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Preliminary laboratory studies of shear stress partitioning

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Introduction

In the saltation layer the moving grains carry part of the momentum while in the flow above the horizontal momentum is carried entirely by the fluid. As explained by Owen (1964) the saltation process thus leads to a partitioning of the shear stress in the saltation layer between the wind flow and the saltating particles. Ultimately this leads to an upward convexity of the velocity profile near the bed. The influence from moving grains shear on the vertical wind speed profile in the saltation layer has been deduced from numerical models of the saltation process (e.g. Sorensen, 1985; McEwan and Willetts 1991). Calculations have indicated that for moderate friction speeds there should be a noticeable increase in the wind speed (expressed as a deviation from the logarithmic wind law) up to a few centimeters above the bed (e.g. Sorensen, 1985).

The experimental verification of this influence has been debated earlier a matter for debate over the years (Butterfield, 1999). The reasons are several including the obvious fact that it is difficult to measure precisely the air speed shortly above a grain bed, which systematically deforms because of moving ripples. Furthermore, most (if not all) aeolian laboratory studies have been made in wind tunnels where a horizontal pressure gradient influences the wind profile during saltation. Thus the upper part of the wind profile deviates from its ideal log-linear shape because of the influence from a slight wake at the top of the boundary layer (White, 1991). Also Froude Number effects may have influenced some results obtained in wind tunnels with a small cross section (White and Mounla, 1985). Finally, results from atmospheric investigations and wind tunnels show that the shear stress will only attain its surface value near the bottom of the boundary layer (e.g. Garrett, 1994).

In order to overcome some of the problems outlined above the long aeolian wind tunnel at the University of Aarhus was modified so that the boundary layer thickness could be increased. Furthermore, a technique based on measuring the shear stress in the saltation layer using hot-wire anemometry was introduced. Previous use of this sensor (Rasmussen and Sørensen, 1998) indicated that it survives several hours of use in the saltation layer. In the following the new experimental set-up will be described including some of the rather cumbersome hot-wire calibration experiments. Finally initial measurements made over a stationary grain bed will be presented.

Experimental set up

The 20 m long, horizontal wind tunnel at the University of Aarhus is a low speed, open circuit suck-down tunnel. It is driven by an axial fan at the flow outlet Its width and height are 0.6 m by 0.9 m, and there is a small bell-mouth and filters at the entry while moving particles are collected in a large settling chamber (with filters) just in front of the fan. The fan can be set at fixed RPM with a resolution of about 1 %. Enhanced growth of the boundary layer is made immediately downstream from the entry using turbulence spires and roughness arrays.

For each of five nominal values of friction speed u_* (0.20, 0.30, 0.40, 0.60, and 0.75 m/s), corresponding sets of turbulence spires and roughness block arrays (Irwin, 1981) are placed in the first 2.5 m downwind of the entry. The spires produce a boundary layer thickness of 15 cm approximately 2.5 m downwind of the entry while the roughness block arrays are designed to match values of aerodynamic roughness length (z_0) typical for aeolian grain beds. In the experiments reported here, a 0.5 cm layer of almost uniformly sized quartz sand or gravel was spread on the bed between the roughness array and the sand collector.

While the wind tunnel was being modified calibration experiments were made with the split-fiber sensor. In principle the sensor records the velocity (speed and direction) of a two-dimensional flow using signals from the two electrically separated half parts of a platinum coated cylindrical ceramic fiber (D=200 μm). Thus the friction speed (stress) can be obtained as the time average of the product $u^* = (\sqrt{-\overline{u'w'}})$ where u' and w' are the fluctuating components of the horizontal and vertical velocities, respectively. However, the velocity signal depends on flow direction and vice versa (Rasmussen and Sorensen, 1998), but existing information on experimental error and calibration procedure for this sensor is scarce. Therefore several sensors were calibrated with an automatic calibration system (DANTEC, 90H10) using different calibration procedures and different settings of the electronics. In the calibrations reported here the sensor was first placed perpendicular to the flow (zero pitch) and the output was measured for 15-20 velocity readings. Next, the sensor was placed at a fixed pitch of -60° and the output was recorded once more for 10-15 velocity readings. This was repeated for every 10° increase in pitch angle in the interval -60° to +60°.

In the wind tunnel vertical profiles of the wind speed and the shear stress were recorded above a quiescent grain bed. At each height data were recorded at a rate of 100 Hz continuously during 400 seconds. The profiles were obtained for different wind speeds below the saltation threshold at the centerline of the tunnel approximately 15 downstream from the entry.

Results and Discussion

Results from a simple velocity calibration of a split fiber sensor which is placed with the fiber perpendicular to the flow at zero pitch angle is presented in figure 1. The bridge signals from the lower and upper sensor halves, is denoted by V1 and V2, respectively, and the total output (V=V1 + V2) is shown versus the velocity of the calibration jet. When a 4-th order polynomial is fitted to the calibration points the standard error on the deviation between observations and fit is only 0.04 m/s.

The directional response of the sensor is investigated using the voltages obtained for different velocities of the jet (U) and pitch-angles (θ). The voltage at zero velocity recorded from the sensor halves is denoted $V_{0,1}$ and $V_{0,2}$, respectively. Thus the logarithm of the increase in signal relative to the zero-value for the two sensor is $\log(V_1-V_{0,1})$ and $\log(V_2-V_{0,2})$, respectively which is plotted in figure 2.

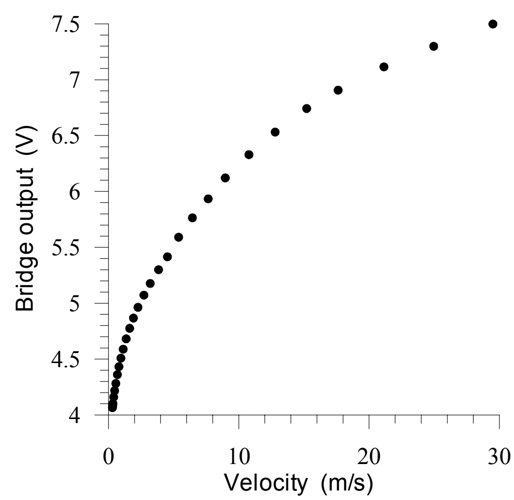

Figure 1. Calibration characteristic of sensor 5.

It is seen that the data are almost uniformly distributed for the range of angles and speeds tested here. At very low speeds there are small irregularities in the signals. However, the Reynold's at such low speeds is small (Re≈100) indicating that cooling is influenced in a complex manner by the flow around the fiber. For aeolian work, however, such low speeds (< 1 m/s) are far below the saltation threshold and will not be discussed in further detail.

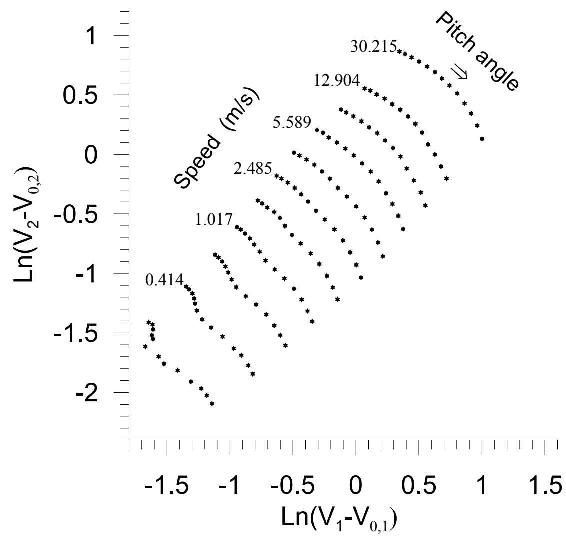

Figure 2. Logarithm to change in output for increasing speed and pitch angle (-60º - 60º).

With the calibration device used in the set-up reported here, very consistent readings were obtained. Setting a similar overheat temperature for the two sensor halves appears to produce almost identical calibration runs. Therefore it was decided to convert data via interpolation within the calibration matrix (conversion of low speed-readings is slightly different, but will not be discussed here). Initially is found the four calibration values surrounding a given set of reduced bridge voltages. Then interpolation is made between these four points in order to calculate the weighing factors for conversion of the corresponding sets of speed and angle measurements. The standard error between the calculated and measured velocity readings is only 49 mm/s for velocities up to 12 m/s when this procedure is used with the calibration data given in figure 1. At higher velocities there is somewhat larger deviation so that for the entire set of values in the range 1-30 m/s the standard error is 19 cm/sec.

Two vertical profiles of the horizontal speed (u) measured above flat beds of different grain size are presented in figure 3. Profile A was measured above a bed of uniform sand with diameter 0.54 mm while profile B was measured above a bed of gravel with median diameter 5 mm. A line representing the logarithmic wind profile $u = \frac{u_*}{\kappa} \log \frac{z}{z_0}$ was fitted to each set of data, but only data points up to 120 mm above the bed were used in the fit. In both cases the observed velocities follow the logarithmic law quite well. The values of aerodynamic roughness length (z_0) and friction speed (u_*) for the two profiles are $z_{0,A}=6.8 \cdot 10^{-5}$ m, $z_{0,B}=2 \cdot 6 10^{-4}$ m, $u_{*,A}= 0.21$ m/s, and $u_{*,B}= 0.37$ m/s.

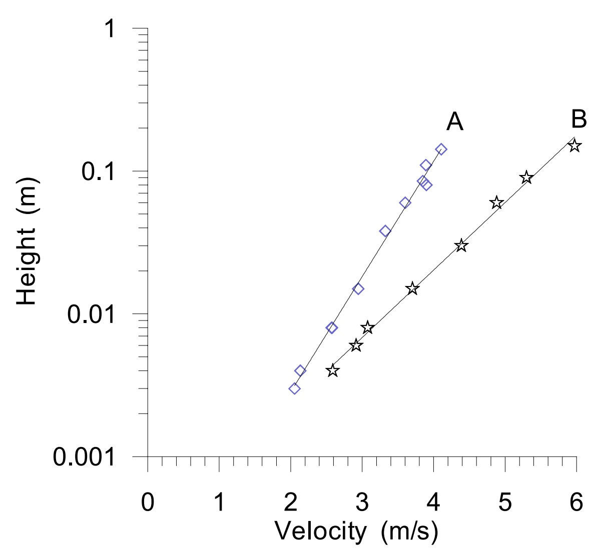

Figure 3. Wind speed profiles measured above uniform sand (A) and gravel (B).

At the same heights where the horizontal wind speed was measured the shear stress and hence the friction speed can be calculated, too. For the two beds the u_*-values normalised with the value found at 4 mm height are listed in Table 1. The values are found from averaging over four runs at each height.

The two profiles both have a fairly uniform stress near the bottom. However, for the profile above the smoother surface and at lower friction speed the stress decreases from about 2 cm above the bed, while for the rougher bed and higher speed the decrease starts at about 6 cm height. Also above this bed there is more scatter in the values. At the top of the profiles the stress decreases rapidly above approximately 10 cm height.

Height (A) (m)	$u_*(z)/u_{*,A}$	Height (B) (m)	$u_*(z)/u_{*,B}$
0.004	1.00	0.004	1.00
0.008	0.98	0.006	1.04
0.008	0.99	0.008	1.02
0.015	0.98	0.015	0.95
0.038	0.93	0.030	1.00
0.060	0.88	0.060	1.00
0.085	0.81	0.090	0.91
0.110	0.71	0.150	0.44
0.142	0.13		

Table 1. Normalised friction speed as function of height above two grain-beds.

Conclusions

The measurements presented here clearly points in the difficulties in investigating experimentally in the laboratory the influence from stress partitioning in the saltation layer. The decrease of the stress with height even when there is no saltation makes it difficult to establish a proper reference for the measurements in the densest cloud of particles. More experiments are needed in order to determine how the height of the constant stress zone depends on bed texture and friction speed. In addition it may seem necessary to compare stresses made in the saltation layer to values obtained above quiescent beds of similar roughness.

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