A wind engineering approach to understanding lodging

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SUMMARY:
Lodging, the failure of crops at the stem or anchorage, due to strong winds and severe rainfall, can be a significant problem in the agriculture industry. To develop an understanding of the phenomenon, this paper considers the dynamic motion of crops while interacting with the wind. A mechanical model has been used as a conceptual framework that represents crops as harmonic oscillators and expresses the failure criteria as a function of agronomic, dynamic/aerodynamic, and soil parameters. Through a novel experimental setup, the dynamic/aerodynamic parameters have been determined and used in a systematic parametric analysis to examine their importance in lodging. It is shown that aerodynamic factors play a crucial role in the phenomenon, especially when crops form interlocked canopies. Moreover, different growth stages of crops were found influential on the dynamic movement of crops which ultimately varies the risk of lodging during the season.

Keywords: Crop lodging, Wind effects on cereal crops, Crop aerodynamics

1. INTRODUCTION

Strong winds and heavy rainfall can cause crop lodging, the failure of plants at the roots or along the stem. A generalised lodging model was developed by [1] and represents individual plants as a series of connected dynamic harmonics oscillators. Using the model, the authors established the following relationship for the wind speed which would cause stem failure ($\overline{U}_{Ls}$) as:

$$\overline{U}_{Ls} = \left(\frac{\omega_n^2\left(\frac{x}{g}\right) S_s}{\left(1+\omega_n^2\left(\frac{X}{g}\right)\right)(0.5\rho A_{CF}X)\left(\cos\left(\alpha\frac{x}{l}\right)-\cot\alpha\sin\left(\alpha\frac{x}{l}\right)\right)\left(1+I\left(4g_{MB}^2+g_{MR}^2\left(\frac{\pi}{4\theta}\right)\right)^{0.5}\right)}\right)^{0.5} \quad (1)$$

Where ω_n is the radial frequency $(= 2\pi f_n, f_n$ is the natural frequency), S_s is the stem strength, X is the height of the centre of mass of the canopy, g is the gravity acceleration, x is the distance up the stem from the ground, ρ is the air density, A_{CF} is the plant drag area, l is the length of stem, I is the turbulence intensity, θ is the damping ratio [1] and α is a dimensionless parameter which can be approximated as: $\alpha = \frac{3}{\omega_n^2(\frac{X}{g})}$. g_{MB} and g_{MR} are the peak factor of broad banded and resonant moments respectively. Similarly, the failure wind speed at the anchorage system of the plant ($\overline{U}_{LR}$) can be expressed as:

$$\overline{U}_{LR} = \left(\frac{R_s}{\frac{((1+\omega_n^2(\frac{X}{g}))}{\omega_n^2(\frac{X}{g})}(0.5\rho A_{CF}X)(1+2Ig_{MB})}\right)^{0.5} \quad (2)$$

Where R_s is the root strength, S is the soil shear strength, d is effective root diameter, and γ is a constant.

The model developed by [1] has been developed as a conceptual framework to understand lodging. In order to apply it to specific crops, it needs to be calibrated appropriately, as it has been demonstrated [2] that the stem strength, root anchorage and failure mode can vary between different types of crops and different types of varieties of the same crop. Several different approaches have been used over the years to calibrate the model, the majority of which involve either invasive measurements in the wind tunnel or in the field [3,4]. This paper introduces a 'non-intrusive' experimental approach to studying wind-crop interactions through a 'visual', particle tracking approach. The methodology is outlined in section 2, and section 4 presents the results. Finally, a discussion is provided in section 5.

2 EXPERIMENTS METHODOLOGY

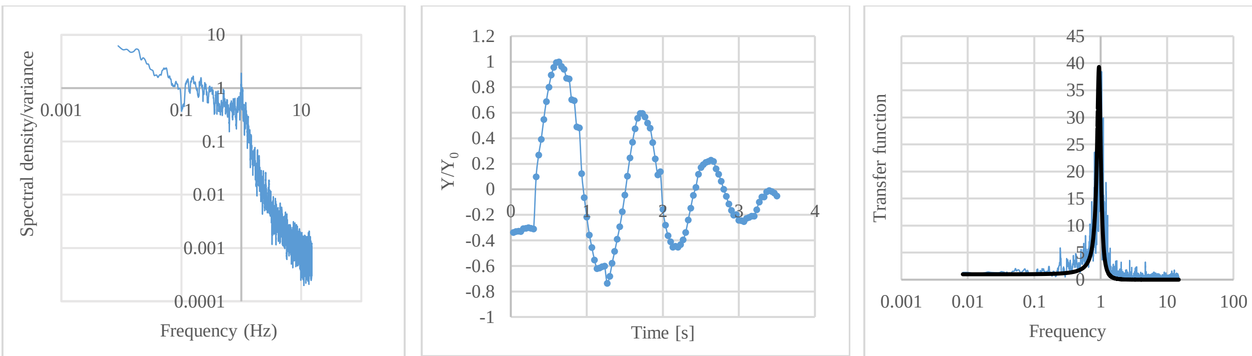
The approach outlined below can be used on a variety of different plants. However, for illustration purposes, we will focus on commercially grown winter oats planted at the Teagasc Research Centre, County Carlow, Republic of Ireland (52.86 °N, 6.92 °E, 57 MSL). The experimental setup includes two 100 Hz sonic anemometers (Gill Instruments Ltd) to measure the three components of wind velocity at two different heights (0.3m and 1m above the ground). In addition, a precipitation monitor was placed 2.5 m above the ground to detect any rainfall events. (Figure 1.a). To record the plant's displacement in two perpendicular planes (East-West and North-South), two video cameras (Lorex, LW2770 series) are mounted at crop height. In addition, a single oat panicle is painted red which represents our target plant (Figure 1.b). (several different target plants can be monitored using different colours if desired, although experience has shown that colour which contrasts sharply with the background is advisable). All the data streams from the equipment are synchronised, enabling the different streams of data to be time-stamped and logged as appropriate. The videos are subsequently post-processed using a tracking code written in MATLAB.

a) Experimental measurements b) Oat target position in front of cameras

Figure 1. The experimental set up [5]

3 RESULTS

As noted in equation (1), the natural frequency is a fundamental parameter used in the conceptual lodging framework. Using the tracking data, there are several ways in which this can be evaluated: via the spectral power density, the displacement time series and via a transfer function approach (see figure 2). It is also possible to obtain the damping ratio from figure 2.b if a logarithmic decrement approach is considered. As illustrated in equation (1), the damping ratio is another key parameter.



(a) (b) (c)

Figure 2. (a) Crop displacement spectra normalized by variance (b) Streamwise oat displacement in time (damping ratio=0.1) (c) Transfer function (normalized ratio of displacement spectrum to wind spectrum). Black line is 2DOF fit (Natural frequency = 1Hz, Damping ratio= 0.08) [5].

Finally, the plant drag area (AC_F), i.e. the plant area perpendicular to wind (A) multiplied by the drag coefficient (C_F), can be determined either directly from measurement, inspection of video time series (assuming the video camera resolution is appropriate) or from a relationship between the mean plant displacement ($\bar{Y}$) and the mean wind velocity ($\bar{U}$) as given in equation (3) [1,5]. Given the uncertainties involved with direct measurement, it is recommended that equation (3) is used.

$$\bar{Y} = \left(\frac{0.5\rho/\mu}{(2\pi f_n)^2}\right) AC_F \bar{U}^2. \qquad (3)$$

Figure 3 illustrates the changes of $K = \left(\frac{0.5\rho/\mu}{(2\pi f_n)^2}\right)\bar{U}^2$ versus the mean displacement. A linear trend has been fitted to the data which gives AC_f ~0.017m^2. However, a reasonable degree of variability is evident. Such variability is indicative of natural variability which tends to arise when working with biological systems.

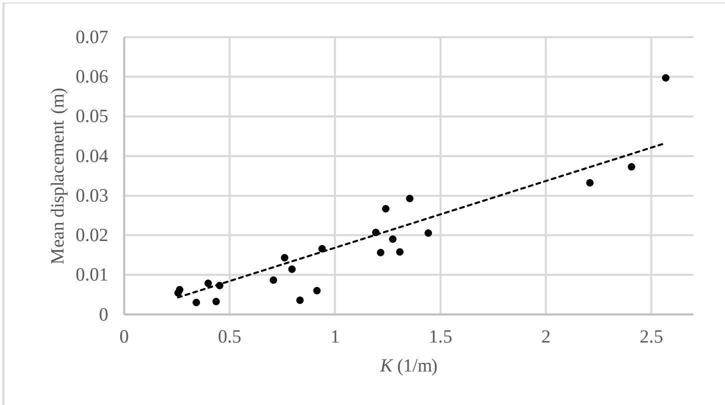
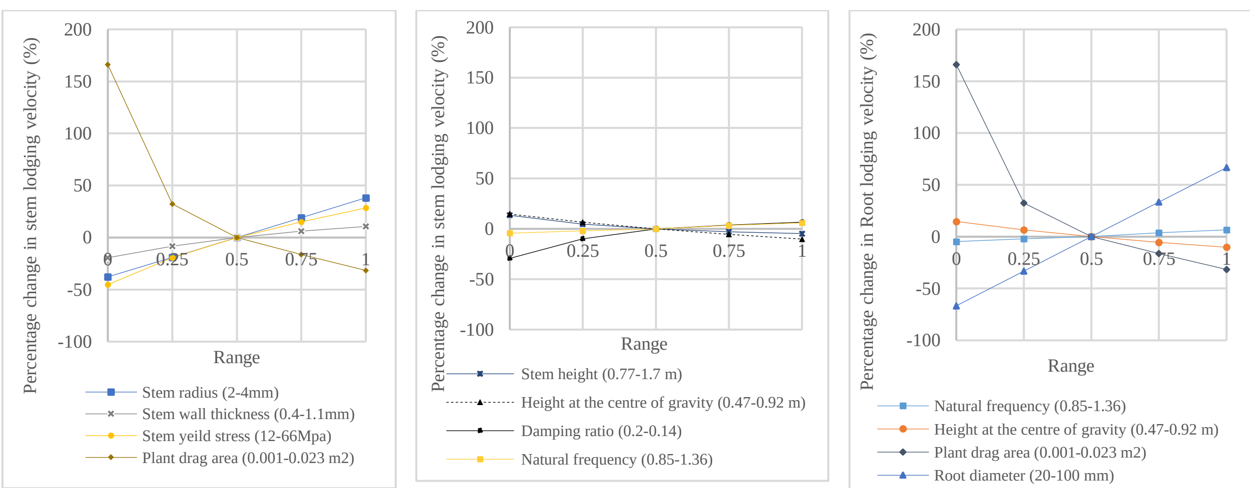


Figure 3. Mean displacement versus $K = (\frac{0.5\rho/\mu}{(2\pi f_n)^2})\bar{U}^2$, line shows linear regression (R^2 = 0.83) [5]

Whilst equations (1) and (2) contain several parameters, not all the parameters contribute in the same manner. Figures 4 a, b and c show the results of a parametric analysis that was undertaken to investigate the relative impact of different parameters on the failure wind speed. Each parameter was varied from the lowest to the highest values which were observed during the measurement trials and the percentage of change in the stem/root lodging speed was compared with the mean stem/root failure velocity. Figure 4a and 4c show that the plant drag area is the most influential parameter for both stem and root lodging, where the lodging velocity can reduce by three times ($\bar{U}_{Ls}$ =4.5-16.3m/s, $\bar{U}_{LR}$ =5-18.1m/s). The natural frequency, and damping ratio have comparatively lower effects on stem/root lodging wind speed (Figures 4b and 4c).



(a) (b) (c)

Figure 4. Stem lodging velocity changes with (a) stem radius, stem wall thickness, stem yield stress and plant drag area (b) stem height, height at the centre of gravity, damping ratio and natural frequency (c)root lodging velocity changes with natural frequency, height at the centre of gravity, plant drag area, root diameter [5].

4 DISCUSSIONS

This research has illustrated how traditional wind engineering methods can be adapted to provide an understanding of crop failure mechanism crops due to the action of the wind. Several, approaches have been suggested to obtain key parameters in. It is noted that different parameters have different impacts on crop failure with the plant drag area was found to be most important parameter for the specific crop examined.

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