computational results of Hosseinverdi and Fasel¹⁰ also showed that the effect of the separation bubble on the stationary crossflow mode varied significantly depending on the wavelength of the mode. It is the growth and interactions of all these modes that leads to the overall behavior of the stationary crossflow vortices, as shown in Fig. 9. These results also illustrate that while the region close to the step plays an important role in the initial growth of the stationary crossflow disturbances, there are other destabilizing effects of the mean flow as it recovers from the step that cause longer term growth of some of the stationary crossflow modes.

RMS contours of the fluctuating velocity component, u'_{rms} , are shown in Fig. 13 at $y = 0.5$ mm. There is a large amount of fluctuation occurring for the square step case, particularly downstream of $x - x_s = 10$ mm. The fluctuations actually begin shortly downstream of the step, and are located spatially in span at distinct locations corresponding to regions of high wall-normal and spanwise shear. These were previously measured for other step heights⁵ using time-resolved PIV to have high frequencies, indicating that they are likely secondary instabilities caused by the strong modulation of the mean flow. The amplitude of the initial fluctuations near the step are not very large, and they start to decay in amplitude until 10 mm downstream of the step, where they begin to grow significantly in amplitude and spread in the spanwise direction. Interestingly, the fluctuation amplitude does not appear to be directly related to the amplitude of U'_{rms} , nor with the amplitude of $\frac{\partial U}{\partial y}$ or $\frac{\partial U}{\partial z}$, indicating that something about the flow recovery downstream of the separated region is highly destabilizing for these instabilities. The growth actually does, however, seem to correlate well with the growth of V'_{rms} . The strong growth of these disturbances does not occur until right at the end of the separated region, so it seems unlikely that they are related to any sort of shear-layer instability. This again illustrates the importance of understanding the stability of the boundary layer farther downstream of the step, since this is where transition is finally triggered. For the 45° ramp case, there are some limited fluctuations noticeable starting at around 10 mm downstream of the step, though the amplitude is fairly low and there is also quite a bit of noise in these plots so it is difficult to discern exactly what the behavior is. The amplitude of the fluctuations grows downstream, and in this case seems to be

more directly related to the behavior of the stationary crossflow mode. As mentioned earlier, this case did result in some strong turbulent fluctuations at the farthest downstream measurement location $x - x_s = 46$ mm, though still only at some local spanwise locations, indicating that the flow was starting to undergo transition and would likely become turbulent shortly downstream. The 30° ramp case resulted in some fairly weak u'_{rms} fluctuations at very localized spots, though they are difficult to distinguish from the background noise.

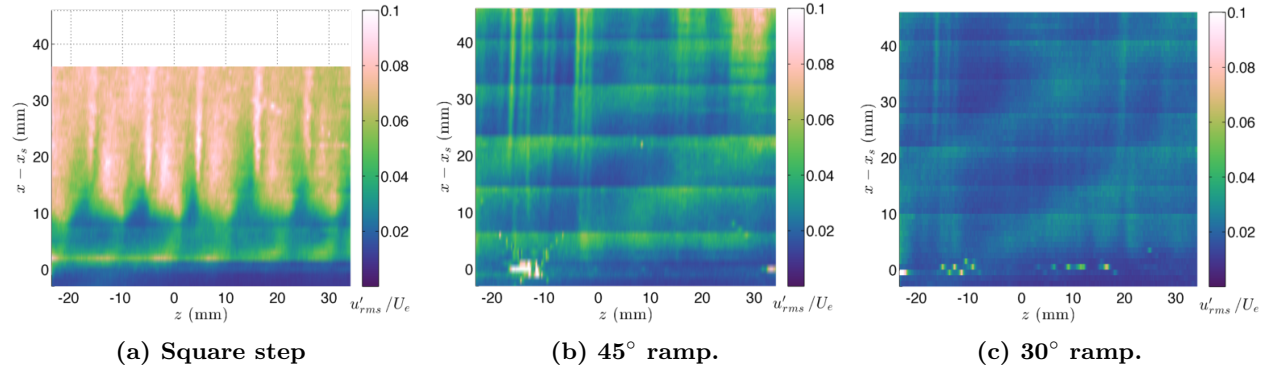


Figure 13: Planform view of u'_{rms} contours at $y=0.5$ mm.

C. Conclusions

Stereo PIV results were presented downstream of a square 1.95 mm forward facing step, along with two ramped steps of the same height at 30° and 45° . The shape of the forward-facing step had a significant impact on the stability of the stationary crossflow vortices through the effects of the step on the mean flow, and these results shed more light on the mechanisms that cause transition downstream of a swept FFS. The ramps were successful at mitigating the effects of the adverse pressure gradient near the step, as they eliminated the separation downstream of the step, as well as the crossflow-reversal region. The initial strong growth of the stationary crossflow disturbance is believed to be caused by this separated and crossflow-reversal region, due to the strong inflection points that occur. It was found, however, that even though crossflow-reversal and separation did not occur for the 45° ramp case, there was still some small growth near the wall for this case, indicating that the inflection points caused by the nearly-separated flow or the nearly-reversed crossflow may be enough to slightly destabilize the stationary crossflow disturbances in this region. Obviously, the effect of this region becomes stronger as it becomes larger and as the crossflow reversal and separation become stronger.

There are two important regions to consider downstream of the step. The first is the near-step region, where the inflectional profiles appear to dominate the stability characteristics of the flow. For the square step, this region results in some very strong flow modulation, as evidenced by the large values of U'_{rms} , however, transition did not occur until farther downstream. In this near-step region, some high-frequency fluctuations were measured, but they did not reach large enough amplitudes near the step to cause transition. They did, however, appear to feed into the unsteady disturbances that grew to large amplitudes farther downstream.

The second important region is the flow-recovery region downstream of the separated, or nearly-separated profiles. After the initial growth and decay of the stationary crossflow vortices in the near-step region, there is a second strong region of growth. It was shown that there are multiple stationary crossflow modes present downstream of the step, and these modes are affected differently by the mean flow. Some are destabilized near the step and grow to large amplitudes, but then decay. Others are less affected near the step, and instead grow fairly consistently from the step or from the end of the separated region. In some cases these modes grow and overtake the initial dominant mode. There are some harmonics present that start to grow during this flow-recovery region, particularly for the square step case. This behavior provides evidence that the strong growth in this flow-recovery region is at least partially attributable to nonlinear effects. This was also seen in previous results by comparing growth rates of stationary crossflow disturbances downstream of the same step but with different initial stationary crossflow amplitudes.

The unsteady disturbance results also highlight the importance of this downstream region. For the square step case, the high-frequency unsteady disturbances that were initiated in the near-step region initially

decay until this flow-recovery region is encountered, at which point they are amplified significantly. These instabilities initially correspond to regions of high wall-normal and spanwise shear, indicating that they are high-frequency secondary instabilities caused by the mean flow modulation. However, the growth patterns of these instabilities do not appear to correspond directly to the amplitude of the wall-normal or spanwise shear. Thus, there appears to be some strongly destabilizing effect of the mean flow downstream of the separation bubble for these high-frequency disturbances. Even though the 45° ramp was successful at mitigating the near-step effects, the destabilizing effect of the downstream region was enough to cause significant growth of the stationary crossflow instabilities, leading to early transition, though the flow was not measured to be fully turbulent at the end of the measurement region, only locally transitional. The 30° ramp was successful at delaying transition to at least beyond 100 mm downstream of the step, which was the farthest downstream measurement plane for this case. The stationary crossflow vortices were still somewhat destabilized by this step, reaching amplitudes approximately twice that of the baseline case, but this was not enough to cause premature transition.

Overall, both ramps were largely successful at mitigating the near-step effects due to the reduced adverse pressure gradient, and the resulting reduced impact of flow separation or crossflow reversal. However, since there are lingering downstream effects of the flow recovery that continue to cause growth of the stationary crossflow, the 30° ramp was more successful at delaying transition because it was able to better mitigate the downstream region of growth. However, we cannot completely separate the effects in the near-step region from what happens downstream, since there do appear to be some nonlinear effects contributing to the second region of growth, meaning that the amplitude of the instability that is reached upstream could be important in generating the nonlinear interactions. Additionally, the high-frequency secondary instabilities that are generated near the step appear to feed into the unsteady instabilities that grow farther downstream. Thus, what happens near the step does not necessarily stay near the step, and it is important to understand the stability characteristics of the flow both near the step and farther downstream.

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