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AN EXPERIMENTAL ANALYSIS OF THE WIND INDUCED FAILURE OF WHEAT CROPS

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Abstract

This paper describes the results of an experimental investigation into the lodging process of wheat crops. Simultaneous analysis of velocity data, calibrated strain gauge and video footage provide a unique insight into the mechanisms involved. A wavelet analysis of plant displacement during a root lodging event yields the interesting result that the natural frequency of the plant actually increases during failure. The paper attempts to interpret this phenomenon by using results obtained from a numerical model of a column subject to large scale oscillations.

Introduction

Lodging, the wind induced permanent displacement of cereal stems from the vertical can cut the profitability of a cereal crop drastically through reduced grain quality and lower yield. In the UK widespread lodging occurs on average once every four years (Berry et al. 1998). In 1992, 16% of the UK wheat crop was lost due to lodging at an estimated cost to growers of €190 million.

It is generally accepted that two types of lodging occur, namely stem lodging and root lodging. Stem lodging results from the bending or breaking of the lower culm internodes, whilst root lodging is due to failure of root anchorage and results in straight, unbroken culms leaning from the crown. Theoretically it is possible that both types can occur simultaneously, however to the best of the author's knowledge this has never been scientifically recorded. Debate is continuing amongst scientists and growers as to whether stem lodging or root lodging predominates; whatever the form of lodging, it is generally agreed that it is due to an interaction of the plant with the characteristics of the rain, wind and soil.

Since lodging often occurs in hostile conditions, it is not surprising to realise that the lodging events themselves have rarely been observed in any scientific way. This is due simply to the unpredictable nature of such events in both spatial and temporal terms, and the difficulty of making field measurements in often hostile weather conditions. Baker 1995 developed a theoretical model which predicted the wind induced base bending moment on a plant as a result of sudden (stepped) gust of wind. This model was later extended (Baker et al. 1998) and using probabilistic techniques was applied to a wheat crop in order to predict lodging.

The experimental work described in this paper was initially undertaken in order to ascertain the applicability of this theoretical model and if appropriate to provide calibration data. It is worth acknowledging that the weakest part of the model was considered to be the interaction between the root and soil structure. As a direct consequence it was decided that the experiments should be undertaken in a commercially grown field of wheat thereby ensuring that the soil conditions were realistic. In order to generate appropriate wind conditions a portable wind tunnel was developed and placed over the crop. Summary details relating to this wind tunnel are presented below, whereas for an in depth analysis the reader is referred to Sterling et al. 2003.

This paper is organised into a number of distinct sections. The next section is concerned with the field tests and summarises the husbandry treatment and experiments that were undertaken. The analysis section first interprets the velocity data using traditional spectra methods and then introduces the concept of wavelet analysis in order to provide an insight into the intermittent nature of the wind. The wind induced motion of the plant is then analysed using both spectra and wavelet techniques. The lodging section of the paper specifically focuses on the observed failure of an individual plant and by using wavelet analysis provides an insight into the physical processes that occur during failure. These processes are interpreted through recourse to a previously developed numerical model. The final section summarises the main issues raised in the paper.

Field tests

Full details of the experiment programme and its implications on the model mentioned above can be found be found in Sterling et al. 2003 and Berry et al. 2003 respectively. Brief details are presented below in order to provide a framework for the data analysis presented in this paper.

The field experiments were conducted in a specially constructed wind tunnel. The wind tunnel was essentially a 3m square cross section extending 10m in length. An important design requirement was that the wind tunnel needed to be portable, both in terms of being easily positioned in different parts of a field and in terms of undergoing transport from the place of design and manufacture (The University of Birmingham, UK) to the location of the field trials (ADAS Rosemaund, Herefordshire, U.K). To this end, the final design comprised four 2.4m sections bolted together. Three out of the four sections were constructed out of marine plywood while the remaining (end) section utilised polycarbonate sheeting. Polycarbonate sheeting was specifically adopted to enable observations of the crops to be made from outside of the wind tunnel. An irrigation tube located on the roof of the end section provided a convenient way of wetting the crop/soil and thereby examining the effect of crop wetness and soil moisture content on lodging. The wind was provided by six axial flow fans with a blade diameter of 710mm, arranged in two rows of three just above the crop height. In order to reduce the swirl from the fans and to induce small scales of turbulence, a rectangular wooden grid, (250mm by 250mm) and wire mesh (10mm by 10mm) was placed immediately in front of the fans. The fans were capable of forcing air at relatively low mean velocities of between $1ms^{-1}$ and $6ms^{-1}$, with gusts of up to $8.5ms^{-1}$. The rotational speed of the fans was controlled through a frequency transformer and based on a wind velocity time series. The wind velocity input to the fans was based on a filtered time series of actual velocities measurements recorded directly above a wheat crop in an open field.

The wind velocity was measured by means of a sonic anemometer (3 axis research ultrasonic anemometer, Gill Instruments, U.K.) sampling at a rate of 20.8Hz. In addition to measuring the wind velocity, the actual force on the plant was obtained by monitoring a calibrated strain gauge (Kyowa type KFG-5-120-C1-11). The strain gauges were connected via an electronic bridge, to a data logging system which was able to sample at the same rate as the ultrasonic anemometer; thus enabling a direct comparison between wind velocity and the force exerted on the plant.

The experimental data analysed in this paper was obtained from a winter wheat (*Triticum aestivum* L.) cutliver cv. Merica. The wheat was sown into two sets of 6 plots (each measuring 3.5 m x 12 m) at 450 seeds m^{-2} on the 13 October 2000. The sand:silt:clay ratio was 9:71:20 and the phosphorus and potassium indices were above two for the soil and as such were not limiting for plant growth. Six series of wind tunnel tests were undertaken between the 23rd June to 1st August 2002.

Analysis

Before any detailed measurements on the lodging process could be undertaken, it was imperative to ensure that the wind tunnel was capable of generating the correct conditions. Velocity profiles above the crop at the measuring section were found to correspond well to a logarithmic law. The value of the displacement plane thickness (d) non-dimensionalised by the average crop height was 0.63. The average value of turbulence intensity defined as the standard deviation of streamwise velocity divided by the mean streamwise velocity was of the order of 40%. These statistics are within the range obtained by others (Kaimal and Finnigan 1994) who undertook measurements in plant canopies in natural wind. Fig. 1 presents the streamwise velocity spectra measured at the average crop height for both natural and generated conditions, and when combined with the previous mentioned statistics confirms that the wind tunnel is capable of generating the appropriate flow conditions, (in an average sense). The spectra in Fig. 1 have been divided by their respective variances to aid direct comparison. For a full description of the performance characteristics of the wind tunnel the reader is referred to Sterling et al. 2003. The major deficiencies with using the wind tunnel are in the simulation of lateral fluctuations, (due to the wind tunnel constraining the flow direction), and an under prediction of the ratio of gust velocities to mean velocities. Despite these drawbacks Sterling et al. were able to conclude that the wind simulation was satisfactory for the purposes of the current analysis.

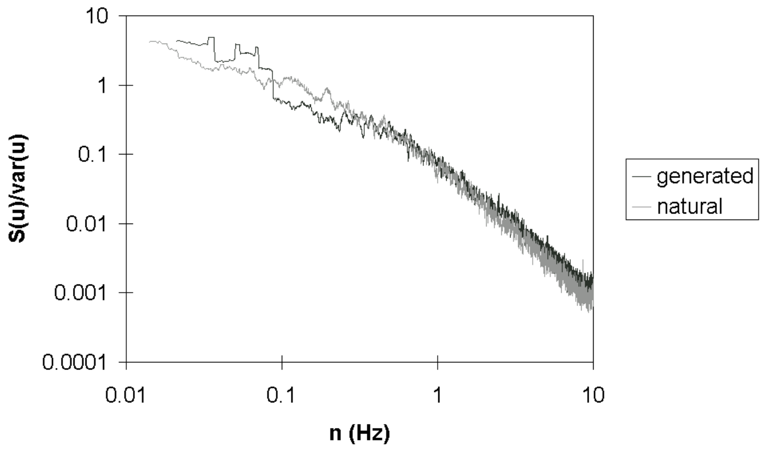

Fig. 1: Streamwise velocity spectra measure above a crop in natural and generated conditions.

The spatial and temporal variability of a plant canopy is evident even in the presence of light winds. The coherent structures present in the flow and their respective vorticities cause sections of the crop to oscillate in phase leading to the visual appearance of a wave travelling over the canopy. The spectra presented in Fig. 1 essentially average the frequency-energy relationship over the entire measuring time. In order to examine how this relationship may evolve with time the streamwise velocity has been analysed through the use of a Morlet wavelet function:

$$\psi(\eta) = \pi^{-1/4} e^{i\omega_o \eta} e^{-\eta^2/2} \qquad \text{Eqn. 1}$$

where η is a non-dimensional time period (defined as time/scale), ω_o is a non-dimensional frequency here taken as 6 (Farge, 1992) and $i = \sqrt{-1}$. Fig. 2 shows a sample of the instantaneous streamwise velocity (at crop height) interpreted through wavelet analysis. The vertical axis in Fig. 2 represents the wavelet scale increment, j, where S_j is the scale define as $0.096(2^{0.5\,j})$. The horizontal scale of Fig. 2 is the time elapsed since recording began and the contours represent regions of constant energy, lighter colours containing higher energy. A striking feature of Fig. 2 is that the energy contained at each wavelet scale (which in this analysis can be consider to be the equivalent to the inverse of frequency) can be clearly seen to vary throughout the measurement period. Although Fig. 2 only presents four minutes worth of data, this intermittency is apparent throughout of the whole recording period.

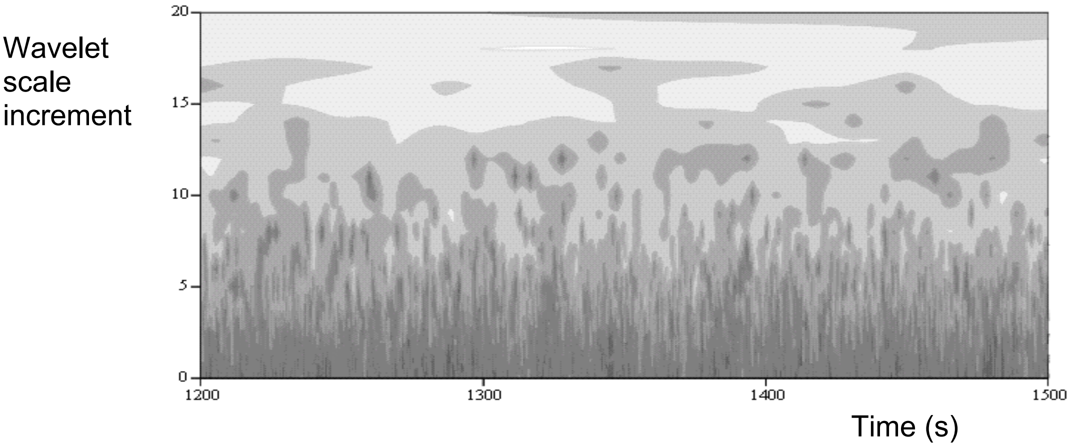

Fig.2 A scalogram of streamwise velocity.

A noticeable feature of Fig. 2 is the apparent high energy content which occurs for short periods of time (approximately 5 seconds) at frequencies of approximately 0.7Hz (wavelet scale value 8). It is also apparent that the average distribution illustrated in Fig.1 does not illustrate the true picture since a given energy amount of does not only vary with time but varies across a wide range of frequencies. This suggests that that the coherent structures present in the flow exist in an average sense and are subject to significant vortex stretching, i.e. the deformation of the structures due to the shear in the flow cause the energy to be distributed across a range of frequencies.

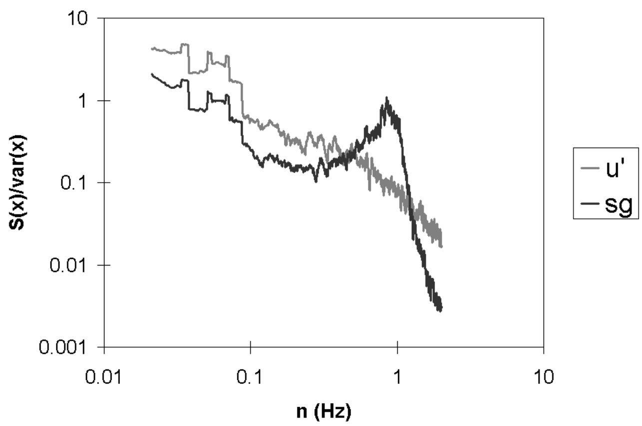

Fig.3 Displacement (sg) and velocity (u') spectra corresponding to a single stem.

Fig. 3 illustrates the displacement time series of a calibrated strain gauge (sg) and corresponding streamwise velocity (u') analysed in the frequency domain. Fig. 3 illustrates that the majority of the plants induced vibration occurs around its lower natural frequency. It can also be appreciated that actual frequency of the plant is of the utmost importance. For example if the frequency reduced from 0.9Hz (as in Fig. 3) to 0.1Hz, say, then there would be more energy available in the wind at this particular frequency. This would result in a relative increase in loading, which implies that the plant would be more prone to lodging. It is perhaps interesting to note that the natural frequency of forest trees varying depending on their location. For example, Marshall 1998 states that trees at the edge of a forest are stiffer and as a result have higher natural frequencies. Marshall argues that this is due to the trees growing to adopt the stronger wind forces experienced at the edge. However as discussed above, the increase in natural frequency shifts the tree away from the high energy end of the velocity spectrum. This shift along the spectrum reduces the available energy to load the tree and as such reduces its likelihood fail.

As highlighted earlier the wind loading experienced by the plant occurs as a result of discrete coherent gust penetrating the canopy. Although significant energy dissipation occurs at the plants natural frequency there are periods throughout the loading cycle when the plant is stationary. The data presented in Fig. 3 essentially averages the energy content per frequency throughout the entire recording period. In order to examine the intermittency of the plant dynamic a wavelet analysis was undertaken, subject to the constraints outlined above. Fig. 4 shows five minutes worth of data from this analysis which corresponds to the same recording period as the data presented in Fig. 2. The intermittency of the plant dynamics around the natural frequency is apparent (wavelet scale ≈ 7). Unlike the streamwise velocity a high energy content frequently occurs at lower wavelet scale and supports the results presented in Fig. 3.

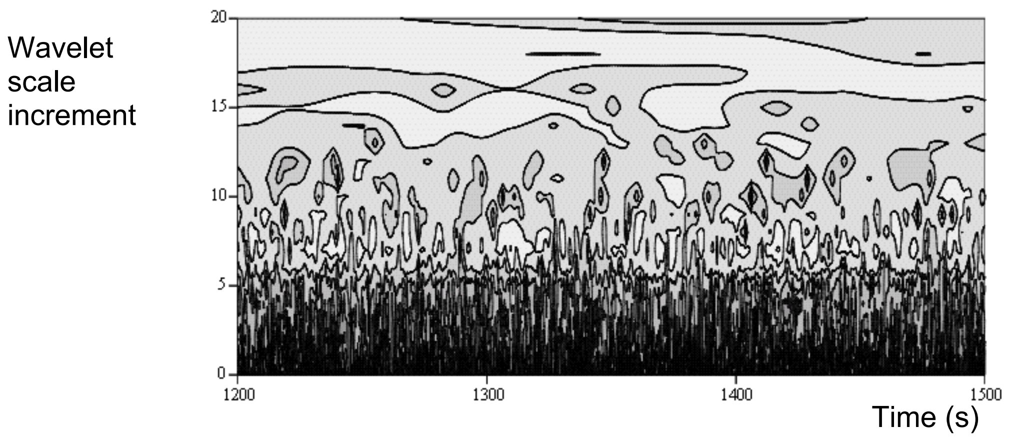

Fig. 4 is the wavelet stuff relating to a strain gauge displacement time series.

Lodging

To the best of the authors knowledge, prior to the above experiments, the actual lodging process had never scientifically been observed. Throughout the course of the tests both stem and root lodging were observed to occur on different plants. In addition to the force and velocity measurements each test was also monitored using standard video recording equipment. The incorporation of this analysis enabled a stem lodging event to be observed. During a period of relatively large oscillations one of the plants was observed to fail through breaking of the second internode above the ground. It is worth noting that the actual failure occurred after a period of approximately 10 seconds of the plant undergoing large oscillations. There are potentially a of number explanations why the plant did not fail instantly: the previous wind loading had not been of sufficient strength to overcome the bending strength of the plant; the previous arrival of gusts large enough to cause failure occurred out of phase with the plant movement and as such the dynamics of the plant reduced its effectiveness; the previous repetitive loading and corresponding oscillations of the plant had been sufficient to begin to induce mechanical failure of the stem, thereby increasing the likelihood that the plant would fail under lower wind loading conditions. Unfortunately since the only plant that was observed to stem lodge was not strain gauged, it is difficult to state with confidence which of the above scenarios is the most probable. What is obvious is that since the plants are subject to large oscillations more work is required particularly concerning the effects that repetitive loading may have on the strength of the stem, before the physics of stem lodging can be fully understood.

Although the stem lodging process was not able to yield any strain gauge information, the same is not true of the root lodging event which was observed. Observation of the video recording showed that root lodging was a gradual failure which occurred over a period of approximately 5 minutes. During this event the displacement of the plant was monitored continuously via a strain gauge. In order to investigate the failure mechanism occurring during such an event, a wavelet analysis similar to the above was undertaken. Rather than performing this analysis across the entire frequency range attention was restricted to a selection of frequencies located around the initial natural frequency of the plant, since Figs. 3 and 4 illustrate that this is where most of the energy resulting from the plants motion resides. Since wavelet analysis allows the relationship between energy and frequency to be observed throughout time, it is possible to evaluate how the natural frequency of the plant changes during the wind loading. A detailed analysis of the experimental data pertaining to all of the wind tunnel tests revealed that the plants natural frequency remained reasonably constant throughout the loading period, except during a root lodging event. Fig. 5 illustrates the distribution of a plants natural frequency during such an event. The evidence presented in Fig. 5 suggests that in this particular experiment the plants natural frequency actually increases from approximately 0.6Hz to 1Hz.

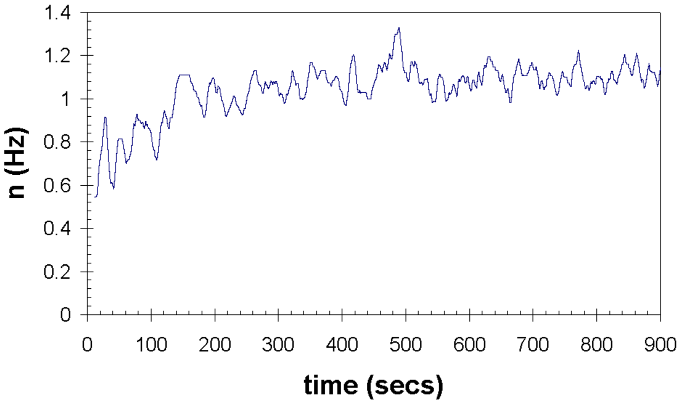

Fig. 5 Variation in natural frequency during root lodging.

This increase in natural is at first perhaps counter intuitive until one appreciates that the plants are subject to large oscillations and as such the orientation and self weight of the plant may be important, (unlike the situation for small oscillations). Little, 1998, undertook a detailed numerical simulation of columns subject to dynamic loading. Little demonstrated that for steel columns subject to large amplitude vibrations, a small value of imperfection or curvature results in axial strain which in turn leads to a stiffening effect. This increase in material stiffness results in an increase in natural frequency. Little further illustrated that the larger the curvature of the column, the larger the increase in natural frequency. Through his analysis Little was able to illustrate that this behaviour was independent of the material property. A possible analogy between Little's columns and wheat plants can be drawn, albeit with some imagination since Little applied different boundary conditions to that which would be needed to draw direct parallels. In strong winds wheat plants are subjected to large scale oscillations and invariably have some degree of curvature in the stem. During a root lodging event, the failure of the anchorage mechanism will cause the plant to rotate in the downwind direction. This rotation will increase the displacement of the centre of gravity about the vertical axis and as a result increase the self weight moment about the base. This increase in self weight moment will further increase the curvature of the stem and hence increase the natural frequency of the plant. This process will continue until the plant has root lodged or until the surrounding plants stop further displacements. It must be stressed that the authors offer this explanation as a possible hypothesis, and it is hoped that in future the model of Little can be modified to validate or disprove this theory.

As the plant begins to root lodge a break in the top of the canopy occurs. This opening of the canopy increases the depth of penetration of the next gust at that particular location and ensures that it is not only the top part of the plant that is loaded. This increases in loading further increases the base bending moment and increases the likelihood of further failure of the root/soil mechanism.

Concluding Remarks

This paper has presented selected results of field experiments on wheat crops undertaken in order to understand the lodging process. Analysis of the plants displacement has shown that the plant can be considered to act as a damped harmonic system oscillating in its primary mode shape. A wavelet analysis of the displacement has shown that the motion of the plant is complex and intermittent. A similar analysis based on the streamwise velocity confirms the existence of coherent structures and suggests the occurrence of vortex stretching.

Both stem and root lodging events have been scientifically observed, the former through video footage. Stem lodging was observed to occur over a period of seconds where root lodging was a more gradual failure extending over a period of approximately five minutes. The natural frequency of the plant was found to increase during the failure process. A tentative explanation of root lodging has been suggested based on a numerical model developed by Little 1998. The explanation is based on the assumption that as the plant begins to failure the curvature of the plant's stem increases and as such increases the axial strain. This increase in axial strain increases the natural frequency of the plant when subject to large oscillations, in keeping with the findings of Little 1998.

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