THE ORIGIN OF AEOLIAN DUNES – THE FLUID DYNAMICS OF EARLY-STAGE PROTODUNE DEVELOPMENT MEASURED IN A REFRACTIVE-INDEX-MATCHING FLUME ENVIRONMENT.

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Introduction: Understanding the initiation of aeolian dunes poses significant challenges due to the strong couplings between turbulent fluid flow, sediment transport, and bedform morphology [1]. While much is known concerning the dynamics of more mature bedforms [2], open questions remain as to how protodunes are formed, as well as the mechanisms by which they continue to evolve. The structure of the turbulent flow field influences the transport or deposition of sediment, thus controlling the initial formation of sand patches, yet is also strongly influenced itself by local conditions such as surface roughness and moisture. Furthermore, an additional feedback on the flow and transport is exerted by the sand patches themselves once they begin to form.

As protodunes begin to develop from this initial deposition, their morphologies possess unique characteristics involving a reverse asymmetry of the stoss and lee sides, wherein the crest begins upstream, close to the toe, and gradually shifts downstream toward the "regular" asymmetric profile exhibited by more mature dunes [3]. However, these early stages of development also involve very gentle slopes and low profiles which make field measurements of the associated flow particularly challenging.

The current research effort involves a combination of field measurements, documenting the initiation and morphological development of sand patches and protodunes, in concert with detailed measurements of the flow-form interactions in a laboratory flume. The work presented herein focuses primarily on experiments conducted in a unique flow facility wherein high-resolution measurements of the turbulent flow field associated with the early stages of protodune development are obtained utilizing particle-image velocimetry (PIV) in a refractive-index-matched (RIM) environment.

Methods: Laboratory experiments were conducted in a uniquely designed RIM flume at the University of Notre Dame in the *Turbulence Laboratory for Energy and the Environment*. The RIM approach involves using an aqueous solution of Sodium Iodide (NaI) as the working fluid in place of water, as well as the use of solid (i.e., fixed-bed) protodune models. The solid and liquid phases have the same refractive index, rendering the model effectively invisible. Thus, the RIM technique facilitates flow measurements extremely close to model surfaces and enables unimpeded optical access, both of which are critical to obtaining high-fidelity measurements near the model surface. Such measurements are key to understanding the flow-form feedback processes. It should be noted that there is no mobile sediment in the flume, and thus its effects on the flow-form feedback cannot be accounted for in the laboratory.

The morphologies of the protodune models used in the flume were idealized versions of natural protodunes measured in the field. Natural protodunes exhibit a wide array of specific shapes, but a general characteristic of their development is that as they mature and grow, their crest position shifts from being found upwind near the toe to downwind with a steeper lee side. Thus, in order to capture this key morphological characteristic, four different protodune models were fabricated mimicking this transition of the crest position. This fabrication began with a baseline model whose morphology was sourced from a natural protodune measured in the field. This morphology was altered to be idealized and symmetric about the centerline, and then using computer-aided design (CAD) software its crest was shifted.

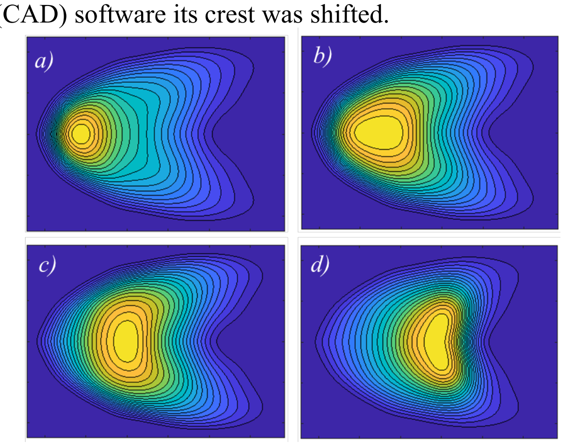

Figure 1: Four idealized protodune model morphologies, showing gradual transition of crest from upstream (a) to downstream (d).

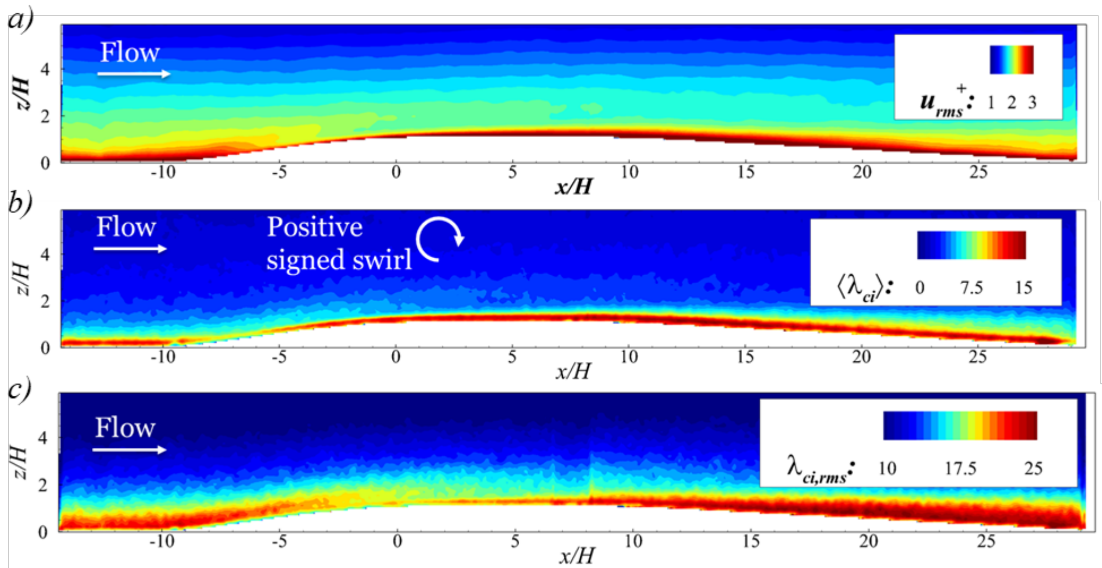

Figure 2: Flow fields measured in x-z *centerline plane over protodune model from Fig. 1b, showing (a)* rms *of streamwise velocity fluctuations, (b) mean swirling strength, and (c) rms of swirling strength.*

The protodune models are immersed within the logarithmic region of a turbulent boundary layer in the flume (crest height at approximately $H/\delta = 0.1$) in an effort to match the dynamic flow conditions the natural protodunes are exposed to in the field. The flow field around the models is measured using planar PIV in all three planes (*x-z*, *x-y*, *y-z*) separately. Each planar measurement yields the velocity components within the plane.

Results: Initial results showing statistics of the turbulent flow over the protodune model corresponding to Fig. 1b are shown in Fig. 2. While the protodune model has an extremely high aspect ratio and gentle stoss and lee side slopes (approximately 9 degrees maximum slope on stoss side, and 4 degrees maximum slope on lee side), the presence of the model induces a noticeable perturbation to the turbulent boundary layer.

In terms of the velocity fluctuations, u_{rms}, shown in Fig. 2a, a clear amplification is visible in the toe region. This is followed by a decrease over the stoss side as the flow adjusts to the influence of the topography. These results are in keeping with what has been shown for flow over more mature dunes.

The characteristics of the spanwise vortex structures in the flow are described by the mean and *rms* swirling strength values shown in Figs. 2b-c. Swirling strength is a measure of local rotation in the flow, indicating the presence of a vortex core, and relies on measures of instantaneous velocity gradients. Mean swirling strength thus indicates a predominant orientation or bias in the swirling motion, while *rms* values reflect a characteristic intensity at each point in the flow field. What these results show is that the presence of the protodune perturbs not only the velocity fluctuations, but also has an influence on the organization of vortices in the incoming flow as they encounter the protodune. Positive mean swirling near the bed in the incoming flow shows the characteristic distribution in the incoming boundary layer, while the decrease over the toe region suggests a change in the structure of the vortices. Likewise, there is a drop off in the intensity of the swirling motions measured in this *x-z* plane as the flow passes over the crest.

Conclusions: The initial results presented herein demonstrate the utility of PIV measurements made in a flume environment to capture the flow field over protodunes and reveal the flow-form interaction occurring during early-stage protodune development. Such detailed measurements of the flow are extremely challenging, if not impossible, in the field. Therefore, the results shown here can be used to inform measurements of morphology changes, transport, and point-wise measurements of flow in the field, and thus build a more complete picture of the feedback mechanisms driving protodune development.

References:

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