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Technical Notes

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Roughness-Induced Bypass Transition, Revisited

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Introduction

THE role of surface roughness in boundary-layer transition is an area of active research. Ongoing experiments and numerical simulations are addressing issues of roughness receptivity, transient growth, and bypass mechanisms. As part of these efforts, a comparison of direct numerical simulations (DNS) by Rizzetta and Visbal [1] (hereafter RV) and experiments by Ergin and White [2] (hereafter EW) revealed inconsistencies in transition location and disturbance evolution downstream of a spanwise array of cylindrical roughness elements. This Note presents new experimental data intended to help resolve these discrepancies and to answer questions raised by the previous work.

Experiments on bypass transition behind three-dimensional roughness elements are described by EW. In those experiments, spanwise arrays of cylindrical roughness elements were placed in a flat plate boundary-layer flow 300 mm (x_k) downstream of the plate's leading edge. The steady and unsteady disturbances of the streamwise flow, U' and u', respectively, were measured using hot-wire anemometry. The experiments were conducted using several values of the Reynolds number based on roughness height $Re_k = U_k k/\nu$, where k is the height of an individual roughness element and U_k is the unperturbed velocity at the roughness height. The DNS of equivalent configurations that match the EW experiment's freestream velocity, roughness element dimensions, and incoming flow profile were performed by RV. At $Re_k = 334$, RV found complete transition and fully turbulent flow about 100 mm or $158\delta_k$ downstream of the roughness elements {δ_k is the boundary-layer scale at the roughness location $\delta_k = [(x_k - x_{\mathrm{vle}})/Re']^{1/2}$, where x_{vle} is the location of the virtual leading edge, and Re' is the unit Reynolds number U_∞/ν}. EW reported complete transition about 240 mm or $378\delta_k$ downstream of the roughness elements, more than twice the distance than was found by the DNS. Additionally, qualitative differences exist between the experimental and simulated velocity contours. Specifically, the DNS results show three distinct decelerated zones in the wake of the roughness elements, whereas EW showed only one broad decelerated zone.

These discrepancies prompted a reexamination of the EW experiments in comparison to previous roughness-induced transition experiments to determine potential causes. A previous study [3] found that total stationary disturbance energy

$$E_{\mathrm{rms}} = \int_0^\infty (U'_{\mathrm{rms}})^2 \, \mathrm{d}\eta$$

(U'_{rms} is the spanwise rms of the streamwise velocity disturbance; η is the wall-normal Blasius coordinate) generated by roughness elements scales as Re_k^2. Whereas the EW results confirm this trend, the scaled E_{rms}/Re_k^2 data obtained by EW falls below data reported in [3–5]. This fact, combined with the qualitative differences between the EW and DNS results in the wake profiles and transition location, create concern that the EW experiments might have been flawed. In particular, the inconsistencies might occur if the Re_k values reported by EW were erroneously large. The procedure used by EW, systematically increasing the roughness height to perform experiments at progressively larger Re_k, means that if the reported Re_k values are incorrect, they are all likely to be in error by an amount corresponding to a constant roughness-height offset. With this in mind, the EW results [2] were published with the caveat that validation of the roughness heights was needed. This need motivates the present experiments.

The objective of this work is to reproduce two of the EW cases in an attempt to confirm the Re_k values reported by EW and to reconcile the discrepancies between EW and RV. To achieve this, the reported nondimensional parameters of the EW and RV studies are reproduced, and the boundary-layer disturbance profiles, the disturbance energy, and the transition behavior are measured. To reconcile the difference in transition location between EW and RV, an $Re_k = 334$ configuration is examined. An $Re_k = 202$ configuration is also examined to ensure that previous laminar results are reproducible and that the expected Re_k^2 scaling applies.

Experimental Setup

The present experiments were performed using a flat plate in the Case Western Reserve University Wind Tunnel, the same facility used by EW. For brevity, only aspects of the setup that differ from EW are described here. Most significantly, in the time between the EW experiments and the present work, the plate was modified to include a means of mounting replaceable roughness sheets on the plate [6]. This modification was permanent and makes exact duplication of the EW experiments impossible. Specifically, the roughness elements had to be located significantly farther downstream of the leading edge as compared with EW. Despite this, it is possible to duplicate the important nondimensional parameters of the EW experiments and the RV simulation. The present experiments seek to match the EW Re_k and Re_{δ_k} (the boundary-layer-scale Reynolds number at $x = x_k$) values while holding all length ratios equal to the EW values.

A trial-and-error approach was used to find a set of target operating conditions that provide the desired experimental parameters. A summary of the dimensional and nondimensional EW parameters and the target parameters of the current work is given in Table 1. These parameters give the specifications necessary to manufacture roughness to be placed on the flat plate. The dimensions of the flat plate allow nine cylindrical elements on a spanwise spacing of

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$\lambda_k = 22.84$ mm and with diameter $D = \lambda_k/3$ to be placed at $x = 412.5$ mm. Spanwise phase-locked averaging is performed over the center seven elements. The roughness insert is an aluminum plate with machined brass plugs serving as the roughness elements. A schematic of the roughness insert and its dimensions can be found in [6].

Because the process of attaching the roughness insert to the flat plate requires the entire plate be removed from the wind tunnel, it is necessary to verify alignment for zero pressure gradient flow with the roughness installed. Unfortunately, δ_k cannot be reliably measured at x_k because of the presence of the elements. Nor can smooth-plate scans be used for this purpose because installing the roughness insert following a smooth-plate scan could change the pressure gradient and stagnation point location. Therefore, alignment was verified using a series of boundary-layer scans performed in the region just upstream of the roughness elements and far downstream of the roughness in the fully laminar configuration ($Re_k = 202$). Wall-normal velocity profiles are used to calculate the displacement and momentum thicknesses upstream of the roughness, and fits to these curves are used to determine the boundary-layer thickness scale δ_k. The results of this process, the realized experimental parameters, are given in Table 1. These show some small discrepancies with the target values. However, the match is quite good for the term of primary interest Re_k. Given the complexities of properly repeating a previous experiment, the setup is judged to be adequately close to that used by EW to proceed.

Results

The specific items of interest in the present work are the transition location for $Re_k = 329$ (the Re_k value realized during the present bypass experiment) as well as velocity contours and the disturbance-energy evolution. The focus of the reported results is on the difference in the scaled disturbance energy E_{rms}/Re_k^2 between EW and [3–5], as this most directly addresses the possible error in the Re_k values reported by EW. The transition location and the finer-scale structures in the streamwise velocity contours are also examined.

To begin, Fig. 1 shows the evolution of the steady and fluctuating streamwise flow in the wake of the $Re_k = 329$ roughness elements. Figure 1a shows a distinctive jagged pattern of multiple high- and low-speed regions in the roughness wake. Within this field, the highest velocity fluctuations are focused in the area of strongest shear. As the flow progresses downstream, Figs. 1c and 1d show how quickly localized breakdown leads to turbulent wedges behind each element. Localized turbulence is evident about $59\delta_k$ downstream of the roughness. In the EW experiment, localized turbulent breakdown occurred starting about $79\delta_k$ downstream of the roughness, whereas in the RV simulations, this occurred about $65\delta_k$ downstream. Thus, the present experiments tend to confirm the earlier breakdown observed by RV. However, many experiments have shown the breakdown point to be quite sensitive to numerous factors (see [7], for example), and so a large variance between similar setups is not unexpected.

Comparing these results to the EW data, EW's Fig. 13 in particular, the uniformity of the breakdown pattern here is striking. The fact that all of the roughness elements lead to breakdown at nearly the same x location and proceed toward fully turbulent flow at the same rate is quite different than was observed earlier. The difference might be a result of using machined roughness elements here as opposed to the paper elements used by EW.

Figure 2 compares conditions about $15\delta_k$ downstream of the roughness for the high-roughness configuration of EW and the present experiment. At this location, both experiments reveal jagged velocity contours that include strongly decelerated wakes behind the roughness elements. The roughness of the current experiment generates a somewhat stronger U'_{rms} profile with significantly stronger spanwise shear, $\partial U'/\partial z$, than was observed by EW. Perhaps, as a consequence, stronger unsteady fluctuations are measured in the current experiment than previously.

The fact that the two experiments show slightly different U'_{rms} profiles is not surprising given the sensitivity to Re_k and the difficulty in realizing a precise Re_k value. More surprising is that the two experiments' contour plots have notably different qualitative features. In particular, the current experiments show three distinct decelerated zones, whereas the EW results show only a single broad decelerated zone behind each roughness element. The current results are more similar to the simulation results of RV than are the EW results. The reason for the different experimental results is unknown. The wider spanwise spacing between the roughness elements relative to the hot-wire size here as compared with EW might help resolve these fine-scale features. Or, it might be that the machined, sharp-edge roughness elements used here actually produce these fine-scale features and that these features were simply not present in the EW experiment that instead used stacked paper disks as roughness elements. That is, the sharp-edged roughness elements used here are more similar to the precise computational boundaries imposed by RV, and these sharp edges could be responsible for the fine-scale features of the velocity contours.

Because of the difference in transition location between EW and RV, a velocity contour comparison is not given by RV. Generally speaking, the RV contours show finer-scale features than EW and, in particular, tend to show three decelerated zones rather than EW's single zone. A comparison between RV and the present results is given in Fig. 3. Both the contour shapes and disturbance amplitudes are in reasonably good agreement. The DNS satisfactorily reproduces the roughness wake and, as discussed previously, the current experiments are able to capture the three decelerated zones predicted by the DNS, whereas EW does not. Some finer-scale features exist in the DNS data that are not observed in the experimental data. This may be a result of the finite spanwise extent of the hot wire or the hot wire's spanwise sampling interval. Additionally, there is some discrepancy between the height at which specific velocity contours fall. This may be a result of how the boundary-layer thickness δ is estimated in the experiment and in the DNS. Ongoing work is examining these discrepancies in greater detail.

In light of the discussion to this point, the notion that the Re_k values reported by EW are incorrect remains plausible. Preliminary disturbance-energy comparisons strengthened this possibility. As explained before, previous work [3] established Re_k^2 as a meaningful disturbance-energy scaling. The three EW configurations, $Re_k = 202$, 264, and 334, follow this trend, but the collapsed

Table 1 Experimental configuration. Parameters given in only the low-*k* columns apply to both the low- and high-*k* configurations

	EW, reported		Current, target		Current, realized	
Parameter	Low k	High k	Low k	High k	Low k	High k
x_k, mm	300	——	412.5	——	412.5	——
λ_k, mm	19.00	——	22.84	——	22.84	——
D, mm	6.35	——	7.61	——	7.61	——
k, μm	714	918	862	1115	862 ± 25	1115 ± 25
$Re' \cdot 10^{-3}$, m^{-1}	764	——	632	——	625 ± 13	644 ± 13
δ_k, μm	634	——	766	——	764 ± 2	810 ± 2
Re_{δ_k}	484	——	484	——	478 ± 10	520 ± 11
Re_k	202	334	202	334	202 ± 13	329 ± 21

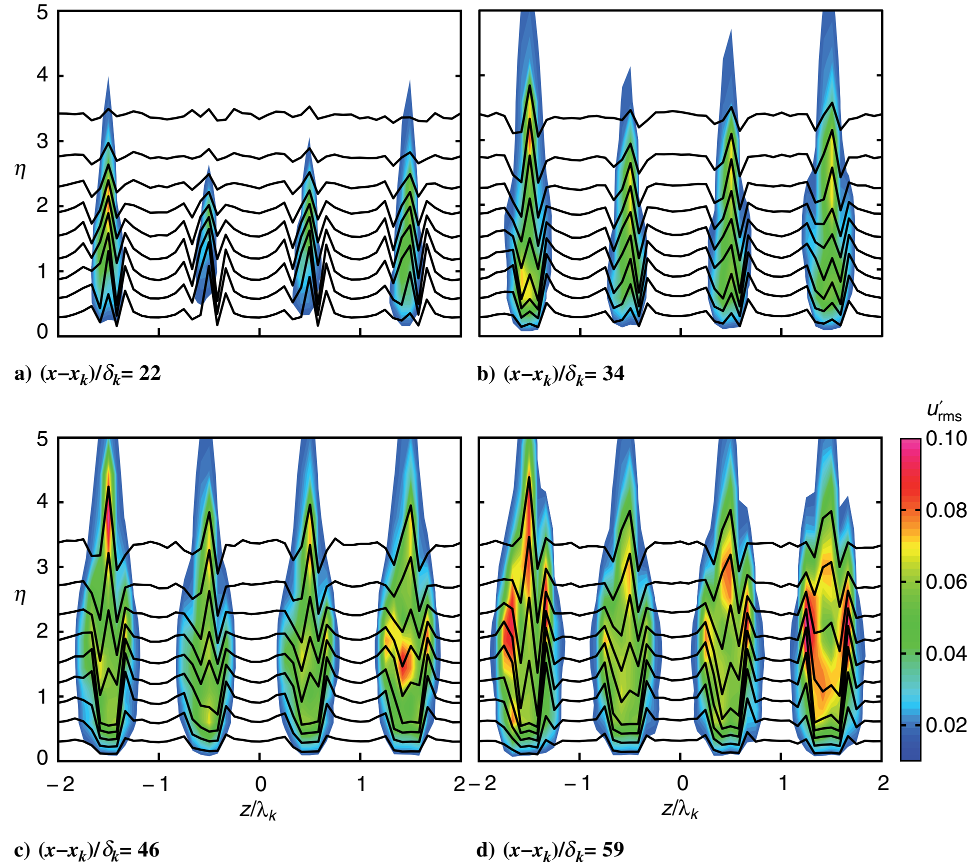

Fig. 1 Streamwise velocity contours for $Re_k = 329$. Black lines correspond to 10% steady-velocity contours; colors are unsteady fluctuations.

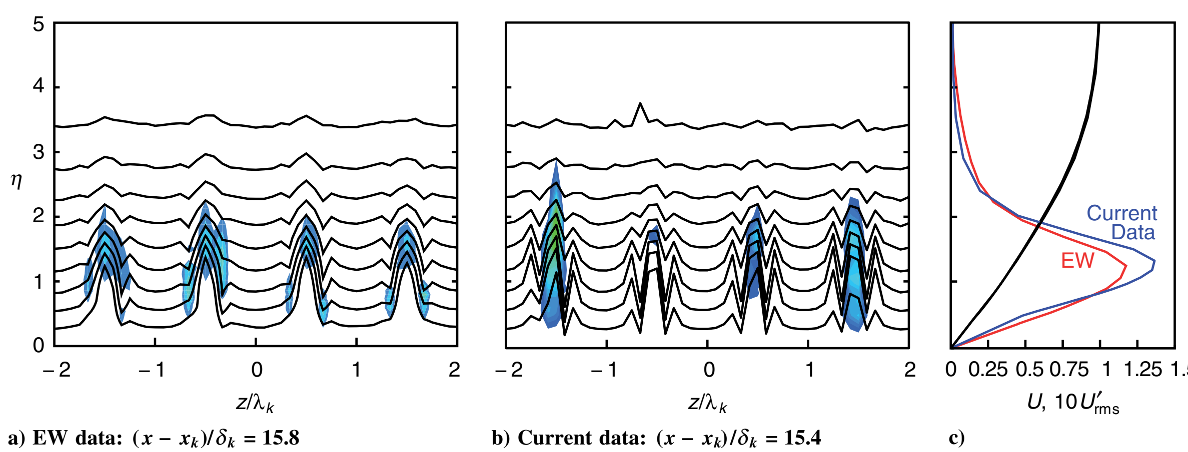

Fig. 2 Near-wake steady and unsteady streamwise velocity contours and profiles. Color contour levels represent u'_{rms}; both color scales match the scale of Fig. 1.

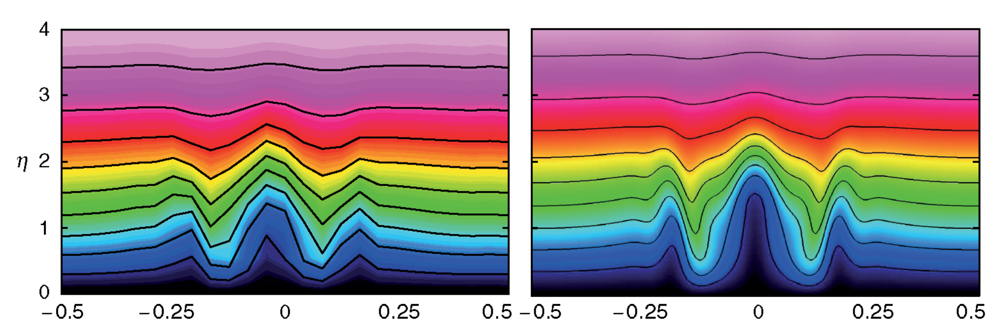

Fig. 3 Near-wake streamwise velocity contours. Current experimental results for $Re_k = 329$, $25\delta_k$ downstream of the roughness are at left; RV simulation results for $Re_k = 334$, $26\delta_k$ downstream are at right. Contour levels match the levels of Fig. 1.

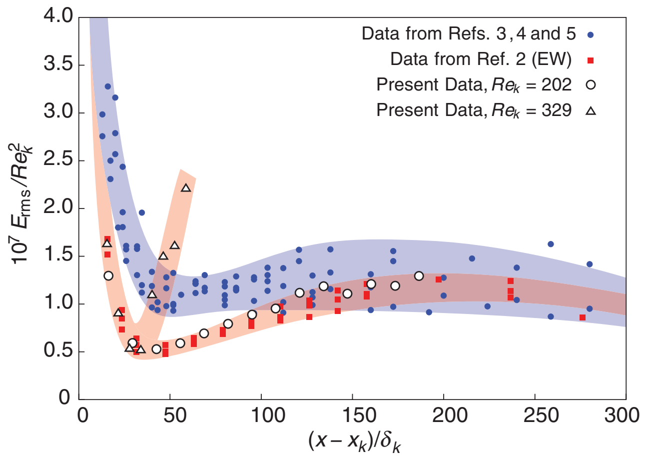

Fig. 4 Scaled disturbance energies.

E_{rms}/Re_k^2 curve representing the EW data is markedly different than in earlier experiments [3–5]. Specifically, Fig. 4 shows that the scaled total disturbance energy E_{rms}/Re_k^2 measured by EW (red squares) decreases more rapidly than the previously obtained data (blue circles) and reaches a minimum value about half that of the previous data. These differences could be an indication that EW's reported Re_k values are systematically too high because if Re_k values were consistently smaller than were reported, the curves would be in better agreement in the near-wake region. However, in the far-wake region, the EW energy levels grow more rapidly and reach levels equal to the earlier values. Thus, the discrepancy between the experiments cannot be explained by a simple scaling error.

The current experiment's E_{rms}/Re_k^2 values eliminate the possibility that the EW Re_k values were reported incorrectly. The present data (open symbols) in Fig. 4 clearly show that the scaled EW energy data is correct and repeatable; no systematic Re_k error is evident. The present data is remarkably consistent with the data obtained by EW, especially considering the sensitivity of these experiments and that the current data is obtained using a wholly different set of dimensional parameters than the EW experiments. The data for $Re_k = 202$, which is most similar to EW in terms of Re_k, Re_{δ_k}, and λ_k/δ_k, shows an energy evolution that is completely consistent with the EW results. Furthermore, despite the more-rapid transition onset, the data for $Re_k = 329$ collapse to the EW results through the energy minimum. After that point, strong spanwise shear develops, and the steady-disturbance energy begins to grow rapidly. Soon thereafter, at $(x - x_k)/\delta_k = 59$, localized turbulence is observed. Downstream of this point, the spanwise mixing provided by turbulence would quickly act to decrease the spanwise variations. U'_{rms} would decrease, as would E_{rms}.

In addition to validating the Re_k values quoted by EW, Fig. 4 shows a previously undocumented dependence of the disturbance energy on Re_{δ_k} and/or λ_k/δ_k. The previous experiments [3–5] (blue symbols in Fig. 4) were performed at somewhat lower values of Re_{δ_k} and higher values of λ_k/δ_k than the EW experiment and the current experiment. White et al. [3] had $Re_{\delta_k} = 431$ and $\lambda_k/\delta_k = 32.8$, whereas EW had $Re_{\delta_k} = 484$ and $\lambda_k/\delta_k = 30.0$. These differences may be responsible for the differences in the E_{rms}/Re_k^2 slopes and minima. This result was unexpected and, in planning the present experiments, Re_{δ_k} and λ_k/δ_k were considered to be of secondary importance to Re_k. However, it appears that these differences may well be the source of the discrepancy between the EW and prior experimental results.

Conclusions

The main objective of this work is to validate previously reported results of a roughness-induced transition experiment, particularly values of the Reynolds number based on roughness height Re_k. Concern about the accuracy of these values arose due to discrepancies between direct numerical simulation results and the reported experimental values in terms of transition location and velocity contour details, as well as the apparent energy difference between the experiments in question and earlier roughness experiments. The disturbance energies obtained in the present study reproduce the scaled values from the earlier results nearly perfectly and provide clear evidence that the previous work quoted correct Re_k values. However, velocity contours obtained in the present experiment are much more similar to the numerical simulation than to the earlier experimental measurements. The experiments and simulation all show the onset of turbulent fluctuations between 59 and 79 boundary-layer thicknesses δ_k behind the roughness elements. However, compared with the other two studies, the earlier experiments show a much longer length for these fluctuations to spread and achieve fully turbulent flow. That result may be due to the nonuniformity in the breakdown pattern observed in the earlier work.

One important new conclusion is the sensitivity of the disturbance energy to the Reynolds number based on the boundary-layer scale Re_{δ_k} and/or the dimensionless spanwise spacing of the roughness elements λ_k/δ_k. It is thought that differences in disturbance-energy evolution between the several previous experiments is mostly due to differences in those values. In the context of transient growth theory, both values are significant. First, λ_k/δ_k and its harmonics are not constant when δ_k changes but λ_k does not. Thus, the various experiments have different nondimensional spanwise wavelengths. This results in different distributions of continuous spectrum modes and different degrees of suboptimal disturbance growth. Second, even when λ_k/δ_k is matched between experiments, if Re_{δ_k} is different, then the precise details that describe the continuous spectrum modes are different, and this could result in different transient growth and decay rates. It is unclear whether the differences here can be attributed more to different nondimensional wavelengths or to different Reynolds numbers. Nevertheless, the role of these factors cannot be overlooked.

Acknowledgments

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