Determination of crop dynamic and aerodynamic parameters for lodging prediction

Joseph, Genora; Mohammadi, Mohammadreza; Sterling, Mark; Baker, Christopher; Gillmeier, Steffi; Soper, David; Jesson, Mike; Blackburn, A.; Whyatt, J.D.; Gullick, D.; Berry, P.; Hatley, D.; Finnan, John; Murray, Jon

DOI:
10.1016/j.jweia.2020.104169

Determination of crop dynamic and aerodynamic parameters for lodging prediction

G. M. D. Joseph[1] *, M. Mohammadi[1], M. Sterling[1], C. Baker[1], S. G. Gillmeier[1], D. Soper[1], M. Jesson[1], G. A. Blackburn[2], J. D. Whyatt[2], D. Gullick[2], J. Murray[2], P. Berry[3], D. Hatley[3], J. Finnan[4]

1 School of Engineering, the University of Birmingham, Edgbaston, Birmingham B15 2TT, UK

2 Lancaster Environment Centre, Lancaster University, Lancaster, LA1 4YQ, UK

3 ADAS Rosemaund, Preston Wynne, Hereford HR1 3PG, UK

4 Teagasc, Oak Park, Carlow R93 XE12, Republic of Ireland

Keywords: Lodging, crop aerodynamics, natural frequency, damping ratio, canopy drag area.

Abstract

This paper considers a process through which the wind costs the agricultural industry hundreds of millions of pounds per year - crop lodging. Lodging is the displacement of crops by wind (and rain) that can result in either stem breakage or uprooting. In particular this paper builds upon recent work to develop a generalised model of the lodging process and presents the results of several experimental campaigns to identify dynamic and aerodynamic parameters that are required as inputs to the model in order to estimate lodging wind speeds. These experiments were carried out at various sites in the UK and the Republic of Ireland to determine the natural frequencies, damping ratios and drag areas of maize, oats and oil seed rape. The experimental methodology, which was based upon the tracking of plant displacements, was shown to be robust, and consistent values of the parameters were obtained, albeit with much larger experimental uncertainties than would normally be expected in wind engineering applications. The values of these parameters were also consistent with those of earlier measurements for wheat. The generalised model was then used to determine lodging wind speeds for the three crops, and an assessment was made of the effect of experimental uncertainties in dynamic, aerodynamic and agronomic variables on the predicted values. In broad terms the generalised lodging model was shown to well describe the crop behaviour for isolated crops, and it was shown that it could be used in a simplified form for interlocked crop canopies. It was also shown that uncertainties in the aerodynamic parameters resulted in uncertainties of around an order of magnitude in lodging risk, whilst typical variations between plants in some crop parameters (notably stem strength and radius) could result in lodging risk uncertainties of two orders of magnitude.

1. Introduction

Lodging is the permanent displacement of crop stems from their (original) vertical position, due to a combination of high winds and heavy rain, and can result in significant crop yield reductions (Berry et al., 2000). The phenomenon affects a wide range of crops – wheat, barley, rice, oats, maize, oilseed rape etc., and is a problem of significant concern in many countries around the world. There are two basic failure modes – stem lodging (failure at some point of the stem above the ground) and root lodging (failure at the root/soil interface). These two lodging mechanisms are illustrated in Figure 1 for the three crops with which this paper is mainly concerned - oats (*Avena sativa*), maize (*Zea mays*) and oilseed rape (OSR, *Brassica napus*). Whilst the primary loading on the plants that causes lodging to occur is the wind, heavy rainfall can affect the soil conditions and increase the likelihood of root lodging.

The costs of lodging can be considerable. For example, in the UK it is estimated that as a direct result of lodging in OSR, yield is reduced by ~46% resulting in losses of ~£120 million per year (Kendall et al., 2017). Stem lodging of maize accounts for worldwide yield losses of up to 20% (Flint-Garcia et al., 2003), whilst a further 20% reduction in yield can be attributed to root lodging. The costs incurred by lodging arise as a direct consequence of yield loss and indirectly from reduced grain quality, increased drying, increased susceptibility to plant pathogens and pests, and the increased difficulties associated with harvesting (Crook and Ennos, 1993; Berry et al 2003, Berry et al., 2004, Berry and Spink 2012, Sterling et al 2018). Furthermore, the effects of crop lodging can directly and indirectly impact on a number of the United Nations Sustainable Development Goals (United Nations 2018), in particular: no poverty, zero hunger, good health and well-being, and responsible consumption and production. Some researchers have suggested that climate change may exacerbate the issue in certain parts of the world (Challinor et al., 2010; Mohammadi et al, 2020), particularly through heavier rain fall increasing the susceptibility of crops to root lodging.

Whilst much of the basic work in this area has been carried out by agronomists and plant scientists, some experimental work looking at tree behaviour in high winds from an engineering perspective has been carried out both by one of the author and his co-workers (Baker and Bell, 1992; Roodbaraky et al, 1994) for urban trees, and by Boldes and his colleagues in Argentina (Boldes et al 2001, 2002, 2003) for forest trees and shelterbelts. Computational studies of flows within canopies are also reported by Hiraoka (1993) and Hiraoka and Ohashi (2000). More recently Rhee and Lombardo (2018) have begun to consider tree and crop failure as indicators of the strength of tornadoes.

Over the last two decades, research has been carried out by some of the authors to understand the mechanisms of lodging and, in doing so, to enable the best application of remedial measures/interventional (management) approaches. As a result of this work, a mechanical model of the lodging process was developed in which a single plant is represented as a damped harmonic oscillator (Baker, 1995; Baker et al, 1998; Berry et al, 2006). Applying a representative wind gust, it was possible in this model to calculate the wind-induced bending moment at the base of the plant, which was compared with the stem failure moment and the failure moment of the root plate. An improved model was subsequently developed (Baker et al., 2014) which was generalised for any plant type and enabled canopy interactions with the environment to be taken into account. The model allows for consideration of both individual plants and crops with interlocked canopies, such as OSR. In addition, a more complex, stochastic, representation of the wind was used. For crops that oscillate as isolated plants (e.g., wheat), the generalised model reduces to that described in Baker (1995). This model is being used in a number of linked multi-disciplinary investigations to study the lodging of a variety of crops around the world, based on a range of aerodynamic, climate and agronomic studies, with a view to incorporating of the results into a GIS framework that can be used to identify crops at risk of lodging, or, conversely, the development of more risk resistant crops (Berry et al, 2019).

In order to apply the new model, a variety of aerodynamic and plant related parameters are required. The focus of the current paper is to present a viable methodology for determining these parameters using *in-situ* measurements of wind over the crop canopy and the corresponding wind-induced displacement of the crop. Section 2 of the paper briefly outlines the generalised lodging model and how it is parameterised. Section 3 outlines the methodology of the field experiments undertaken on oats, maize and OSR. Experimental results are set out and discussed in section 4 and some concluding remarks are made in section 5.

(a) (b) (c)

Figure 1 Images of a) stem lodging in oats (photo credit Teagasc), (b) root lodging in maize (photo credit CIMMYT) and (c) stem lodging in OSR (photo credit ADAS UK)

2. The Generalized Lodging Model

As noted above, the authors have developed a model of the lodging process that can predict, for specific wind and rain conditions, the probability of root and stem lodging. This will not be described in detail here, and the reader is referred to Baker et al (2014) for further details. Here it is sufficient to say that a mechanical analysis of individual plants or an interlocked canopy of multiple plants, assuming the crop can be represented by point masses at the top of weightless, elastic stems, results in a model of plant or canopy dynamics that can be represented by a simple two degree of freedom oscillator. This allows the calculation of the crop displacements and bending moments under the action of a fluctuating wind load at the canopy top. This is solved using the normal wind engineering frequency domain approach that allows the displacement and stem bending moment spectra to be determined. The one-second peak values of this bending moment at different points along the plant stem are then calculated from these spectra, and compared with the stem failure moment to check for the occurrence of stem lodging, while the minute averaged values are compared with the root plate failure moment, to check for the occurrence of root lodging. The output from the model can be succinctly expressed in the form shown in Figure 2, where the regions of root and stem lodging are shown in terms of daily rainfall (*i*) and hourly mean wind speed ($\overline{U}$) at the canopy top. The major boundary between the regions has a simple parabolic form. In Figure 2, $\overline{U}_S$ is the mean wind velocity below which no lodging occurs; $\overline{U}_{LSB}$ is the mean wind velocity where stem breakage occurs at the base of the stem (note this is a vertical line and thus the value is not dependent on rainfall); $\overline{U}_{LR}$ is the mean wind velocity which results in root lodging in all circumstances; and i_o is the daily rainfall above which root lodging always occurs, even at very low wind speeds. These parameters are themselves somewhat complex algebraic functions of a range of measurable parameters. For example the stem lodging velocity at the base of the stem ($\overline{U}_{LS} = \overline{U}_{LSB}$) is given by

$$\overline{U}_{LS} = \left(\frac{n(2\pi f_n)^2 (X/g)(\sigma\pi a^3/4)\left(1-\left((a-t)/a\right)^4\right)}{\left(1+(2\pi f_n)^2(X/g)\right)(0.5\rho A C_F X)\left(1+6.86 I_u \left(1+0.087\left(\frac{\pi}{4\theta}\right)\right)^{0.5}\right)} \right)^{0.5} \qquad (1)$$

The parameters in this equation are in one of three categories.

- Crop geometric and material parameters – the number of shoots per plant n, the centre of gravity height X, the stem failure strength at the base σ, the stem radius at the base a, and the stem wall thickness at the base t;
- wind turbulence characteristics at the top of the canopy, in particular the along wind turbulence intensity I_u;
- plant dynamic and aerodynamic characteristics – in particular plant or canopy natural frequency f_n, and damping ratio θ and drag area AC_F per plant.

Also note that ρ is the density of air, and g is the acceleration due to gravity. Similar expressions can also be developed for stem lodging velocities at an arbitrary point up the stem away from the base, and for root lodging velocities. The latter will of course also be a function of various root and soil characteristics. Further details are given in Baker et al (2014).

The crop geometric and material properties and root characteristics required for the model were measured by using a range of agronomic methods and are reported elsewhere (Berry et al, 2000). This paper is concerned with the determination of the wind turbulence characteristics and the plant dynamic and aerodynamic characteristics for three crop types –maize, oats and OSR. These three crops represent different degrees of plant interlocking – a maize crop consists of essentially independent plants; an oat crop in the later growth stages can be regarded as mildly interlocking, and an OSR crop as very interlocked.

The model of course has limitations – the description of the crop dynamic behaviour is very idealised, and does not allow for major variability in the dynamic parameters during the root lodging process, where failure is likely to be progressive. It should primarily be regarded as a framework for considering experimental results, and as a method for identifying the sensitivity of lodging to different parameters.

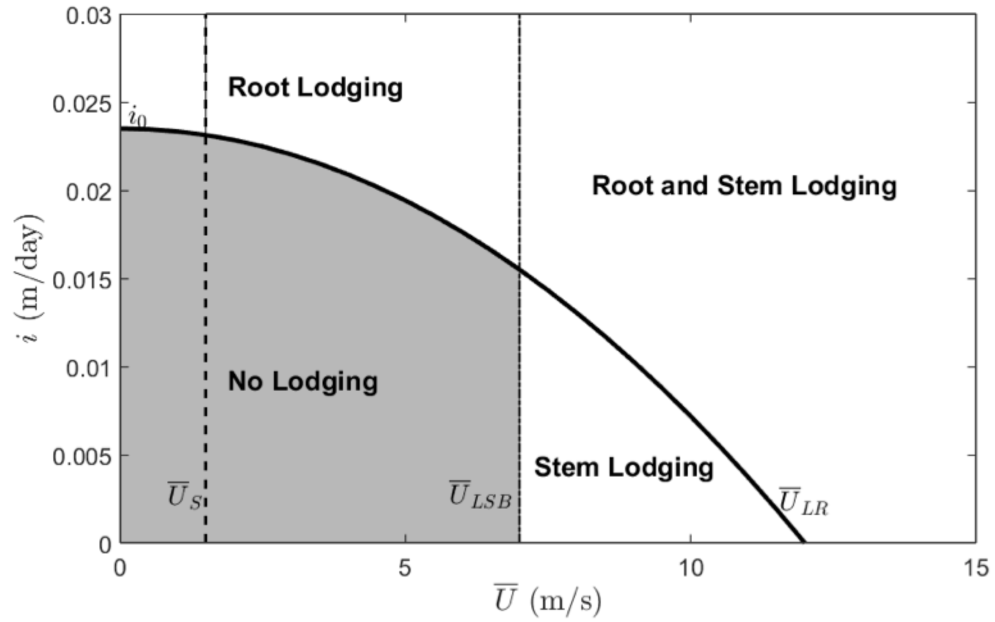


Figure 2 The parabolic lodging relationship (Baker et al., 2014).

3. Aerodynamic Experiments

3.1 Experimental set-up

The experiments reported below were undertaken at various farm locations in the UK and the Republic of Ireland (Table 1). The primary objective of these experiments was to observe the effects of wind and rain on the motion of three specific crops, namely oats, maize and OSR, selected because of differences in their canopy morphologies which leads to variations in canopy interlocking. Wind conditions and plant displacement were simultaneously measured. The experiments were conducted after panicle emergence for oats, at cob maturity for maize and flowering stage for OSR, which corresponded with the periods when the plants were most vulnerable to lodging. The equipment used in all three experiments is illustrated in Figure 3 and consists of two ultrasonic anemometers (Gill Instruments R3-100, 100Hz research anemometers), two high definition CCTV cameras (Lorex, LW2770 series) operating at a frame capture rate of 30 frames per second, and a rain gauge (ThiesClima precipitation sensor). The ultrasonic anemometers measured all three components of velocity. For each dataset the raw values were transformed to give horizontal velocities in the average flow direction, u_x: horizontal velocities normal to the average flow direction u_y; and vertical velocities, u_z. Note that one anemometer was positioned with a horizontal axis, to be as close as possible to the canopy top. To measure crop movement, one camera was set up to capture crop displacement in the East-West plane, whilst the other recorded displacement in the North-South plane. A 12V 65Ah deep cycle lead acid battery was used to power the sensors and camera. Target plants were selected, based on visual similarity to average plant properties (e.g. height, morphological characteristics such as number of cobs for maize). Visible aerial parts of the target plant were painted red, to enable detection and tracking of plant deflections by a bespoke pixel tracking code written in MATLAB (further details provided in the Appendix)). This power source and the associated data logging equipment were stored in a watertight box, to prevent water ingress into components. Figure 3 shows the equipment configuration in the field for the three crops and highlights the challenges that exist for some crops, most notably maize, where the height of the crop can present practical challenges.

Table 1 Locations and dates of the lodging experiments

Crop	Crop height (m)	Farm	Location	Coordinates	Elevation above sea level (m)	Experiment dates
Maize	2.5	ADAS Gleadthorpe	Mansfield, Nottingham, UK	53.22N, 1.11W	49.0	28/09/17–02/10/17
Oats	1.0	Teagasc, Carlow	Carlow, Republic of Ireland	52.86N, 6.94E	54.0	31/05/17–15/06/17 29/05/18 – 30/06/18
OSR	1.6	ADAS Terrington	Terrington, King's Lyn, Norfolk, UK	52.77N, 0.32W	4.0	16/05/18–24/05/18

(a) Maize (b) Oats (c) OSR

Figure 3 Equipment set up in the field.

3.2 Tracking crop deflections in MATLAB

Work by Py et al (2006) has demonstrated the utility of video tracking methods to monitor the oscillatory motions of plants and it was shown that compared to accelerometer based techniques, video-based methods allowed for precise determination of the zero displacement position of a plant and since these methods do not require sensors affixed to the plants, they do not add mass and alter the dynamic response characteristics of the plant. The current work differs somewhat from Py et al (2006) which used video tracking to study the global motion of the crop canopy in the form of Honami waves due to the downward transfer of momentum from coherent structures in the canopy mixing layer. Here, a two-camera configuration allows oscillations of individual marked plants to be captured in the wider horizontal field of view of each camera. The cameras have been calibrated using the MATLAB Camera Calibrator application to determine camera intrinsic parameters including lens distortion. From these observations, the dynamic response spectra of the plants and their corresponding aerodynamic characteristics were obtained.

A bespoke tracking program was developed in MATLAB to read the imported video files and detect red pixels in the video frames. Figure 4 illustrates a typical video image where the target plant (painted red) is highlighted by a white cross. As the tracking program progresses through the individual frames of the video file, a two dimensional array of centroid coordinates is created – expressed in Figure 5 as a pixel displacement time history. The Appendix gives more detail of the method that was used.

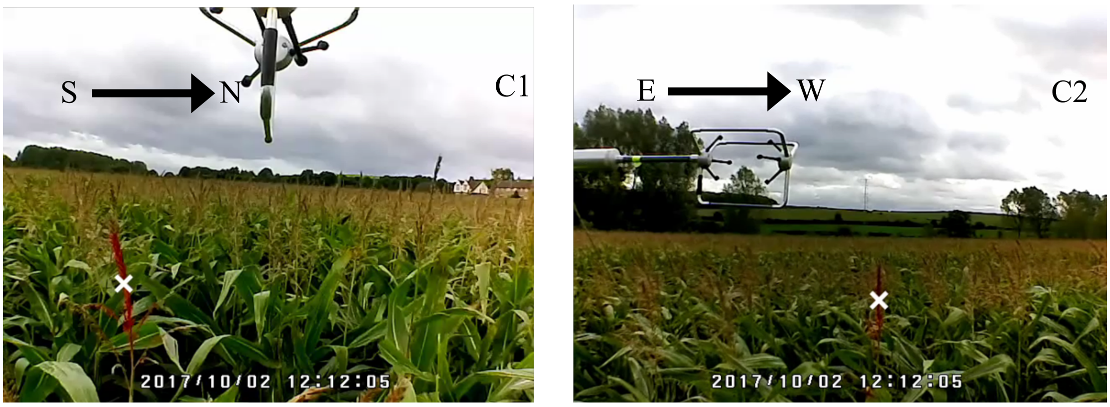
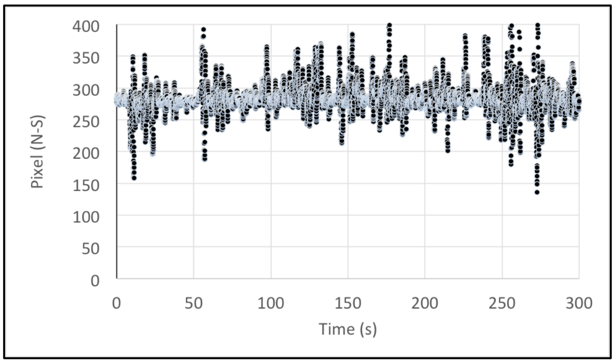
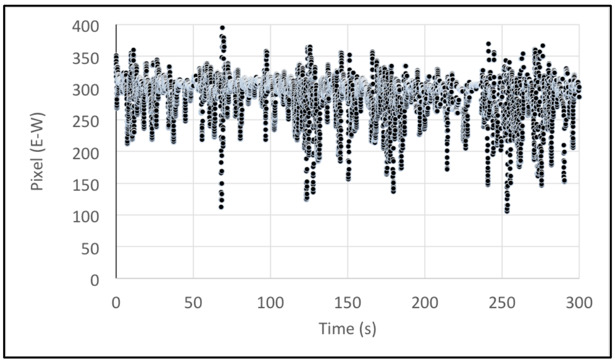


Figure 4 *Centroid tracking of maize tassel in a single video frame for each camera, C1 and C2.*



(a)



(b)

Figure 5 Example of oats pixel displacement time histories (a) Camera 1 (b) Camera 2

4. Results and Discussion

4.1 Canopy top flow parameters

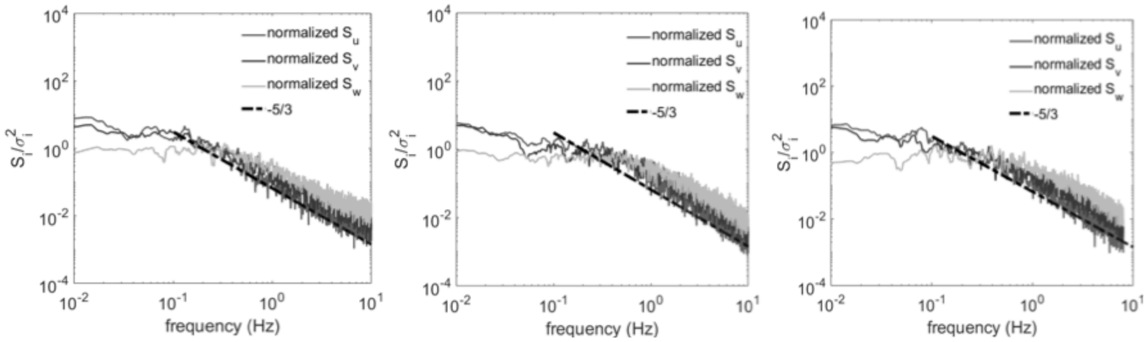
In this section and subsequent sections relevant parameters have been averaged over 20, 10 minute, datasets for oats, 17 for maize and 18 for OSR. Table 2 shows average values across all the datasets at crop height of σ_i/u_* where σ_i is the standard deviation of the velocity component *i* and u_* is the friction velocity given by $\sqrt{u_x u_z}$; I_i, the turbulence intensity of the velocity component *i* ($\sigma_i/\overline{U}$); and L_i/h, the integral length scales of the velocity component *i* normalised by crop height *h*. The latter is obtained by two methods – the integration of the area under the velocity component autocorrelation curve for all components (to the point of the first zero crossing), and a von Karman fit to the velocity power spectrum for the *u* component only. Standard deviations of σ_i/u_* and I_i are also given, which allows the variability between datasets to be appreciated. Ranges of experimental data from a number of other sources are also given. In general the turbulence parameters were found to be in good agreement with those in the literature, corresponding to near-neutral stratification above a wheat canopy (Finnigan, 2000 and Sterling et al., 2003). The turbulence intensity over the interlocked OSR crop is lower than over the other crops, and the longitudinal length scales are somewhat larger. The high values of the components of turbulence intensity just above the canopy are worthy of note, being very much higher than over simple flat terrain (which one would expect to be around 0.2 to 0.3), which again reflects the values found in previous research. The length scales estimated from a spectral fit are somewhat below the equivalent autocorrelation values. The autocorrelation method tends to over-predict the length scales due to the uncertainty associated with the precise position of the zero crossing value.

The wind power spectra, S_i, for each of the three crops, normalized by the variance, σ_i^2, are illustrated in Figure 6. The slope of the *u* and *v* spectra are consistent with Kolmogorov's -5/3 power law in all three crops, implying that the turbulent energy cascade over the crop canopy exists in the inertial subrange, where the flow can be considered locally isotropic (Katul et al. 1997). These spectra above the crops are similar to those measured by other authors in the past such as those reported in Finnigan (2000).

Table 2: Values of wind turbulence statistics for oats, maize and OSR

(standard deviation of values from the range of datasets given in brackets; for the length scales, the normal type are values obtained from velocity autocorrelations, and the italics from a spectral fit using the von Karman form)

	Maize (h=2.5 m)	Oats (h=1.0 m)	OSR (h=1.6 m)	Panofsky and Dutton (1984)	Finnigan (2000) Wheat	Sterling et al (2003) Wheat
σ_u/u_*	2.04 (0.24)	2.33 (0.50)	2.20 (0.08)	2.39	1.8 – 3.0	2.11– 2.12
σ_v/u_*	1.85 (0.17)	1.99 (0.36)	1.78 (0.09)	1.92	-	-
σ_w/u_*	1.19 (0.07)	1.29 (0.12)	1.13 (0.03)	1.25	1.0 – 1.3	1.04 – 1.10
I_u	0.59 (0.04)	0.62 (0.02)	0.46 (0.03)	-	0.4 – 0.6	0.48 – 0.74
I_v	0.54 (0.08)	0.54 (0.04)	0.37 (0.02)	-	0.4 – 0.6	0.44 – 0.61
I_w	0.35 (0.05)	0.34 (0.005)	0.23 (0.01)	-	-	0.25 – 0.36
L_u/h	3.83	2.03	5.87	-	-	3.5 – 6.7
	1.20	*0.87*	*1.83*	-	-	
L_v/h	2.99	2.17	2.58	-	-	1.6-3.7
L_w/h	0.25	0.28	0.48	-	-	0.2 – 0.3



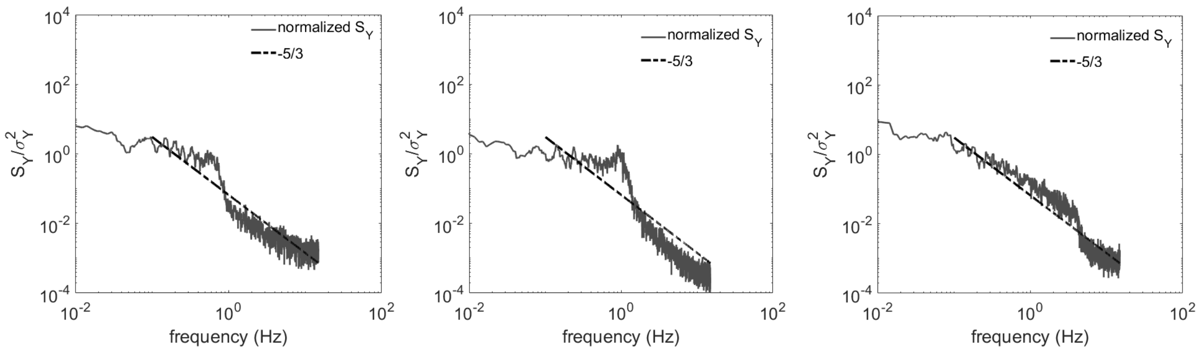
(a) Maize (b) Oats (c) OSR

Figure 6 Wind velocity component power spectra at crop height.

4.2 Natural frequencies

The displacement spectrum describes the dynamic response of a plant in the frequency domain and identifies the energy associated with plant oscillations at different frequencies. Examples of the along-wind displacement spectra over a 10-minute interval are shown in Figures 7(a) to 7(c) for target maize, oats and OSR plants. Similar to the velocity power spectra, the displacement spectra have been normalized using the variance. The fundamental natural frequency, f_n, of each species can be determined from the peak of the corresponding displacement spectra, which represents the first mode of vibration; average values for oats and maize are 1.1Hz and 0.7Hz respectively. For these crops, the natural frequency of plant oscillations fall within the inertial subrange, consequently, it is expected that turbulent eddies in this range dominate the lodging process. However, for the OSR data (Figure 7c) there is less evidence for a peak, although one can perhaps be discerned at around 2 to 3Hz. This difference in behaviour for OSR will be discussed below. The mean and the standard deviations (SDs) of the natural frequency data obtained from the power spectra are shown in Table 3, together with the value for wheat from Baker et al (2014) and Berry et al (2003). In wind engineering terms the spread of natural frequencies seems high. However such variability is a feature of biological systems, and similar spreads of data will be observed in the other parameters that are considered in this paper.

Natural frequency may also be estimated by manually displacing a single shoot during still, dry weather conditions and timing the corresponding oscillations once released. This method is described in full by Berry et al. (2000) but essentially requires a plant to be isolated from its neighbours and the aforementioned process repeated around 80 times and the means and standard deviations of the frequency calculated. It only of course gives the primary natural frequency. This method is not ideal for two reasons. Firstly, it can potentially damage an area of crops during the isolation process and secondly, for an interlocked (or heavily damped) plant, it can be impossible to perform. Table 3, summarises these results and compares them with those obtained from the spectral fit. For maize the spectral estimates are less than the agronomic measurements, and the standard deviation bands of the two methods do not overlap. For oats, the measured frequencies are similar to those for wheat reported in Sterling et al (2003), and the spectral estimates are somewhat higher than the agronomic measurements and again the standard deviations do not overlap. For OSR the spectral measurements are significantly higher than the agronomic measurements. The authors are of the view that in crops with significant canopy interlocking and more pronounced damping, the spectral method is a more appropriate way of determining the natural frequency of plants, as canopy damping may lead to rapidly decaying oscillations that are difficult to observe.



(a) Maize (b) Oats (c) OSR

Figure 7 Typical streamwise displacement spectra

Table 3 Natural frequencies determined from displacement spectra and oscillating plants

	Spectral estimate		Oscillating plants	
	Mean Hz	SD Hz	Mean Hz	SD Hz
Maize	0.69	0.12	1.0	0.14
Oats	1.1	0.12	0.8	0.18
OSR	2.56	0.45	1.0	0.12
Wheat (Baker et al 2014)	0.95			

4.3 Damping ratio

The dynamic response of a plant subject to a wind-induced displacement can be expressed in the frequency domain as (Sterling et al., 2003):

$$S_Y = |H(f)|^2 \frac{4\bar{Y}^2}{\bar{U}^2} S_U \quad (2)$$

where S_Y and S_U are the spectra corresponding to the plant's displacement and the wind respectively; $\bar{Y}$ and $\bar{U}$ are the mean values of displacement and wind velocity respectively and $|H(f)|^2$ represents the mechanical admittance function. Thus, if S_Y, S_U, $\bar{Y}$ and $\bar{U}$ are known it is possible to obtain the mechanical admittance function. Sterling et al. (2003) show that the mechanical admittance function for an isolated plant can itself be represented in the form of a two degree of freedom oscillator:

$$|H(f)|^2 = \frac{1}{\left(1-\left(\frac{f}{fn}\right)^2\right)^2 + 4\theta^2\left(\frac{f}{fn}\right)^2} \quad (3)$$

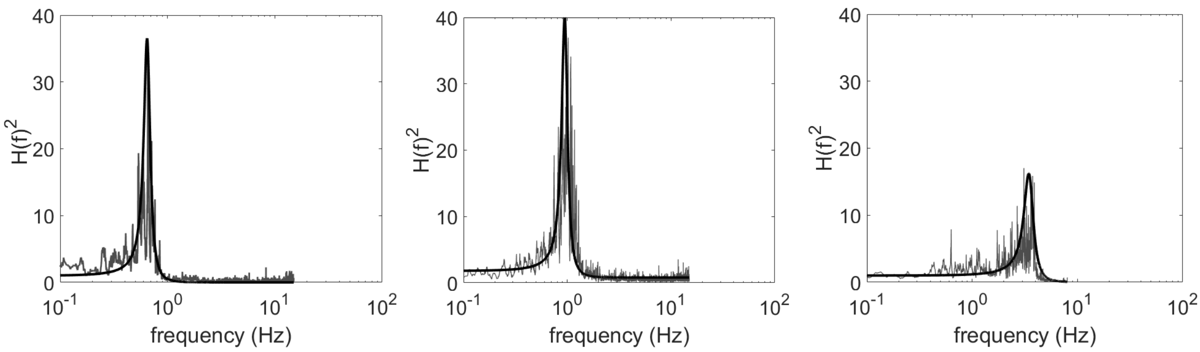
where f_n is the natural frequency and θ is the plant's damping ratio. Fits of this type are also shown on Figure 8. Now it is possible to differentiate this equation and show that the mechanical admittance function has a maximum value when the normalised frequency is $4\theta^2(1-\theta^2)$. Thus it is in principle possible to determine the damping ratio from experimental results for the mechanical admittance.

For both maize and oats, a clear peak can be identified from which the damping ratio can be obtained. However, for the case of OSR, the peak of the transfer function is not so clear, possibly due to the interlocked nature of the canopy, which effectively distributes the damping over a range of possible values. Results for all datasets are summarised in Table 4.

The damping ratio can also be obtained by observing oscillations of individual plants, and finding the ratio of two successive peaks (Clough and Penzien 1993). The damping ratio and the ratio of the *n* and *(n+1)* peak are then related by the simple expression

$$\frac{2\pi\theta}{\sqrt{1-\theta^2}} = \ln\left(\frac{Y_n}{Y_{n+1}}\right) \quad (4)$$

from which a further estimate of damping ratio can be obtained. For oats, maize and for OSR, the two methods give similar values, with the ranges overlapping. In general, as would be expected the damping ratios for OSR are somewhat higher than for oats and maize, due to plant interlocking, although the difficulties in obtaining the OSR values from either method needs to be emphasised. The values for wheat from Baker et al (2014) are also shown and are similar to the values measured for oats.



(a) Maize (b) Oats (c) OSR

Figure 8 Mechanical admittance functions

Table 4 Values of damping ratio from spectral method and oscillating plants

	Spectral method		Oscillating plants	
	Mean	SD	Mean	SD
Maize	0.13	0.04	0.15	0.09
Oats	0.11	0.05	0.10	0.04
OSR	0.13	0.05	0.22	0.08
Wheat (Baker et al 2014))	0.10			

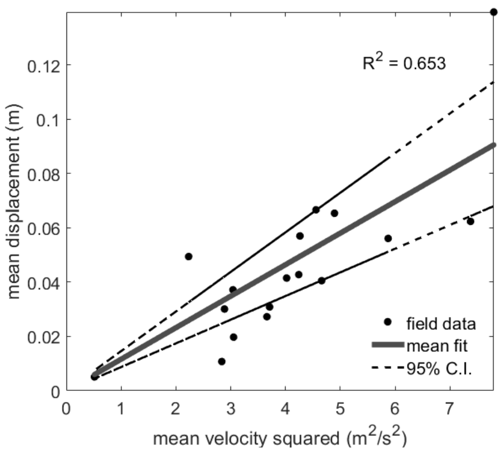
4.4 Drag Area

The drag force is dependent on canopy density, porosity, plant aerodynamic shape and the surface area of the canopy elements. From the lodging model (Baker et al, 2014), the following formula can be derived which relates the drag coefficient to the mean displacement

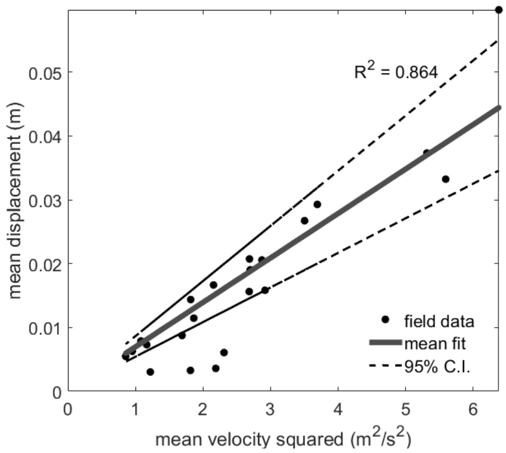
$$\bar{Y} = \frac{0.5\rho AC_F\bar{U}^2}{\mu(2\pi f_n)^2} \qquad (5)$$

where ρ is the density of air, AC_F is the drag area per plant and μ is the effective weight of a plant. Figure 9 plots the mean displacement against the square of the mean velocity as would be suggested by the above equation. There is a reasonably good linear relationship, which enables the parameter AC_F to be determined from the slope of the curve using the above expression. The mean fit and upper and lower bounds of the 95% confidence interval pass through the origin to satisfy the premise of equation (5), i.e. that the mean displacement is zero at zero mean wind speed. The resultant values and the 95% confidence levels are shown in table 6.

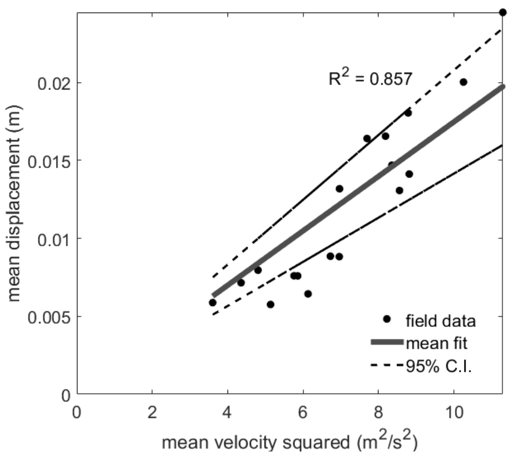
As might be expected, the smallest value of drag area / plant is for oats and the largest for maize, simply reflecting the physical size of the crop. The value for wheat (from Baker et al, 2014) is somewhat lower than that for oats, although it should be noted that the experimental basis for the determination of this drag area was not the same as that reported in this paper and involved the measurement of moments on individual stems to give the drag coefficient (which was close to unity) and a quite crude estimate of the exposed plant area.



(a) Maize



(b) Oats



(c) OSR

Figure 9 Mean displacement of all datasets plotted against mean velocity squared.

Table 6 Drag area values from plot of mean displacements against mean velocity squared

	μ (kg)	Mean	Upper bound	Lower bound
Maize	0.412	0.153	0.191	0.110
Oats	0.040	0.021	0.026	0.017
OSR	0.100	0.073	0.090	0.060
Wheat (Baker et al 2014)	-	0.008		

4.5 Parameter values from displacement time histories

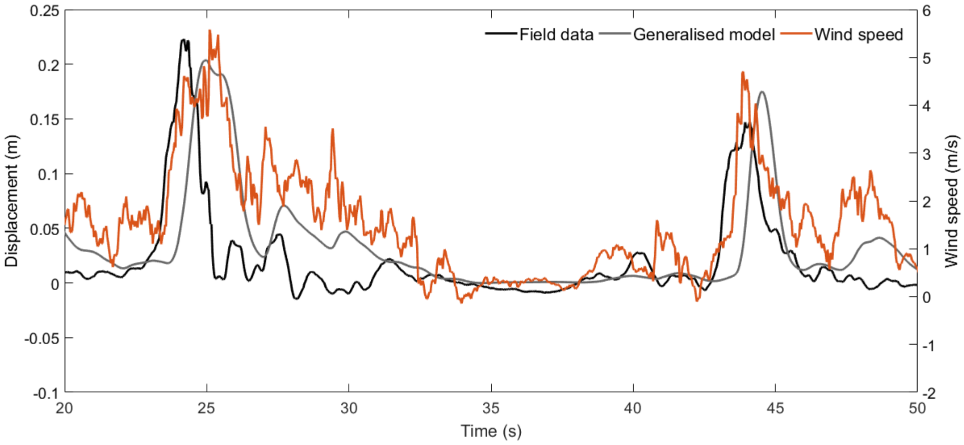
An alternative methodology for determining crop dynamic and aerodynamic parameters is to directly fit the generalised model equation to the measured time histories of crop displacement. From the generalised model, the following equation relating displacement time history $Y(t)$ to wind speed time history $U(t)$ can be derived

$$\frac{1}{(2\pi f_n)^2}\frac{d^2Y(t)}{dt^2}+\frac{2\theta}{2\pi f_n}\frac{dY(t)}{dt}+Y=\frac{0.5\rho AC_F}{(2\pi f_n)^2\mu}\,U(t)^2 \qquad (6)$$

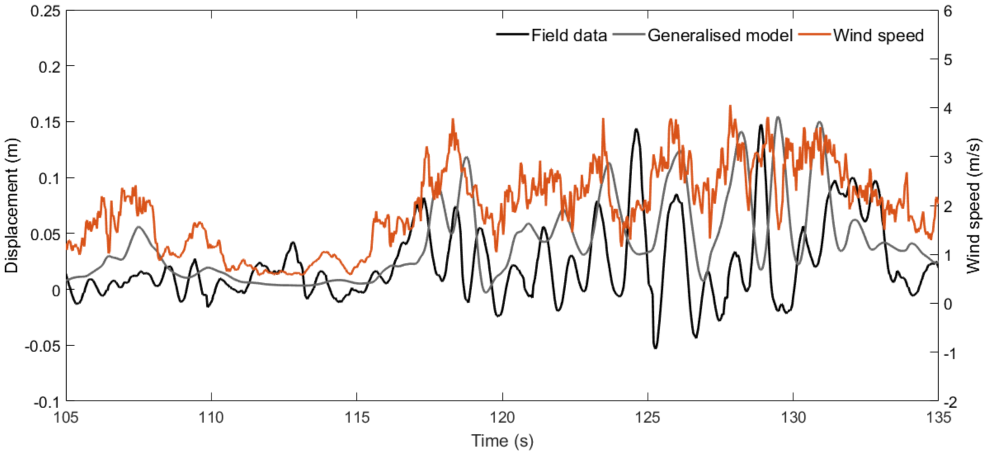
where t is time. Thus for a given wind speed time series it is possible in principle to solve this equation to predict the time dependent plant displacement, and to determine best fit values of f_n, θ and AC_F. Using a fourth order Runge-Kutta approach (Lai et al 2017), the results of such a process are shown in Figure 10 below for oats, maize and OSR, for three datasets that are independent of those used in the earlier analysis and are not related to those shown in Figure 5 or used in the determination of the aerodynamic parameters. The best-fit values of the parameters are shown in Table 7. In general agreement the fit can be seen to be reasonably good, and the best-fit parameters fall mostly within the parameter ranges given in Tables 4 to 6, which gives added confidence in the overall analysis methodology. These figures also allow some more general comments to be made on the adequacy of the modelling process

- The predicted peak displacements for maize, oats and OSR agree well with the field data, although the displacements for OSR are small.
- The model captures the general oscillatory motion of oats quite well.
- Although the peak values are in good agreement, the intermediate values of displacement for maize and oats from the field experiments and the model do not agree terribly well. This is probably due to a ‘friction’ within the plant canopies i.e. a certain wind force is required to make the plants move at all. This could be allowed for in the model, although at the cost of removing the linearity of the solution, but since the peak values are, in practice, what is required, this does not seem to be necessary.

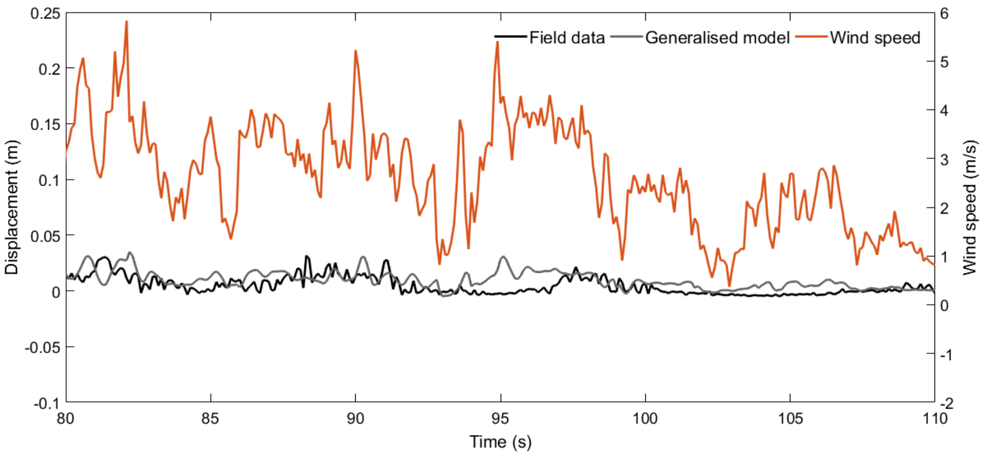
- The displacement for OSR are small, which is due to the fact that the OSR moves as a very large unit, because of the entanglement of the plants in the canopy, and does not react rapidly to sudden changes in wind speed. This suggests that such canopies could be modelled in a much simpler way, assuming the displacements simply follow the wind speed fluctuations averaged over (say) 5 to 10 seconds in a quasi-steady fashion.



(a) Maize



(b) Oats



(c) OSR

Figure 10 Predicted and measured displacement data.

Table 7 Best fit parameters

	f_n (Hz)	θ	AC_F
Maize	0.7	0.1	0.105
Oats	1.0	0.08	0.023
OSR	3.0	0.3	0.071

4.6 Stem lodging velocities

Table 8 brings together the various parameters for different crops, including stem parameters, and gives values of the stem lodging velocity from equation (1). These are between 4.0 and 5.3 m/s, values that at first sight seems rather low. However, it needs to be remembered that these are average velocities at crop height. The gust values at crop height that cause lodging will be of the order of 2 to 2.5 times the values given in the table (due to the high turbulence intensity). The values in the table can also be extrapolated to the normal meteorological measurement height of 10m above ground level through the use of the logarithmic velocity profile. To do so we make the assumption that the roughness length is 0.05m, and that the displacement height is 80% of crop height (both assumptions being somewhat arbitrary). These calculated mean values at 10m height are also shown in the table. Now, the normal definition of strong winds is a mean value of 10m/s at 10m height, and it can be seen that the extrapolated values are in the strong wind range between 11.5m/s and 16.5m/s. For context, in the UK, the 99th percentile average hourly wind speed at 10m height is between 11 and 13 m/s (Cook, 1985), and thus these stem lodging velocities would only be exceeded for a small proportion of the time. This is consistent with the lodging risk of commercial crops for which severe lodging seasons are experienced once every three to four years, when 10-20% of the UK crop experiences some lodging (Berry et al, 1998). This is not a proper statistical measure however and must be regarded as only a qualitative figure. It should be noted however that these extrapolated 10m velocities are very sensitive to the assumptions of surface roughness and displacement height, so should only be regarded as indicating a very approximate value corresponding to the more accurately determined lodging wind speeds at crop height.

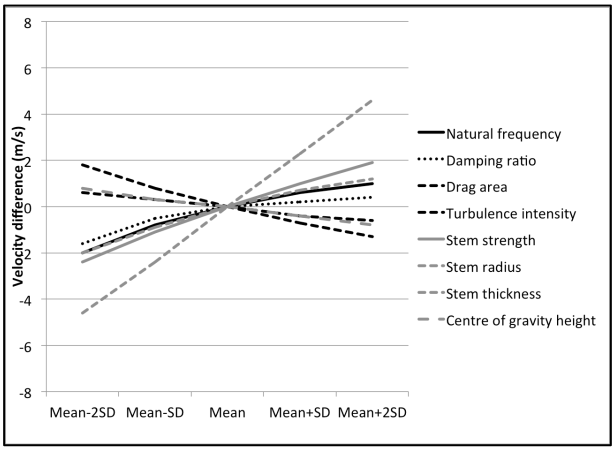
Finally it is instructive to examine how the considerable uncertainties in the lodging velocities due to uncertainties in the parameters measured in these experiments relate to the uncertainties due to variations on plant agronomic parameters. Figure 11 shows a plot of the variation in stem lodging mean wind speed at 10m above the ground for variations in the dynamic and aerodynamic parameters and plant characteristics between the mean value minus two standard deviations and the mean value plus two standard deviations for each parameter. For the agronomic parameters, the standard deviations that are used are typical of those found in field trials for nominally identical plants. It can be seen that in general, the greatest uncertainties in lodging velocities arise because of uncertainties in stem strength and stem radius. Of the parameters measured here, the measured uncertainties in natural frequency and damping ratio do not result in major variations in lodging velocity, whereas variations in the drag area are more significant. Thus, in practical terms, the uncertainties in the dynamic parameters measured here are of less significance than uncertainties in the various agronomic parameters.

To give further context to these calculations, if we assume a wind climate with a Weibull distribution of hourly mean velocities, with a shape factor of 2.0 and a scale factor of 5m/s, which is typical of UK conditions (Cook, 1985), then the risk of those velocities being exceeded is shown in Figure 12. It can be seen that a change of 2m/s results in the risk of the value being exceeded changing by an order of magnitude, and a change of 4m/s results in a two order of magnitude change in risk. Thus, from Figure 11, very broadly, uncertainties in the aerodynamic parameters results in an uncertainty in risk of lodging of an order of magnitude, whilst uncertainties in stem strength and stem diameter results in two orders of magnitude uncertainty in risk. The uncertainties are thus large, and in practical terms the lodging model is best used to compare the risks of different plant characteristics to identify those most associated with lodging, and also to give an indication of regions where lodging risk may become excessive.

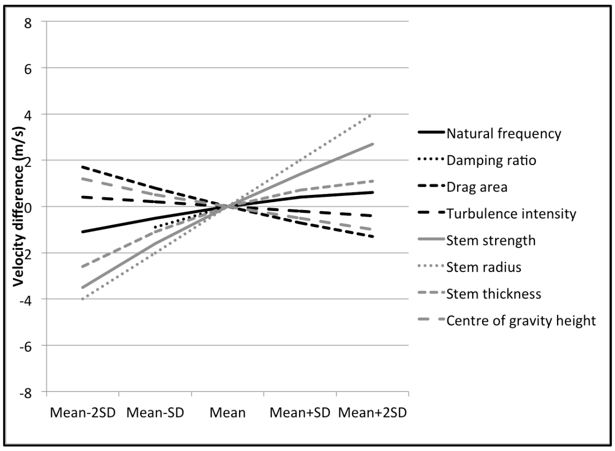
Table 8 Calculated stem lodging velocities

	Maize	Oats	OSR	Wheat (Baker et al 2014)
f_n (Hz)	0.7	1.1	2.6	0.95
θ	0.11	0.11	0.13	0.10
AC_F (m^2) (per plant)	0.153	0.021	0.090	0.008
I_u	0.59	0.62	0.46	0.50
X (m)	0.95	0.63	0.46	0.43
σ (MPa)	21.9	40.0	23.2	30.0
a (mm)	12.5	2.8	6.2	1.65
t (mm)	2.6	0.9	2.4	0.6

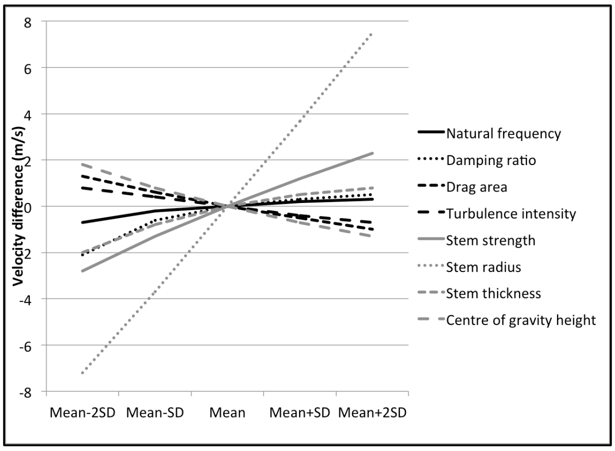
Number of shoots	1	2	1	4
$\overline{U}_{LS}$ (m s^{-1})	5.2	4.0	5.3	4.4
Crop height (m)	2.5	1.0	1.6	1.0
10m wind speed (m/s)	11.5	15.1	14.8	16.5



(a) Maize



(b) Oats



(c) OSR

Figure 11 Variations in lodging wind speed caused by dynamic, aerodynamic and agronomic parameters

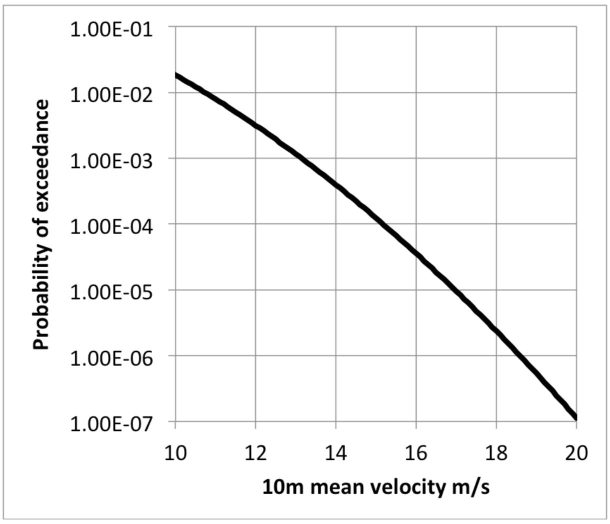


Figure 12 10m mean velocity probabilities

5. Conclusions

From what has been set out above, the following major conclusions can be drawn.

- The experimental methodologies adopted have been shown to be robust and consistent dynamic and aerodynamic parameter values have been derived. The spread of data for the biological systems studied here is large in comparison to normal wind engineering expectations.
- Whilst the measurements for oats and maize show strong peaks in the displacement spectra at the natural frequency, the experimental data for the interlocked canopies of OSR do not indicate a much smaller resonant peak.
- Mean values of the fundamental natural frequency measured from displacement spectra have been determined as 0.7Hz, 1.1Hz and 2.6Hz for maize, oats and OSR respectively. The values obtained from measurements of oscillations of plants are somewhat different to these, due to plant interaction.
- Mean damping ratios for maize and oats are 0.13 and 0.11 from the spectral measurements with the manually oscillated plant measurements being similar, whilst the mean damping ratio for OSR is 0.13 from spectral measurements and 0.22 from the manually oscillate plants.
- The results for natural frequency and damping indicate that canopy interlocking in the OSR crop significantly damps the oscillatory response of a representative plant compared to maize and oats in which canopy interlocking is not as pronounced.
- Mean values of drag area / plant are $0.153m^2$, $0.021m^2$ and $0.09m^2$ for maize, oats and OSR respectively. The values for this parameter show considerable scatter between datasets.
- The parameter values are consistent with those obtained for wheat in earlier investigations.
- Matching solutions of the differential equation for displacement with independent measured data requires parameter values that fall within or close to the measured ranges.

- These calculations also indicate that there may be considerable 'friction' within plant canopies that dampens out plant movement at low wind speeds.
- Further the calculations suggest that to determine lodging velocities for OSR a much simpler methodology could be used, where the response can be modelled in a quasi-steady way, with the canopy moving directly in phase with velocity fluctuations.
- Using the average values of the dynamic and aerodynamic parameters to calculate stem lodging velocities shows that these are approximately equivalent to 10m average wind speeds of 11m/s to 15m/s for the three crops, within the normally defined range for strong winds.
- The sensitivity of the lodging velocities to the uncertainties in the measured dynamic and aerodynamic parameters leads to an uncertainty in lodging risk of the order of one order of magnitude. By contrast, uncertainties in the measurements of stem strength and radius lead to risk uncertainties of approximately two orders of magnitude.

The work described in this paper is one aspect of a number of linked projects that are investigating lodging in various crops in various parts of the world. Future papers will describe how the calibrated lodging model is incorporated into a GIS based model to characterise the spatial distribution of the risk for both stem and root lodging.

Acknowledgements

This study was made possible by funding grants from the British Biology and Biosciences Research Council Global Challenges Research Fund (GCRF BB/P023282), Sustainable Agriculture Research and Innovation Club (SARIC BB/P004555) fund and Teagasc (Walsh Fellowship) the Agricultural and Food development Authority of the Republic of Ireland.

Dedication

This paper is dedicated to one of the authors, John Finnan, who died in an aircraft accident during the course of the research. John's expertise and input was instrumental for the agricultural elements of the research on oats. However, John also had an uncanny knack of delivering a constructive and well-timed challenge on the wind engineering aspects of the research, thereby ensuring that those authors who claim to profess such expertise reflected long and hard on how their message could be delivered more appropriately – something which is key to ensuring successful trans-disciplinary research. Perhaps this is something that we all might like to reflect on as subject boundaries become less opaque – he would have liked that.

References

Baker, C., (1995). The Development of a Theoretical Model for the Windthrow of Plants. *Journal of Theoretical Biology*, 175, pp 355-372

Baker C J, Bell H J (1992) The aerodynamics of urban trees" Journal of Wind Engineering and Industrial Aerodynamics 41-44, pp 2655 - 2666

Baker, C., Berry, P., Spink, J., Sylvester-Bradley, R., Griffin, J., Scott, R., Clare, R. (1998) A Method for the Assessment of the Risk of Wheat Lodging. *Journal of Theoretical Biology*, 194, pp 587-603

Baker C., Sterling, M., Berry, P., (2014) A generalised model of crop lodging. *Journal of Theoretical Biology*, 363 pp 1–12.

Berry, P.M., Spink, J.H, Griffin, J.M., Sylvester-Bradley, R., Baker, C.J., Scott, R.K. and Clare, R.W (1998). Research to understand, predict and control factors affecting lodging in wheat. *Home-Grown Cereals Authority Research Project No. 169*.HGCA, London, 131pp.

Berry, P.M., Griffin, J.M., Sylvester-Bradley, R., Scott, R.K., Spink, J.H, Baker, C.J., and Clare, R.W (2000). Controlling plant form through husbandry to minimise lodging in wheat. Field Crops Research 67, 59-81.

Berry, P. M., Griffin, J. M., Sylvester-Braley, R., Scott, R. K., Spink, J. H., Baker, C., Clare, R. W. (2000). Controlling plant form through husbandry to minimise lodging in wheat, *Field Crops Research*, 67, pp 59–81.

Berry, P. and Spink, J., (2012) Predicting yield losses caused by lodging in wheat. *Field Crops Research*, 137, pp. 19-26

Berry, P., Sterling, M., Baker, C. J., Spink, J. H., Sparkes, D. L. (2003). A calibrated model of wheat lodging compared with field measurements, *Agricultural and Forest Meteorology*, 119, pp 167-180.

Berry, P. M., Sterling, M., Spink, J. H., Baker, C. J., Sylvester-Bradley, R., Mooney, S., Tams, A., and Ennos, A. R., (2004). Understanding and reducing lodging in cereals. *Advanced Agronomy*, 84, pp 215-269.

Berry, P., Sterling, M., Mooney, S. J. (2006). Development of a Model of Lodging for Barley. *Journal of Agronomy & Crop Science,* 192, 151-158.

Berry, P., Blackburn., A, Sterling, M., Miao, Y., Hatley, D., Gullick, D., Joseph, G., Whyatt, D., Soper, D., Murray, J., and Baker, C. J (2019) A multi-disciplinary approach for the precision management of lodging risk. 12th European Conference on Precision Agriculture, 8-11 July 2019. Montpellier, France.

Boldes U, Colman J, Marañón Di Leo J (2001) Field study of the flow behind single and double row herbaceous windbreaks, Journal of Wind Engineering and Industrial Aerodynamics 89, pp 665-687

Boldes U, Golberg A, Marañón Di Leo J, Colman J, Scarabino A (2002), Canopy flow and aspects of the response of plants protected by herbaceous shelterbelts and wood fences, Journal of Wind Engineering and Industrial Aerodynamics 90, pp 1253-1270

Boldes U, Scarabino A, Marañon Di Leo J, Colman J, Gravenhorst G (2003) Characteristics of some organised structures in the turbulent wind above and within a spruce forest from field measurements, Journal of Wind Engineering and Industrial Aerodynamics 91, pp 1253-1269

Challinor, A. J., Simelton, E. S., Fraser, E. D. G, Hemming, D. and Collins, M. (2010), Increased crop failure due to climate change: assessing adaptation options using models and socio-economic data for wheat in China. *Environmental Research Letters*, 5 (3), pp 1-8

Clough, R. W., Penzien, J. (1993). Dynamics of Structures. McGraw-Hill Education

Cook N J (1985) The designer’s guide to wind loading on building structures. Part 1, BRE, Butteworths

Crook, M. J. and Ennos, R., (1993) The Mechanics of Root Lodging in Winter Wheat, Triticum aestivum L. *Journal of Experimental Botany* 44(7) pp 1219-1224.

Flint-Garcia S., C. Jampatong, L.L. Darrah, McMullen, M., (2003) Quantitative trait locus analysis of stalk strength in four maize populations. *Crop Science*, 43, pp 13-22.

Finnigan, J. J., (2000) Turbulence in plant canopies. *Annual Reviews in Fluid Mechanics* 32, pp 519-571.

Hiraoka H (1993) Modelling of turbulent flows within plant/urban canopies, Journal of Wind Engineering and Industrial Aerodynamics 46–47,pp 173-182

Hiraoka H, Ohashi M (2008) A (k–ε) turbulence closure model for plant canopy flows

Journal of Wind Engineering and Industrial Aerodynamics 96,pp 2139-2149

Katul, G., Hsieh, C., Sigmon, J., (1997) Energy-inertial scale interactions of velocity and temperature in the unstable atmospheric surface layer. *Boundary Layer Meteorology* 82, pp 49-80.

Kendall, S., Holmes, H., White, C., Clarke, C., Berry, P., (2017) Quantifying lodging-induced yield losses in oilseed rape. *Field Crops Research*, 211, pp. 106-113

Lai, T., Yi, T., Li, H., and Fu, X., (2017) An Explicit Fourth-Order Runge–Kutta Method for Dynamic Force Identification. *International Journal of Structural Stability and Dynamics* 17(10), pp. 1-21

Mohammadi, M., Finnan, J., Baker, C., Sterling, M. (2020) The potential impact of climate change on oat lodging in the UK and Republic of Ireland, Advances in Meteorology, 2020, 4138469, 16p.

Panofsky, H. and Dutton, J. (1984) Atmospheric Turbulence. John Wiley & Sons, New York, 397 p.

Py, C., De Langre, E. and Moulia, B. (2006) A frequency lock-in mechanism in the interaction between wind and crop canopies. *Journal of Fluid Mechanics*, 568, pp.425-449.

Rhee D, Lomardo F (2018) Improved near-surface wind speed characterization using damage patterns, Journal of Wind Engineering and Industrial Aerodynamics 180, pp 288-297

Roodbaraky H J, Baker C, Dawson A, Wright C (1994) Experimental observations of the aerodynamic characteristics of urban trees, Journal of Wind Engineering and Industrial Aerodynamics 52, pp 171-184

Sterling, M., Baker, C. J., Berry, P. M., and Wade, A. (2003). An experimental investigation of the lodging of wheat. Journal of Agricultural and Forest Meteorology. Vol. 119, Issues 3 –4, 149 – 165.

Sterling, M., Baker, C.J., Joseph, G., Gillmeier, S. Mohammadi, M., Blackburn, G., Whyatt, D., Gullick, D., Berry, P., Hatley , D., (2018) Mitigating yield losses due to lodging of cereal crops, International Workshop on Wind-Related Disasters and Mitigation, Japan.

United Nations (2019) Sustainable Development Goals, https://www.un.org/sustainabledevelopment/sustainable-development-goals/

Appendix

This appendix presents details relating to the framework adopted in the tracking program which was developed in-house by Dr S Gillmeier using the Image Processing Toolbox' and the 'Statistics and Machine Learning Toolbox' available in MATLAB (https://uk.mathworks.com/). The developed code uses the MATLAB HSV (Hue Saturation Value) colour model to read the input video file which is in RGB (red green blue) format and set to detect red pixels in the video frames (Figure A1). A different colour filter could have been applied but red was chosen since it provided an appropriate contrast with the plants. Using hue, saturation and value thresholds corresponding to the HSV ranges of the target red colour in the video file, the colour model masks other colours and outputs a binary image of the target for each frame. In which the areas of detected targets is marked with ones (indicated in white in figure A2a) and the rest of the figure is marked with zeros (indicated in black in figure A2a). A filtering operation is used to isolate the region with the highest concentration of red pixels by eliminating small pixel clusters below a specified size tolerance (Figure A2b); these may arise from objects in the background and would otherwise skew the centre of mass of the target region. The code then calculates the centroid of these isolated pixels relative to the image space in each frame of the video object (indicated with a red cross in figure A2c, corresponding to the red cross in figure A1). As the video reader steps through the frames of a video file, a two-dimensional array of centroid coordinates is created. If the target is not detected, the tracking code records a NaN value. Correction steps have been implemented in the code to account for strong wind conditions when the target is deflected out of the field of view of the cameras; these steps replace NaN values with centroid coordinates determined using the target's trajectory from its last recorded centroid position. In cases where the number of such values exceeded 2% of the record, the entire record is rejected.

The raw output of the tracking code is in the form of pixel displacement time histories in the along-wind and crosswind directions, Figure 5. Using the focal length of the camera lens, the image space occupied by one pixel, the distance of the target to each camera lens aperture and the pixel coordinates of the target at zero stem displacement (i.e. when the target plant is still), the pixel displacement can be converted to displacements in length units.

The MATLAB Camera Calibration App (https://uk.mathworks.com/help/vision/ug/single-camera-calibrator-app.html) was used in order calibrate each of the cameras, i.e., a checkerboard of known dimensions and two contrasting colours was created, positioned at various distances and angles from both cameras and multiple images from each of the cameras where created. This calibration was also supplemented by a rather simple experiment which involved placing a number of different colour dots (of various sizes) on a target and moving the target at a given rate in a known direction with a known velocity, and also by measuring the static deflections of marked crops in wind tunnel conditions.

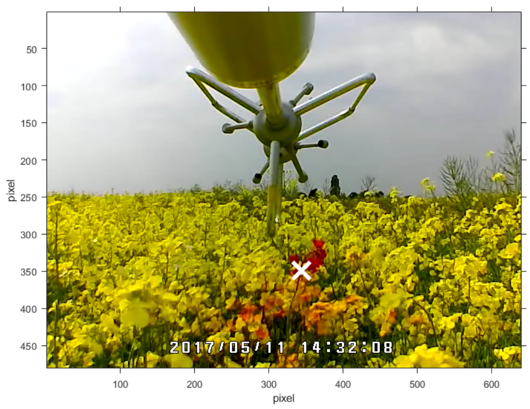
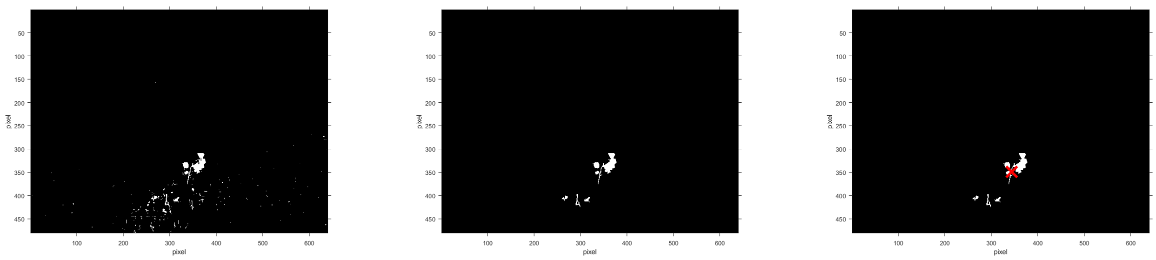


Figure A1: Image of red pixel centroid tracking in a single video frame (OSR flowering)



(a) (b) (c)

Figure A2 Steps in the video analysis procedure