

Effects of Step Shape on Transition over a Swept Backward-Facing Step

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The effect of backward-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 76% of the local unperturbed boundary-layer thickness at the step location, and the shape was varied by placing three ramps of differing slopes and shapes on the downstream face of the step, including a 30° ramp, rounded ramp, and a 5° ramp. In addition, the square step shape (with no ramp) was studied. The 5° ramp was the only one that was successful at substantially delaying transition downstream of the step. Even so, it did not completely mitigate the effect of the step. The 5° ramp significantly altered the mean flow, significantly reducing the separation region downstream of the step. While this geometry still resulted in increased growth of the stationary crossflow instability, it substantially reduced the amplitude of the unsteady instabilities that grew downstream of the step. In particular, this ramp completely eliminated the low-frequency, traveling crossflow mode that was observed in the other cases.

Nomenclature

c	=	chord length, m
C_p	=	Pressure coefficient, $C_p = \frac{p - p_\infty}{\frac{1}{2}\rho U_\infty^2}$
f	=	frequency, Hz
h	=	step height, mm
Re'	=	Unit Reynolds number, m^{-1}
Tu	=	turbulence intensity
U, V, W	=	mean boundary layer velocity in the x , y , and z' -directions, m/s
u, v, w	=	velocity components in the x , y , and z' directions, m/s
U'	=	steady disturbance velocity, m/s
$U_\perp$	=	mean velocity in x_c direction, m/s
u', v', w'	=	fluctuating components of velocity, m/s
u'_{rms}, w'_{rms}	=	temporal root mean square of u', w' , m/s
U_e	=	boundary-layer edge velocity, m/s
U_∞	=	freestream velocity, m/s
x	=	streamwise direction
x_c	=	direction normal to the leading edge
x_s	=	streamwise location of the step
y	=	wall-normal direction
z	=	spanwise direction (parallel to the leading edge)
z'	=	direction normal to side wall
δ	=	boundary-layer thickness, mm
λ_z	=	spanwise wavelength, mm

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I. Introduction

THE utilization of laminar flow control (LFC) to improve aircraft fuel efficiency is an ongoing challenge. Increasing the amount of laminar flow on a vehicle surface can be quite effective at reducing drag 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. If we do not have a clear understanding of the allowable surface excrescence sizes, reasonable manufacturing tolerances cannot be specified.

A better understanding of the mechanisms that cause transition when the surface imperfections are present is crucial to enable development of better prediction models for acceptable roughness levels. The transition mechanisms will vary depending on the type of surface imperfection. While different approaches exist for estimating critical roughness heights [1–9], they are all either empirical or semi-empirical models that depend upon the specific configuration being tested. Historically, these configurations were primarily limited to two-dimensional (i.e., unswept) flows. Somewhat recently, researchers have begun to study two-dimensional excrescences in three-dimensional flow fields. This work is often limited to observing the behavior of the transition front as the step height is increased [9–11], but more recently, researchers have begun to study the flow in more detail. Duncan et al. [12] 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. [13] performed computations to study the interaction between stationary crossflow instabilities and a two-dimensional step excrescence. The backward-facing step (BFS) was found to have little influence on the stationary crossflow instability, but some unsteady instabilities were destabilized. Similarly, Eppink et al. [14] found that backward-facing steps caused only a small localized increase in stationary crossflow amplitude downstream of reattachment, but the primary transition mechanism was related to the unsteady instabilities, while the FFS caused a large growth in the stationary crossflow amplitude [15]. Saeed et al. [16] also found that, downstream of a two-dimensional strip, unsteady disturbances in the flowfield led to earlier transition.

Most of the previous work has dealt with square steps; however, it is common wind tunnel practice to mitigate the effect of steps by fairing them in. Additionally, it has been shown in previous experiments in two-dimensional (unswept) flows, that one can delay transition, or increase the critical step height, by shaping the step. Holmes et al. [1] discussed flight test results showing that rounded steps and ramped steps could increase the critical step-height Reynolds number significantly compared to square steps of 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. Eppink and Casper [17] experimentally studied the effect of forward-facing step shape on transition, testing a square step, a 45° ramp, and a 30° ramp. The 30° ramp was successful at mitigating the effect of the step, while the 45° ramp was only partly successful. The current study applies the same approach to study the effect of step geometry for backward-facing steps. The experimental setup is described in Section II, followed by a discussion of the results in Section III. The discussion will first consider the effect of step shape on the mean flow (Section III.A), followed by a discussion of the impact on the stationary crossflow instability (Section III.B), and, finally, the unsteady instabilities (Section III.C).

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 ($Re' = 2.87 \times 10^6/m$) 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 [18].

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 near the leading edge on the test surface.

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.

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 . These DREs correspond to the large DRE case studied previously [14]. 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 [19].

A high-speed, double-pulsed, Nd:YLF laser provided the laser sheet for the particle image velocimetry (PIV) measurements (see Fig. 1). The laser sheet was set up parallel with the leading edge and the backward-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. 1). To achieve the desired field of view and resolution, 300 mm lenses were utilized, resulting in a total possible measurement area of approximately $60 \text{ mm} \times 30 \text{ mm}$. For the majority of the measurements, the area of interest was reduced to approximately $60 \text{ mm} \times 8 \text{ mm}$ 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 16×16 pixel interrogation size) inside the boundary layer. For the mean flow measurements, data were acquired starting about 9 mm upstream of the step, and moving downstream in approximately 1 mm increments. Five hundred image pairs were acquired at each location. For the high-speed measurements, 10,000 image pairs were acquired at 4.7 kHz , with the area of interest reduced to $40 \text{ mm} \times 7 \text{ mm}$. These image pairs were processed using a 32×32 pixel interrogation size. The high-speed measurements were only performed at limited locations, due to the extra time required for acquiring and processing the data. 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.

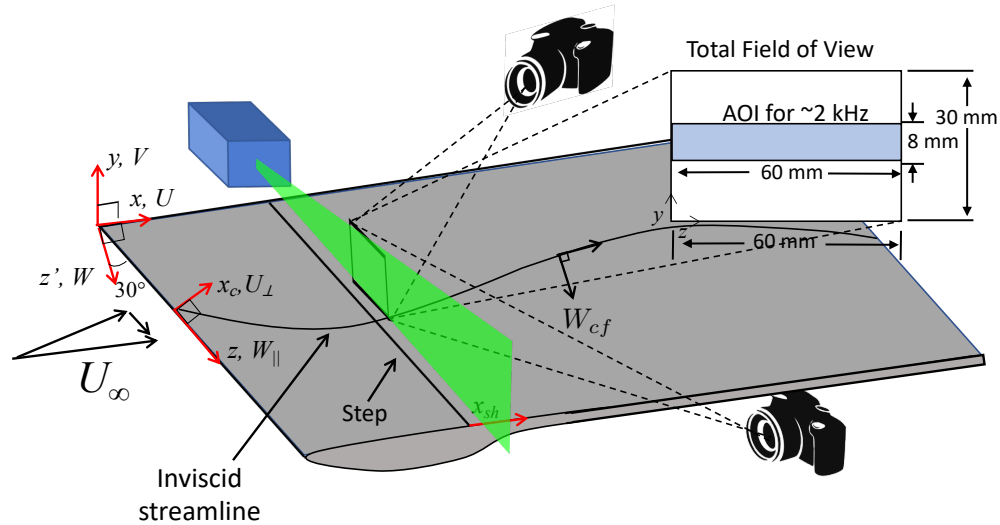


Fig. 1 Sketch of model coordinate system and TRPIV setup.

A single backward-facing step height of nominally 1.83 mm was studied, including a square step, along with two ramps of nominally 30° and 5° , as well as a circular rounded shape. These shapes are depicted in Fig. 2. The square step was achieved using the method described above, by inserting precision shims underneath the upstream plate. Ramps

were added downstream of the square step to create the ramped and rounded shapes. The shapes were created using a polyjet 3D printing technique. The shapes were targeted for a 1.7 mm step height, but the step height of 1.83 mm was ultimately chosen due to the sensitivity of the flow to any overhanging pieces.

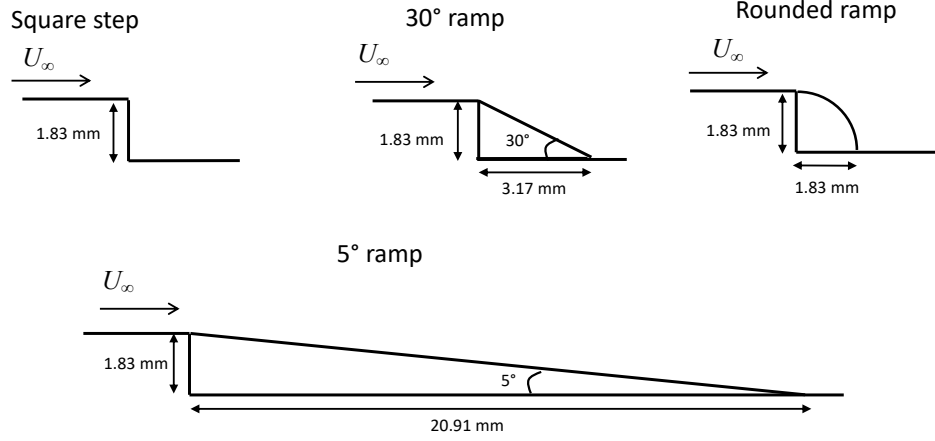


Fig. 2 Sketch of step geometries studied.

III. Results and Discussion

In the previous study [14], backward-facing step heights ranging from 0.86 mm to 1.17 mm were examined in detail. The critical step height was found to be approximately 1.17 mm, meaning that at or above this step height, transition moved upstream relative to the no-step case. Contrary to the forward-facing steps, the backward-facing steps resulted in only a small local increase in the stationary-crossflow amplitude, occurring for a short distance downstream of the reattachment location. However, three different types of unsteady disturbances were identified, corresponding to traveling crossflow (80-200 Hz), Tollmien-Schlichting (200-800 Hz), and shear-layer (800-1500 Hz) instabilities. These unsteady instabilities were found to be ultimately responsible for transition, though the amplitude of the stationary-crossflow vortices was found to play a secondary role in transition through the modulation of the unsteady disturbances, which slightly accelerated transition as the stationary crossflow amplitude was increased. The step causes major changes to the mean flow, which are believed to play important roles in the interaction and destabilization of both the stationary-crossflow vortices and the unsteady instabilities. As was seen for the forward-facing steps, contouring or shaping the steps should reduce the impact on the mean flow, especially on separation, and thus should mitigate the effect of the step on the instabilities. The current work was undertaken to study this effect. Results have been acquired for a square step, for ramps with nominal angles of 30° and 5°, and for a circular rounded ramp. Note that the step height of 1.83 mm is significantly larger than the previously studied largest height of 1.17 mm. The ramps were initially fabricated for use with a forward-facing step geometry, for which the critical step height is larger. Since the ramps already existed, we decided to utilize them to study a backward-facing step of the same height.

The transition behavior of the ramps was studied using naphthalene flow-visualization. The results are shown in Fig. 3. The images have been post-processed to remove the sweep and distortion, and a grid was overlaid to help identify the transition location. The black triangle in the lower left corner is a consequence of the limited view of the camera through the small window. The step is identified by the red line, the flow is from bottom to top, and the streamwise locations on the right are the streamwise distances downstream of the step, $x - x_s$ (see Fig. 1). Note that even though the image is unswept, the distances listed are still the streamwise distances, in order to be consistent with the values used throughout the paper. The white regions indicate areas of laminar flow, since the naphthalene remains on the surface due to the lower shear stress. Naphthalene flow-visualization results must be interpreted with caution, since the results may vary slightly unless one is extremely consistent with how much naphthalene is applied and how long the tunnel is run. Additionally, since the sublimation rate is really a function of wall shear stress, more naphthalene on the surface could be an indication of flow separation in addition to laminar flow. Thus, the results should be interpreted in the context of other, more reliable, measurement techniques. Nonetheless, the results are still useful for obtaining a general and more global idea of the transition behavior. The square step results in transition shortly downstream of the step, at $x - x_s \approx 22$ mm, or $x/c \approx 0.168$. These transition locations were estimated from the images based on an average across the span.

The 30° ramp did not have much effect on the transition front; transition occurred at approximately the same streamwise location as for the square step. The rounded ramp appears to have slightly delayed transition (by a few millimeters) for parts of the span, however, given the small difference and the caution given above about interpreting these results in a quantitative manner, the difference is not large enough to draw firm conclusions. Given that the 30° ramp resulted in practically no change to the transition location, the 5° ramp was tested next, even though a 15° ramp was also fabricated. The 5° ramp resulted in a significant transition delay, with the average transition location occurring around $x - x_s = 198$ mm, or $x/c = 0.238$. Note that the baseline case (no step), which is not shown here, resulted in transition downstream of $x/c = 0.48$. Thus, while the 5° ramp is successful in significantly delaying transition, it is still not able to completely mitigate the effect of the step. It is interesting to compare this case to the FFS, for which the 30° ramp was successful at mitigating the effect of the step [17]. Clearly, a significantly longer ramp is required to mitigate the effect of a BFS.

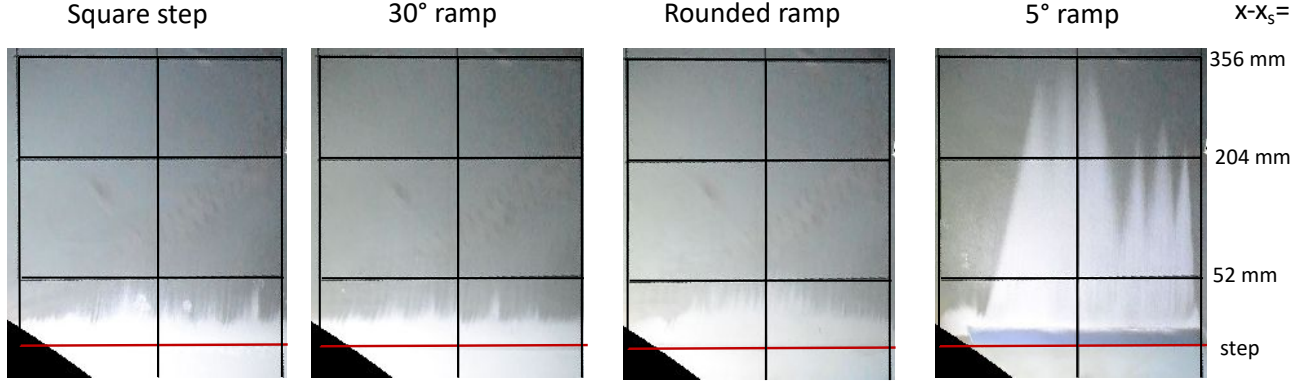


Fig. 3 Naphthalene flow-visualization results.

A. Mean Flow Effects

The effect of the step and ramps on the mean flow are shown in Fig. 4. These figures show the flow component normal to the leading edge ($U_\perp$), normalized by the local edge velocity (U_e). The white contours indicate regions of reversed (or negative) flow. There is not a significant difference between the square step, 30° ramp, and rounded ramp cases. This is not very surprising, considering that the transition front was not changed significantly for these cases. The strongest region of reversed flow occurs approximately 30 mm downstream of the step, followed by reattachment by $x - x_s \approx 38$ mm. The 5° ramp, however, has a significant effect on the mean flow. The reversed flow region is almost completely gone; there are only some weak remnants of recirculation visible between the edge of the ramp at $x - x_s = 20$, and reattachment near 35 mm. Because the reversed flow region downstream of a backward-facing step is so long, and the strongest part (i.e., largest reversed flow velocity) occurs immediately upstream of reattachment, it is apparently necessary to use a ramp that is long enough to interact with this region, in order to have any significant effect on the flow.

The effect that the step has on the crossflow component inside the boundary layer is illustrated in Fig. 5 for all cases. This is the velocity component inside the boundary layer that is normal to the external inviscid streamline. The normal crossflow direction (i.e., that which occurs in the baseline case) is negative in the defined coordinate system (see Fig. 1). For the square step, 30° ramp, and rounded ramp cases, a region of positive crossflow occurs near the wall, below the region of negative crossflow. This positive crossflow region corresponds approximately with the reversed flow region, though it extends approximately 5 mm farther downstream. The separation and crossflow reversal are both caused by the adverse pressure gradient downstream of the step. Crossflow reversal results in an additional inflection point in the velocity profile, and can cause the destabilization of stationary crossflow vortices that are rotating in the direction opposite to the initial primary vortices. The 5° ramp results in significantly weaker regions of both negative and positive crossflow. Again, the crossflow-reversal region behaves similarly to the separated region, though it extends slightly farther upstream and downstream.

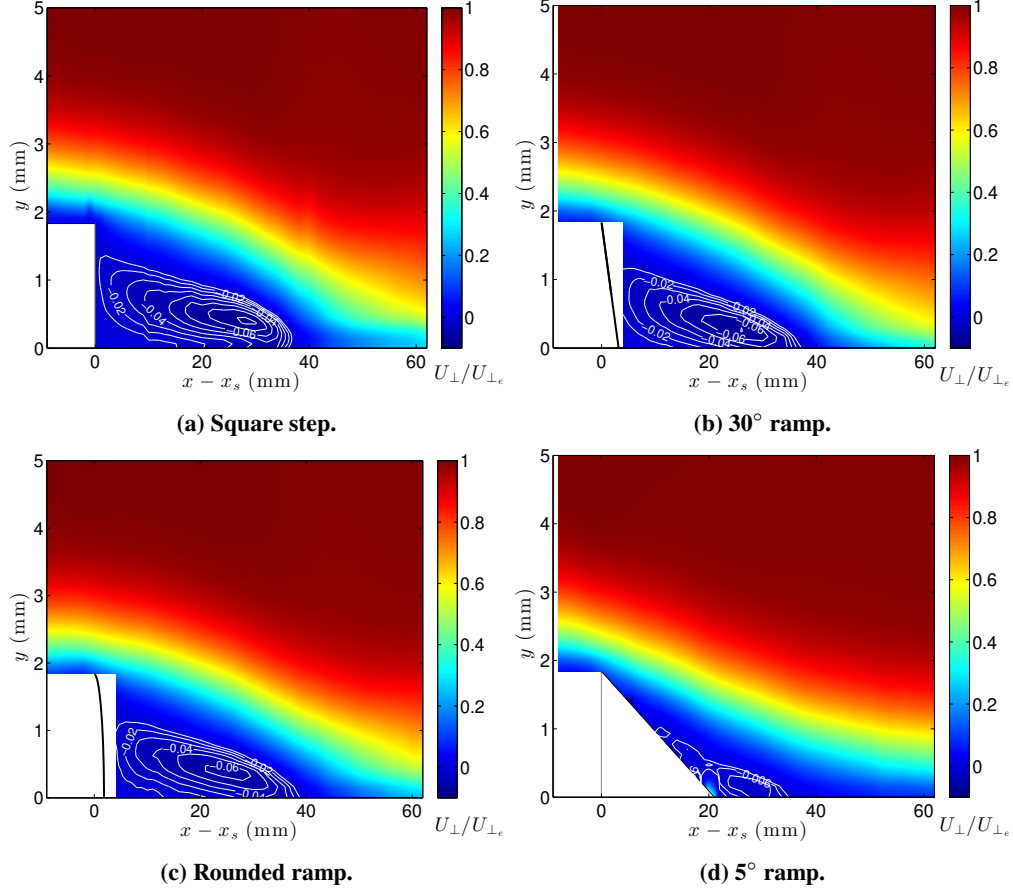


Fig. 4 Spanwise-averaged $U_{\perp}$ -profiles downstream of each step. White contour lines indicate the reversed flow region.

B. Stationary Crossflow Growth

The effect of the step on the stationary crossflow instability is examined in Fig. 6. The U -perturbation profiles are calculated from the RMS of the steady disturbance velocity (U') across the span. The wavelength spectra are 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. Downstream of the square step (Fig. 6a), the incoming (upper) peak decays by about 30 mm downstream of the step, and a second peak forms below this upper peak, starting at approximately 20 mm downstream of the step. This lower peak eventually grows to amplitudes near 3% U_e before decaying. This short region of growth and decay in stationary crossflow amplitude is similar to that seen through the hot-wire measurements performed for the lower step heights [14]. The growth of the lower peak is caused by the appearance of a second inflection point in the W_{cf} profile, which comes about through the crossflow reversal. Similar behavior was seen for the FFS [17], though the effect in that case was much larger due to the stronger inflection point. It is very interesting to note that, despite only minor differences in the mean flow in Figs. 4 and 5, the rounded ramp case (Fig. 6c) results in noticeably different behavior of the stationary crossflow mode. In this case, the incoming (upper) peak continually grows downstream of the step. The initial growth is fairly weak, and then, similar to the square step case, there is a stronger, but short, region of growth and decay shortly downstream of reattachment. There is a lower peak that starts to become apparent at $x - x_s \approx 30$ mm, but it decays shortly after it appears. The behavior of the stationary crossflow instabilities downstream of the 5° ramp is fairly similar to that of the rounded ramp case. The upper peak maintains its initial amplitude from just upstream of the step, until approximately 30 mm downstream of the step, where the amplitude begins to gradually increase. The profile also starts to broaden as this upper peak moves closer to the wall, probably due to the influence of the crossflow reversal region near the wall. The stationary crossflow amplitude continues to grow steadily downstream of reattachment.

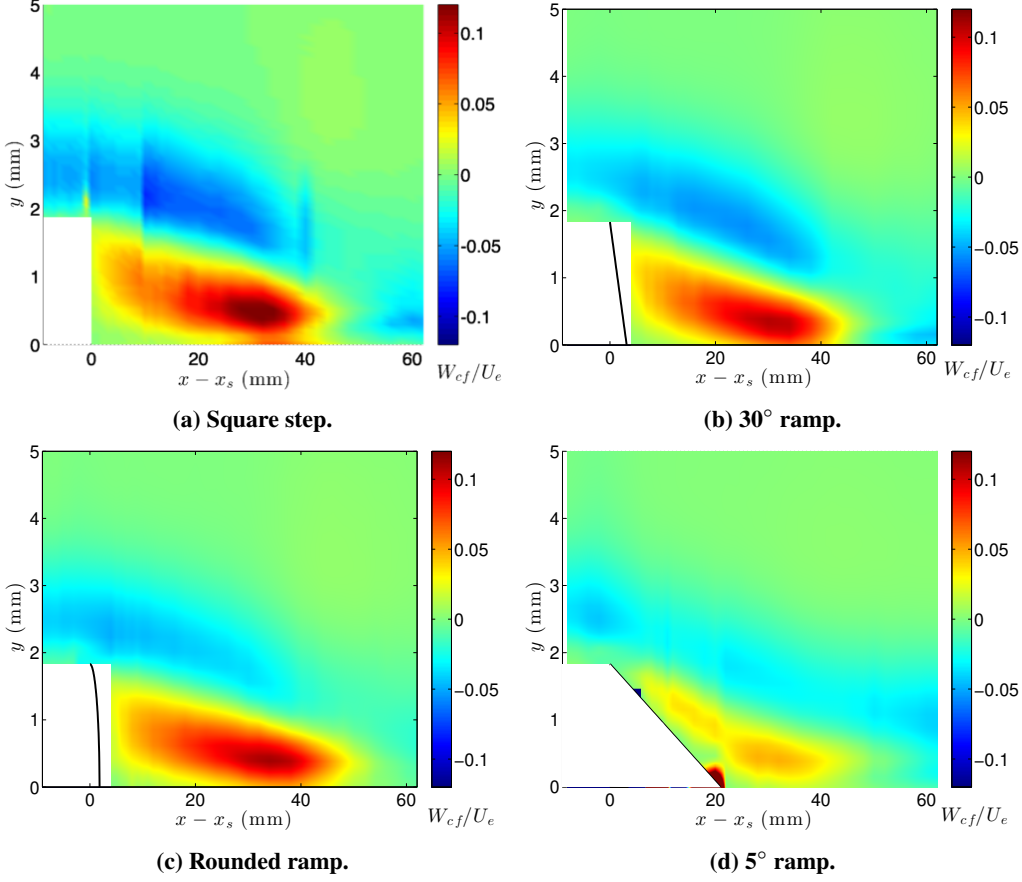


Fig. 5 Spanwise-averaged crossflow velocity (W_{cf}) downstream of each step.

Two different approaches are used to quantify the amplitude of the stationary crossflow instability in Fig. 7. The first approach is to simply take the peak amplitude from the stationary crossflow profile at each streamwise location (Fig. 7a). Using this approach, there appears to be a decrease in amplitude for the square step and 30° ramp cases starting near 10-20 mm downstream of the step, before a sharp increase in amplitude occurs. The rounded ramp case grows steadily, initially, at a similar rate to the no-step case, before increasing sharply near 40 mm downstream of the step. The 5° ramp case grows steadily, initially at a rate similar to the no-step and rounded ramp cases, with a steadily increasing growth rate. The square step, rounded ramp, and 30° ramp cases all saturate in amplitude between 40 and 60 mm downstream of the step, likely due to the fact that the boundary layer is becoming turbulent at this point. The second approach to quantifying the amplitude of the stationary crossflow instability is to integrate across the entire profile: $U'_{rms,tot} = \frac{1}{\delta} \int_0^\delta U'_{rms}(y) \partial y$. This takes into account the energy contained in the double-peaked profiles, which otherwise is neglected when only picking out the peak amplitude. These results are shown in Fig. 7b. With this measure of amplitude, there is no initial decay in amplitude for the square step and 30° ramp cases. Rather, most cases appear to grow at a relatively slow rate shortly downstream of the step, though the growth rate for the rounded ramp case is higher than all the others.

In all cases, the stationary crossflow grows at a higher rate downstream of reattachment relative to the baseline (no-step) case, even though the maximum crossflow velocity is similar to or even lower than in the baseline case. One possible explanation for this increased stationary crossflow growth is that the streamlines begin to exhibit concave curvature as the flow recovers from the effect of the step. It has been shown that concave streamline curvature is destabilizing for stationary crossflow instabilities [20]. Additionally, convex curvature has been shown to be stabilizing for stationary crossflow instabilities [21], which might explain the reduction in amplitude of the upper lobe (i.e., the incoming stationary crossflow instabilities) shortly downstream of the square step and 30° ramp.

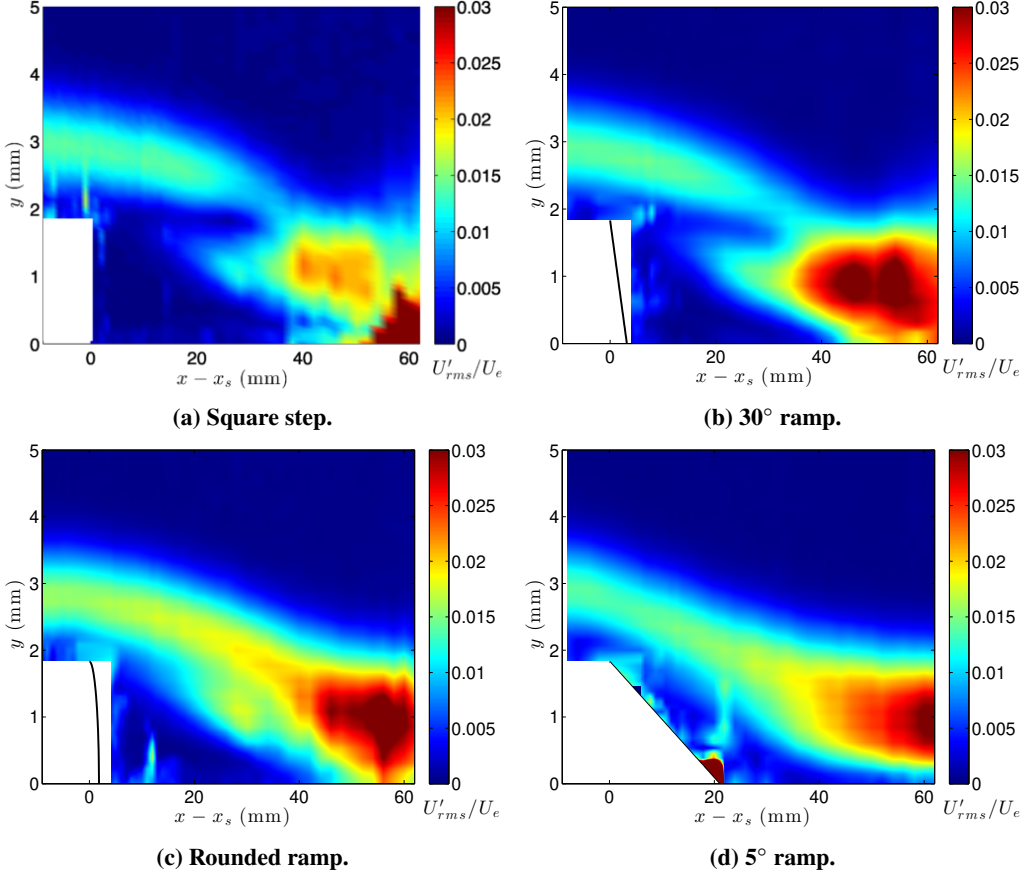


Fig. 6 U-perturbation profiles downstream of each step.

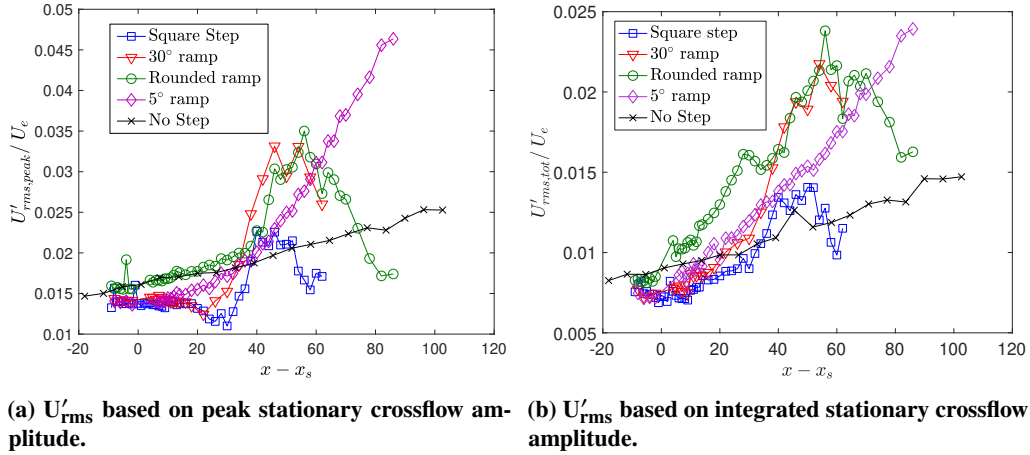


Fig. 7 Comparison of stationary crossflow growth.

The behavior of the stationary crossflow modes downstream of the step is explored further in Fig. 8, in which contours of the stationary disturbance velocity (U') are shown at several different streamwise locations for the square step case. Upstream of the step, the mode looks like a normal stationary crossflow mode, but by 26 mm downstream of the step, it has developed the double-peaked structure, as evident from the stationary crossflow profiles shown in Fig. 6a. There is a clear phase shift of close to 180° between the upper and lower sets of U' disturbances. By 32 mm downstream of the step (Fig 8c), the phase shift between the upper and lower disturbances has diminished significantly, and the

two are starting to merge. The lower set of disturbances likely occurs due to the presence of the positive crossflow region near the wall. Similar behavior was seen downstream of a forward-facing step [15]. The behavior upstream and downstream of the 5° ramp is shown in Fig. 9. In this case, the double-peaked behavior is not evident downstream of the step. Rather, the initial U' -disturbances upstream of the step slowly migrate closer to the wall, as the amplitude increases steadily.

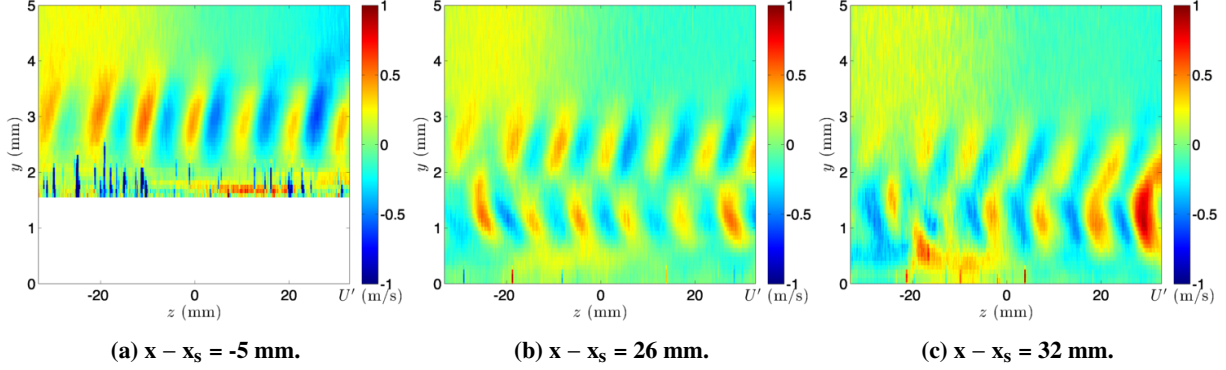


Fig. 8 Spanwise planes of U' -contours at different streamwise locations for the square step.

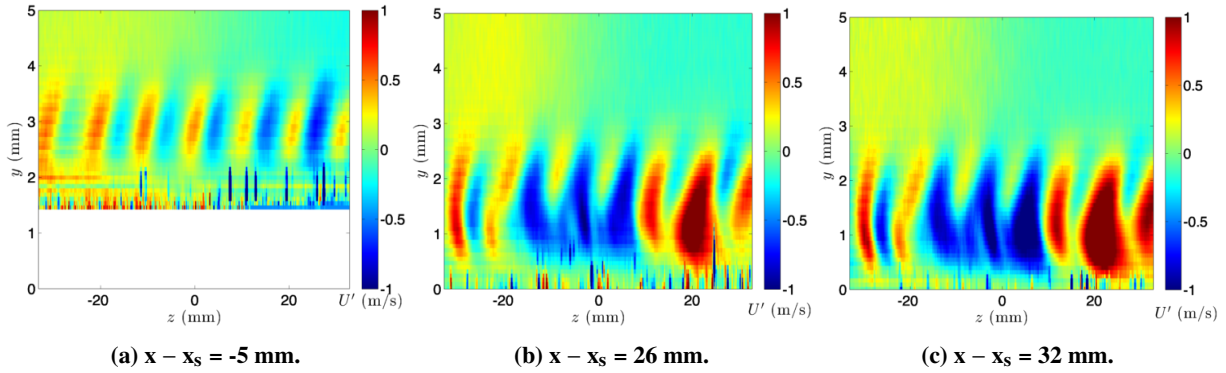


Fig. 9 Spanwise planes of U' -contours at different streamwise locations for the 5° ramp.

C. Unsteady Disturbances

The most important aspect of the flow for backward-facing steps, at least when it comes to transition, is the effect of the step shape on the unsteady disturbances. In a previous study, unsteady disturbances were found to be the primary cause of transition for swept backward-facing steps [14], though the stationary crossflow played a role through the modulation of the unsteady disturbances. Figure 10 shows spanwise-averaged profiles of the fluctuating RMS velocity (u'_{rms}) for each of the cases. The fluctuations for the square step case start the earliest, near 30 mm downstream of the step. The fluctuations for the 30° ramp and rounded ramp start shortly downstream of that location, but also very near 30 mm. Downstream of the 5° ramp, fluctuations are just starting to become visible near 70 mm downstream of the step.

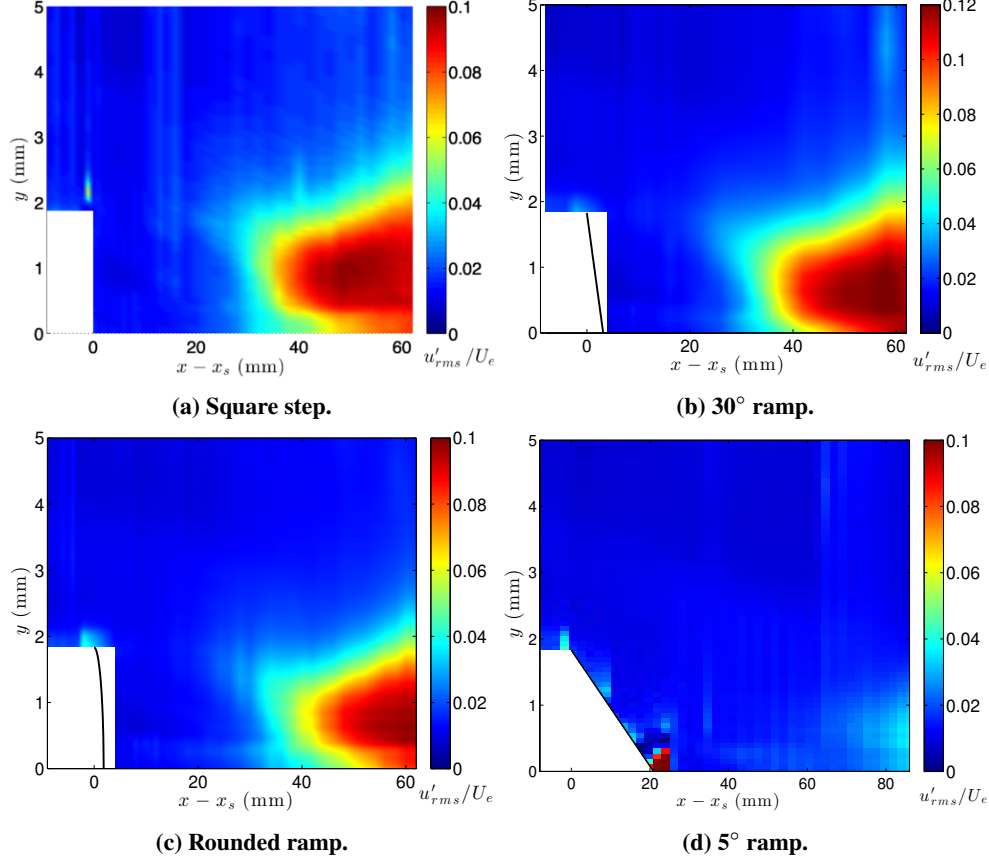


Fig. 10 Spanwise-averaged fluctuating velocity profiles (u'_{rms}) downstream of each step.

To give an idea of the spatial layout of the u'_{rms} fluctuations, planform views of u'_{rms} contours at $y=1.5$ mm are shown in Fig. 11 for the square step and 5° ramp cases. In these figures, the black lines indicate regions of reversed flow near the wall. In the case of the square step, the fluctuations begin near $x - x_s = 30$ mm, as indicated from the spanwise-averaged u'_{rms} profiles. This is about 10 mm upstream of the reattachment location. As the fluctuations develop downstream, they become modulated at the primary stationary crossflow wavelength (i.e., 11 mm). The fluctuations spread in the spanwise direction until, near 60 mm downstream of the step, the modulations are no longer clearly visible, likely because the flow has become nearly or fully turbulent by this point. The 5° ramp exhibits very different behavior. Extremely localized regions of fluctuation start to develop by around 40 mm, or shortly downstream of reattachment, but only between $z=-10$ to 10 mm. Farther downstream, near $x - x_s = 60$ mm, localized fluctuations are observed for $z < -20$ mm. This indicates that the transition mechanisms may be somewhat different between these two cases.

Fig. 12 shows velocity spectra taken at several different locations for each of the four cases. These spectra were averaged across the span at a specific y -location. This y -location varied from case to case, but was chosen as the point at which the u'_{rms} amplitude was the largest. Before the spanwise averaging was applied, the power spectral densities at each point were computed using a hanning window with a 50% overlap and 40 block averages, resulting in a frequency resolution of 9.4 Hz. For the square step, 30° ramp, and rounded ramp cases, this y -location was typically close to $y=1.5$ mm, while for the 5° ramp case, the y -location of the maximum amplitude was typically closer to the wall, at $y=1$ mm.

Some differences are visible in the spectra. In general, the square step, 30° ramp, and rounded ramp cases exhibit similar features in the spectra, however, the amplitude of the fluctuations are generally slightly higher in the square step case. This indicates that the slight changes in the mean flow due to the different ramp geometries do have a slight mitigating effect on the unsteady instabilities. Note that the first spectra shown for the square step case is 10 mm downstream of that shown for the rounded ramp and 30° cases. Unfortunately, the data acquired at $x - x_s = 14$ mm for the square step case were too noisy to generate good spectra. At $x - x_s = 14$ mm, there is a very strong peak near 100 Hz, which corresponds to the traveling crossflow instability identified in previous hot-wire measurements [14]. At $x - x_s = 24$ mm, a high-frequency peak near 1000 Hz starts to become apparent. This peak corresponds to the

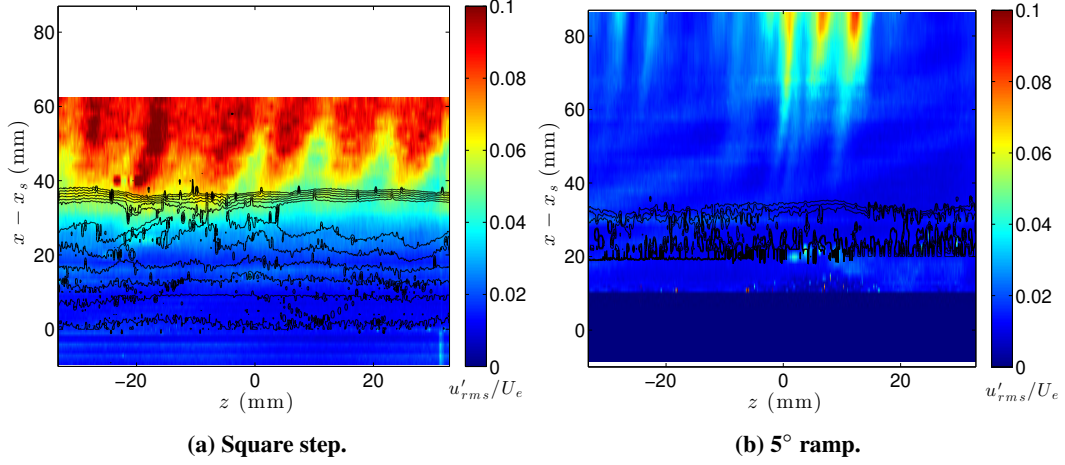


Fig. 11 Planform view of u'_{rms} contours at $y=1.5$ mm.

shear-layer instability identified previously [14]. These peaks grow and broaden as the flow progresses downstream. At $x - x_s = 44$ mm, it is beginning to look as though the flow is nearing the fully turbulent state. The 5° ramp, however, results in substantial changes to the unsteady instabilities, as illustrated in Fig. 12d. Not only are the fluctuation amplitudes lower, but the peak frequencies have also shifted. There are still two peaks generally visible in the spectra, particularly at the two most upstream locations. However, the lower peak occurs at around 200 Hz, and the upper peak occurs at approximately 500 Hz. Spectral broadening occurs starting at $x - x_s = 62$ mm and continues downstream.

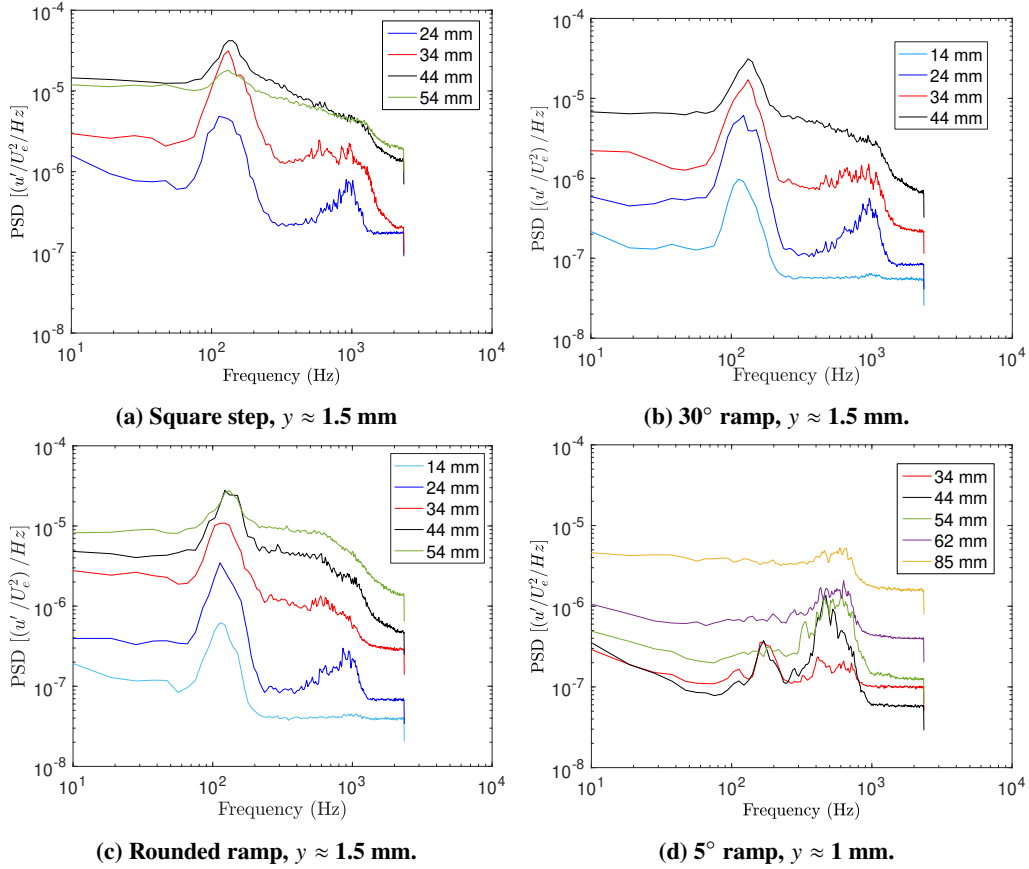


Fig. 12 Spanwise-averaged spectra at the y -locations of the peak u'_{rms} , for several streamwise locations.

To illustrate the behavior of the different unsteady instabilities found downstream of the step, the data were bandpass-filtered into the appropriate frequency bands (as identified from the spectra, and informed by previous work [14]). Then, to produce cleaner results, proper orthogonal decomposition (POD) [22, 23] was performed on each of the bandpass-filtered datasets. Finally, the data were reconstructed using the first 10 POD modes. Results for the square step case at $x - x_s = 24$ mm are shown in Fig. 13. Results are shown for three frequency bands, and at two different time steps for each frequency band. These time steps were chosen appropriately for the given frequency band in order to show the time-dependent behavior of the mode. The lowest frequency band, seen in Figs. 13a and 13d, is a primarily spanwise traveling mode, with a relatively large wavelength (approximately 40-50 mm). The middle frequency band, seen in Figs. 13b and 13e, passes through the spanwise plane, and can be seen as alternating waves of positive and negative velocity. There is some spanwise modulation already evident at this streamwise station. Finally, the highest frequency band, shown in Figs. 13c and 13f, is very highly modulated in the spanwise direction. It also exhibits movement primarily in the out-of-plane direction, though there also appears to be some spanwise (in-plane) motion as well. The behavior of this mode is quite complex and it is difficult to determine exactly how it is behaving from two-dimensional results. For brevity, results for the 30° ramp and rounded ramp cases are not shown, but they exhibit similar behavior in each of the frequency bands. These results are all consistent with the hot-wire measurements reported previously [14].

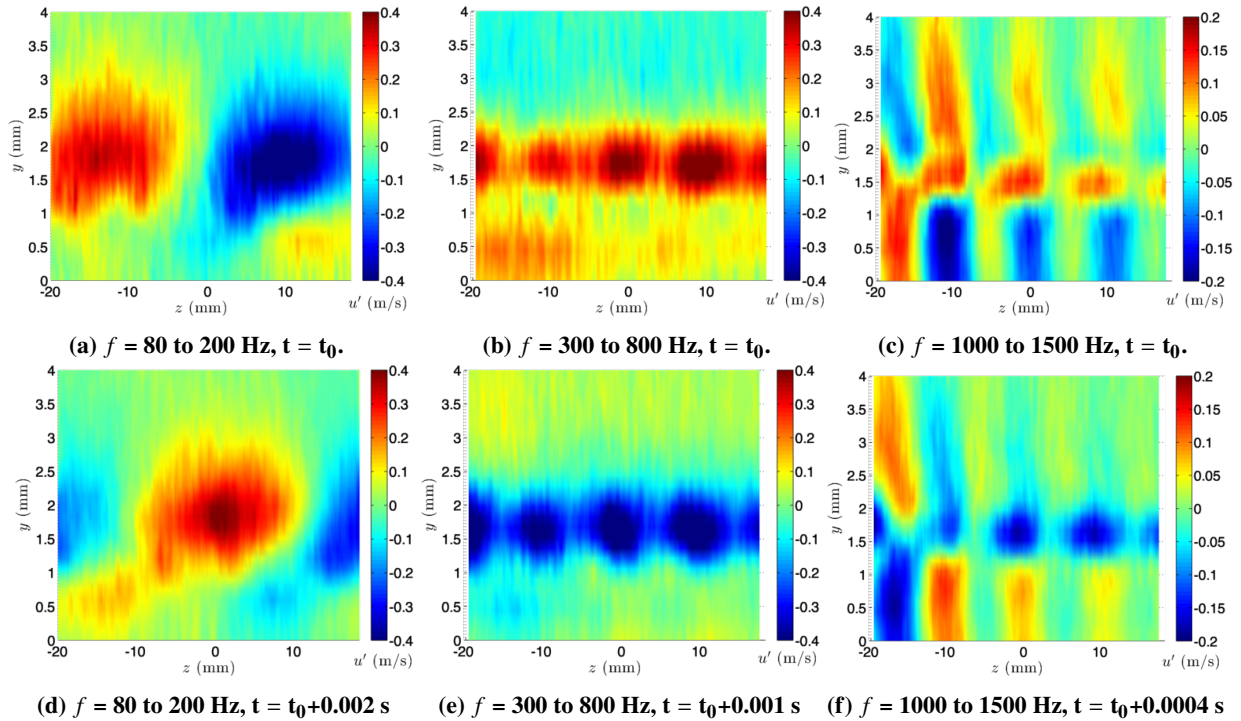


Fig. 13 Bandpass-filtered and POD-reconstructed data for the square step, $x - x_s = 24$ mm

Similar results for the 5° ramp are shown in Fig. 14, but slightly farther downstream at $x - x_s = 34$ mm. In this case, only two distinct peaks were observed in the spectra, so only two frequency bands are shown. The lower frequency band, seen in Figs. 14a and 14c, exhibits behavior similar to the middle frequency band for the square step case. This mode appears to be passing through the plane, with alternating positive and negative velocity fluctuations. The higher frequency band, shown in Figs. 14b and 14d is a bit more complex. Similar to the higher-frequency band for the square step case, this mode is also highly modulated in the spanwise direction, but it still primarily appears to be passing through the plane. In this case, there is no longer any evidence of the existence of the lower frequency, spanwise-traveling mode, as seen in the square step case.

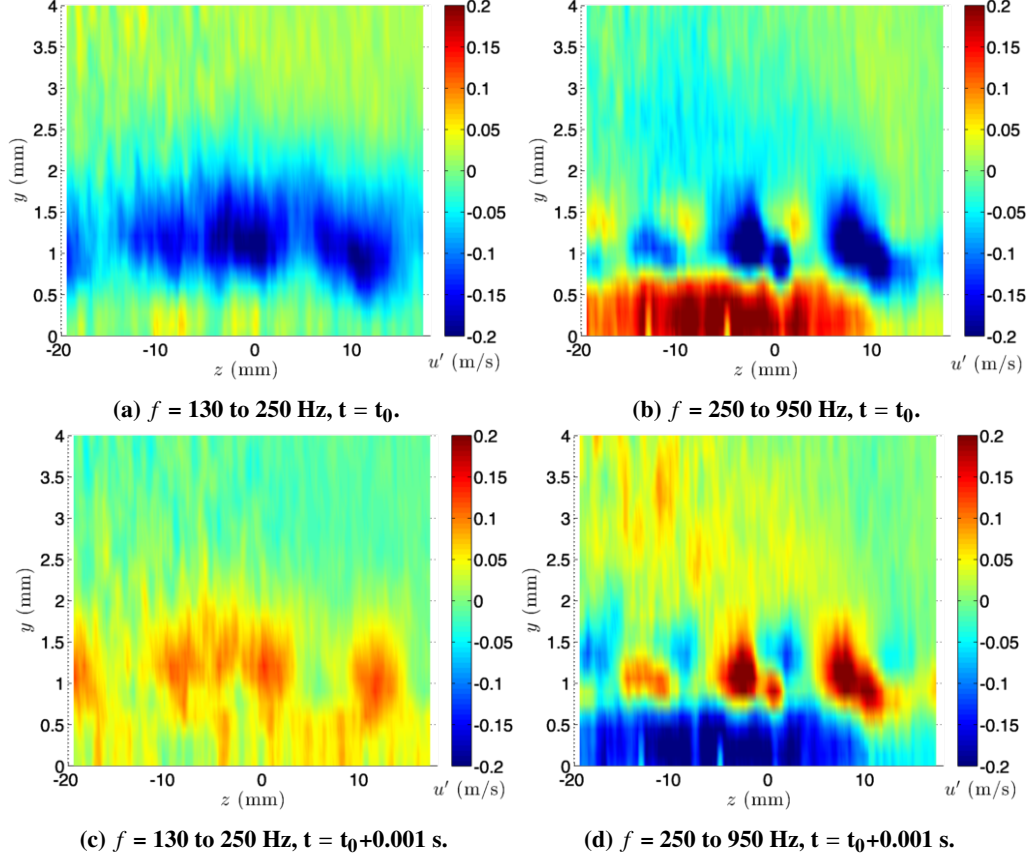


Fig. 14 Bandpass-filtered and POD-reconstructed data for the 5° , $x - x_s = 34$ mm

D. Summary and Concluding Remarks

Several different step shapes for a nominally 1.83 mm backward-facing step were studied to determine the effect on transition. These included a square step, 30° ramp, rounded ramp, and 5° ramp. The square step, 30° ramp, and rounded ramp all resulted in fairly similar results downstream of the step, though transition appears to have been slightly delayed by the rounded ramp. The 5° ramp caused a significant delay of transition relative to the square step case; however, even this gradual of a slope was not enough to completely mitigate the effect of the step. A large separated region was observed downstream of the square step, which was not noticeably mitigated by either the 30° or rounded ramp. The 5° ramp, however, did have a significant effect on the recirculating region downstream of the step.

The square step, 30° ramp, and rounded ramp all caused a localized increase in the growth of the stationary crossflow mode, starting near reattachment. The peak amplitude for these cases was only near 2 to 4% U_e , so stationary crossflow was not the primary cause of transition for these cases. Rather, large amplitude unsteady instabilities destabilized by the step were measured downstream of the step and were the primary cause of transition. Downstream of the 5° ramp, the stationary crossflow mode continued to grow at an increased rate compared to the baseline case and reached amplitudes of near 5% U_e by 100 mm downstream of the step. Transition did not occur until approximately 200 mm downstream of the step for this case, and measurements were not performed this far downstream. However, since velocity fluctuations were starting to become apparent in some localized regions by 60 mm downstream of the step, it is likely that a combination of the stationary crossflow and unsteady instabilities were responsible for transition in this case.

A comparison of the unsteady disturbances downstream of the steps and ramps revealed that the rounded ramp and 30° ramp caused only a slight decrease in the amplitude of the unsteady disturbances. However, the general character of the disturbances remained similar. The 5° ramp resulted in significantly lower amplitude fluctuations downstream of the step. In addition, this ramp appears to have completely eliminated the lower frequency spanwise-traveling disturbance that was prevalent in the other cases.

It is evident from these results that the step shape can be modified to mitigate the effect of a backward-facing step

on transition. However, the initial results show that a much longer ramp is necessary to have any significant effect on the flow when compared to a forward-facing step of the same height. The reason for this appears to be the length of the separation region. Downstream of a backward-facing step, the ramp needs to be long enough to interact with and prevent the strong separated region from forming. This helps to mitigate the unsteady instabilities that otherwise lead to transition shortly downstream of the step.

References

- [1] Holmes, B., Obara, C., Martin, G., and Domack, C., "Manufacturing Tolerances for Natural Laminar Flow Airframe Surfaces," SAE Paper 850863, 1985.
- [2] Fage, A., "The smallest size of a spanwise surface corrugation which affects boundary layer transition on an aerofoil," R.&M. No. 2120, British A.R.C., 1943.
- [3] Carmichael, B., "Surface Waviness Criteria for Swept and Unswept Laminar Suction Wings," Norair Report No. NOR-59-438 (BLC-123), 1959.
- [4] Sedney, R., "A survey of the effects of small protuberances on boundary-layer flows," *AIAA Journal*, Vol. 11, 1973, pp. 782–792.
- [5] Tani, I., "Boundary-layer transition," *Annual Review of Fluid Mechanics*, Vol. 1, No. 1, 1969, pp. 169–196.
- [6] Nenni, J., and Gluyas, G., "Aerodynamic design and analysis on an LFC surface," *Astronautics and Aeronautics*, Vol. 4, No. 7, 1966.
- [7] Crouch, J., Kosorygin, V., and Ng, L., "Modeling the effects of steps on boundary-layer transition," *IUTAM Symposium on Laminar-Turbulent Transition*, Springer, 2006, pp. 37–44.
- [8] Wang, Y., and Gaster, M., "Effect of surface steps on boundary layer transition," *Experiments in Fluids*, Vol. 39, No. 4, 2005, pp. 679–686.
- [9] Perraud, J., and Seraudie, A., "Effects of Steps and Gaps on 2D and 3D Transition," *European Congress on Comp. Methods in Applied Science and Eng., ECCOMAS*, 2000, pp. 11–14.
- [10] Duncan Jr, G., Crawford, B., and Saric, W., "Effects of Step Excrescences on Swept-Wing Transition," AIAA Paper 2013-2412, 2013.
- [11] Rius Vidales, A. F., Kotsonis, M., Antunes, A. P., and Cosin, R., "Effect of Two-Dimensional Surface Irregularities on Swept Wing Transition: Forward Facing Steps," AIAA Paper 2018-3075, 2018.
- [12] Duncan Jr, G. T., Crawford, B. K., Tufts, M. W., Saric, W. S., and Reed, H. L., "Effects of Step Excrescences on a Swept Wing in a Low-Disturbance Wind Tunnel," AIAA Paper 2014-0910, 2014.
- [13] Tufts, M. W., Reed, H. L., Crawford, B. K., Duncan Jr, G. T., and Saric, W. S., "Computational Investigation of Step Excrescence Sensitivity in a Swept-Wing Boundary Layer," *Journal of Aircraft*, Vol. 54, No. 2, 2017, pp. 602–626.
- [14] Eppink, J. L., Wlezien, R. W., King, R. A., and Choudhari, M., "Interaction of a Backward-Facing Step and Crossflow Instabilities in Boundary-Layer Transition," *AIAA Journal*, 2017.
- [15] Eppink, J. L., "The Effect of Forward-Facing Steps on Stationary Crossflow Instability Growth and Breakdown," AIAA Paper 2018-0817, 2018.
- [16] Saeed, T. I., Mughal, M. S., and Morrison, J., "The Interaction of a Swept-Wing Boundary Layer with Surface Excrescences," AIAA Paper 2016-2065, 2016.
- [17] Eppink, J. L., and Casper, C., "Effects of Forward-Facing Step Shape on Stationary Crossflow Instability Growth and Breakdown," *AIAA Aviation 2019 Forum*, AIAA Paper 2019-3532, 2019.
- [18] Saric, W. S., and Reshotko, E., "Review of Flow Quality Issues in Wind Tunnel Testing," AIAA Paper 1998-2613, 1998.
- [19] Eppink, J., "The Interaction of Crossflow Instabilities and a Backward-Facing Step in Swept Boundary Layer Transition," Ph.D. thesis, Tufts University, 2014.
- [20] Collier, F., JR, and Malik, M., "Stationary disturbances in three-dimensional boundary layers over concave surfaces," AIAA Paper 1987-1412, 1987.

- [21] Malik, M., and Poll, D., "Effect of curvature on three-dimensional boundary-layer stability," *AIAA journal*, Vol. 23, No. 9, 1985, pp. 1362–1369.
- [22] Lumley, J. L., "The Structure of Inhomogeneous Turbulent Flows," *Atmospheric Turbulence and Radio Wave Propagation*, Vol. 790, 1967, pp. 166–178.
- [23] Sirovich, L., "Turbulence and the dynamics of coherent structures. I. Coherent structures," *Quarterly of applied mathematics*, Vol. 45, No. 3, 1987, pp. 561–571.