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The Nature of Winds Approaching and Passing Over Shelter Systems

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ABSTRACT

Land undulations cause wind shear which change the turbulence of surface winds; higher r.m.s. turbulence intensities can reach shelter systems. Turbulence estimates are found from the average size of terrain. In horticultural areas turbulence intensities over land may be nearer 40% than 10%. Wind turbulence is graphically depicted on the Van der Hoven spectrum. The high frequency end of this spectrum, which causes wind damage, is distorted by diurnal air temperature changes and more significantly by mechanical wind shear caused by land undulations. This end of the spectrum shifts to the right and upwards for more complex terrain. When winds pass through shelter systems the mean windspeed vertical profile is distorted from the exponential shape. Maximum shear at the first shelterbelt induces maximum turbulence: continual shear generated at successive shelterbelts produces further turbulence and steady vortices. These air motions can induce large plant sway motions as they are closer to plant resonant frequencies. Horticultural shelter systems must reduce mean and turbulent winds by optimised shelterbelt geometry or increased crop resonant frequency.

INTRODUCTION

Variations in earth surface roughness, no matter how small or large, change the turbulent characteristic of the boundary-layer winds passing over the surface. Upwind of shelter the earth's physical roughness varies from 0 m to 1000 m where horticulture is dominant, so r.m.s. turbulent wind speeds can range from 10% to more than 40% above or below mean wind speeds prior to reaching shelter systems.

R.m.s. turbulence intensities can be deduced from the average size of the upwind terrain. Measurements of the roughness effects on wind characteristics have allowed terrain roughness to be classified, ESDU (1974) using 'aerodynamic' roughness heights, normally about 1/10 of the upwind terrain mean physical height variation. Over the Kaimais expected turbulence intensities would be near 30% approaching shelter systems in the horticultural area. Turbulence intensities of 10-15% would come off the Pacific Ocean.

The frequencies of occurrence of turbulent gusts have been examined from very short to very long periods and are graphically represented on the Van der Hoven spectrum of wind frequencies. Air temperature causes bouyancy forces which supplement mechanical mixing caused by terrain changes, altering the right-hand hump of this spectrum. This end of the complete spectrum of wind frequencies represents the damaging energy in wind turbulence approaching any shelter system, Fig.1. The peak of this high frequency spectrum moves to the right and upwards for more complex terrain.

THE SURFACE WIND BOUNDARY-LAYER

The planetary boundary-layer is a region of air movement existing in the lowest part of the broadscale air movements of the atmosphere, which has 75% of its mass below 10 km and 50% below 5.7 km. The air currents result from the differences in solar heating of the earth's surface. The resulting pressure gradient, together with the earth's rotation, produce the wind system present in the free atmosphere.

The lowest 10% of the planetary boundary-layer, the surface boundary-layer, is about 300 m thick. The properties of the air in the surface boundary-layer are related to the properties of the surface by vertical exchange of air momentum which in turn distorts the horizontal wind vectors. Here Coriolis wind direction changes with height are small and can be ignored. Within the surface layer there are two regions with differing properties; an outer layer above the surface roughness in which there is little vertical variation of shear stress or wind direction and an inner or interfacial layer that forms within the depth of any surface roughness with a linear change in shear stress. Turbulence variations in these two lower layers are taken as the prime scaling factor; the eddies interlock and form feedback processes with the related surface as exchange of mass and energy take place. Fluctuations in winds of less than 15 mins are treated as turbulence while fluctuations over longer periods form part of the hourly mean wind speed. Measurements of the mean wind variations with height provide the mean wind profiles, while turbulence changes near the ground, treated statistically, provide horizontal and vertical turbulence intensity profiles and frequency distributions (or spectra).

In the planetary layer as a whole, the power law can be used to define the wind profile which changes with mean terrain roughness, Davenport (1967). Near the ground in open level country or over rough terrain, the logarithmic law defines the mean wind profile. The logarithmic law and the power law are linked by the relation $\alpha = 1/(\ln(z+z_o)/z_o)$, Panofsky (1972).

Davenport (1962) summarises the available information on the power law index, α, for heights 150 m to 300 m above the ground. α increases with roughness and is about 0.22 in open country with high surface roughness. Within shelter systems the power law is of limited use since high aerodynamic roughness (z'_o) and changes in roughness (z'_o/z_o) reshape the velocity profile above high roughness. The power law is used to find the wind forces on tall structures in the rural boundary-layer; nearer the surface interface the logarithmic law applies over open country land surfaces or high even roughness such as forests, Papesch (1984).

Very close to the ground and below the mean height of the roughness geometry, resultant wind speed direction veers because of the net effect of the static pressure and the shear stress distributions just above the stagnant air. Between this zone and the rest of the inner and outer layers, wind direction is considered constant with height up to ≅300 m. So wind direction is related to average terrain roughness, terrain slope and the influence of any major obstructions such as shelterbelts and large buildings.

TURBULENT WND CHARACTERISTICS

Wind speed varies continuously and the amplitude and frequency of its fluctuations vary randomly. Turbullence in viscous fluids is generated as a result of shearing velocity gradients which occur close to any solid boundaries or between air streams flowing at different velocities. These turbulent motions dissipate kinetic energy by viscous action to heat energy to maintain balance. Without shear flow inducements such as a change of roughness height or spacing, a change of terrain, temperature gradients or roughness movement, mechanical turbulence is inertially transferred from larger eddies to smaller, high frequency eddies and finally heat. The term 'size' is used to quantify the 'average' diameter of the rotating eddy masses which produce turbulence. The 'intensity' of turbulence is the ratio of the r.m.s. fluctuating velocity x-component ($\sqrt{u'^2}$, or σ_u) to the mean flow velocity at any instant in that direction. It is proportional to the average of the angular velocities of all the eddies passing a fixed point. Eddies of equal size produce different intensities of turbulence depending on their speed of rotation. The kinetic energy of large eddies is much greater than that of small eddies for a given turbulence intensity, but larger eddies may only affect plant motions just like mean winds, while smaller eddies with angular velocities close to plant resonant frequencies may cause large plant sway motions.

The total wind velocity, the mean wind velocity $\bar{U}$ and a fluctuating wind component, u', is $U = \bar{U} + u'$. $\bar{u}'^2$ is the variance and σ_u is the standard deviation or r.m.s. amplitude of the fluctuating components. The averaging technique, although suspect over abrupt roughnesses where accelerations and pressure changes are rapid, has not been replaced by a better method. $\sigma_u/\bar{U}$ is equal to α, the index in the power law for strong winds, increasing with higher roughness length and decreasing height.

In brief, the properties of wind turbulence are:
- the motions are unpredictable in detail;
- the fluctuations are three dimensional;
- evenly mixed in the fluid (isotropic);
- mechanical turbulence is maintained by shear;
- shear stress is proportional to average eddy size and also to the mean velocity profile;
- viscose shear is small;
- positive atmospheric stability damps low frequency turbulence.

SPECTRA OF SURFACE WIND TURBULENCE

All types of eddies exist in mechanical turbulence of surface winds and are sub-divided as follows:

<u>convectional eddies</u> - caused by convection due to vertical temperature changes;
<u>wave eddies</u> - formed when masses of air, moving with different velocities, meet;
<u>frictional eddies</u> - formed when masses of air pass over rough surfaces;
<u>splashing eddies</u> - formed where an air mass strikes an obstacle (for example, a shelter system border), and breaks up into smaller moving masses.

Within each of these groups some eddy sizes dominate over other sizes; the turbulent wind spectra alter shape and spectra peaks occur where most eddies of a similar size, group. Roughness changes and breaks in land or shelter systems produce spectral peak frequency shifts and even flatten the peak. The turbulent wind components are greatly distorted with a considerable amount of their energy at low frequencies. The low frequency energy persists after traversing large blocks of shelter or negotiating abrupt shelter height changes. The spectra possess 'memory' or consistent distributions, because of changes in upstream terrain or temperature gradients. Spectra have
- wavelengths which are very small relative to obstacles such as shelter systems reaching rapid equilibrium over homogeneous surfaces;
- wavelengths which are large relative to obstacles such as shelter systems remaining unchanged over homogeneous terrain;
- a peak for horizontal eddy components which moves to lower frequencies if flow is uphill, and to higher frequencies if flow is downhill;
- vertical eddy components with a consistent level of peak energy containing less low frequency energy and rapidly reach equilibrium with the homogeneous terrain;
- high levels of turbulence at low frequencies because of large scale terrain changes and any vertical temperature gradients upstream;
- skew, caused by small scale roughness such as shelter geometry or by interaction of the wind with the flexible surface geometry of the plants;
- variable high frequency energy levels which are evident from the outer layer, through transition, to the inner layer over high roughness.

To interpret these properties, spectra are divided into three parts: the low frequency range containing most of the kinetic energy; the inertial higher frequency range; and the dissipation range or Kolmorgorov region. The inertial range transfers energy from the low frequency range to be dissipated as heat in the high frequency region. In the inertial range turbulence is more isotropic than in the low frequency region and very little energy normally enters directly from the atmosphere. Structural motions occur at frequencies within the inertial range and can act as a momentum source to distort the spectra, Finnigan and Mulhearn (1978). A spectral curve of the Gaussian shape with the variance calculated as a function of wind frequency, n, is given in Fig.1.

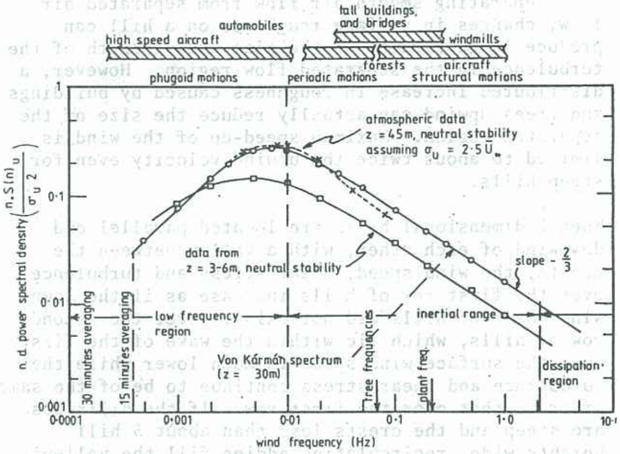

Fig.1: u'- component power spectra (surface layer).

15 minute wind spectral analysis give distributions of the wind variance over the full range of turbulent (mechanically generated) frequencies. At each frequency bandwidth Δn, the variance is

$$\sigma_u^2 = \int_0^\infty \left(\frac{\sigma^2_{u\Delta n}}{\Delta n} \right)_u \cdot dn \ ,$$

where $\sigma^2_{u\Delta n}$ is the mean square value of the fluctuations within the bandwidth at a centre frequency n_c. The quantity $\sigma^2_{u\Delta n}/\Delta n$ is known as the power spectral density and is denoted by $S(n)_{n=n_c}$, and so

$$\sigma_u{}^2 = \int_0^\infty nS(n)\ d(\ln) .$$

Each frequency bandwidth is treated statistically independent of other bandwidths and, for linear processes, the output dynamic response of a structure is found by multiplying the input wind energy at centre frequency by a response function, Davenport (1967); Solari (1982)).

The total spectral variance (the area of spectral distribution nSn versus ln(n)) increases with increasing mean wind speed, roughness and depth of the surface layer. Other mechanical and convective momentum and/or heat sources and sinks contribute to the distortion of this usually Gaussian spectra, such as mean wind accelerations over hills and other large obstacles, pressure changes at the earth's surface and the movements of structures such as tree or crop motion immersed in the surface layer. A method of calculating structural deflections proposed by Solari (1982) and based on previous work by Davenport (1967) has been used to assess tree response, Papesch (1984). Approach spectra shapes and distributions are well documented for various terrain types, ESDU (1974).

TOPOGRAPHY EFFECTS ON SURFACE WINDS

J.C.R.Hunt (1980) describes how 2 and 3 dimensional hills change the surface wind. Downwind of hills (or shelterbelts) on their lee side air pressure rises. For moderate hill slopes (1:5) the air flow separates intermittently while for steeper slopes (>1:3) it separates continuously. The region of separated flow extends up to 10 hill heights downwind and up to 2 hill heights vertically upwards. Associated eddying motions can extend beyond 2 hill heights vertically. The separated flow is similar to that behind any bluff obstacle, such as a fence, shelter system or building. The mean velocity reduces and there is vigorous turbulence within the separated region. From Hunt, Cox (1977) observed that trees on the crest of an escarpment thicken this region markedly. As flow depends critically on the shear stress and velocity near the line separating smooth air flow from separated air flow, changes in surface roughness on a hill can produce large effects on the size and strength of the turbulence in the separated flow region. However, a distributed increase in roughness caused by buildings and trees upwind can actually reduce the size of the separated region. Maximum speed-up of the wind is limited to about twice the upwind velocity even for steep hills.

When 2 dimensional hills are located parallel and downwind of each other, with a valley between the crests, the wind speed, shear stress and turbulence over the first row of hills increase as if the downwind chain of hills did not exist. Over the second row of hills, which lie within the wake of the first row, the surface wind speed is much lower while the turbulence and shear stress continue to be of the same order as that over the first row. If the hillsides are steep and the crests less than about 5 hill heights wide, recirculating eddies fill the valleys. When the winds have components parallel to the ridges or valleys, then flow along the valleys may develop. Such winds may promote mixing in the valleys but are unlikely to be faster than the winds on the hill crests. The velocity profile over the crests assume a new logarithmic form above the hill crests while turbulence reduces rapidly up to about 3 hill heights.

These hill effects on surface winds may similarly occur within smaller scale shelter systems.

SHELTER SYSTEM EFFECTS ON SURFACE WINDS

Isolated buildings, trees and hills experience winds with turbulence intensities from 10% to 40% depending on their location and the general upwind 'aerodynamic' roughness (z_o). The eddies are larger than the obstructions and so increment the mean wind drag forces. If obstructions are elastic and able to store strain energy, they oscillate with damping motion. The first shelter belt of a shelter system is affected in this way. The forces from turbulent wind speed components are low because their eddy sizes are much larger than the physical heights of shelterbelts or buildings. Incident turbulent wind loads on the first shelterbelt add about 25% more wind force to this first shelterbelt.

On passing over a shelter system the mean wind speed profile is drastically changed. Full recovery to the original boundary-layer exponential shape returns around 15H to leeward of the system. The mixing process which assists the boundary-layer to return to its original shape is decreased as the side width of the system is increased from say ½H to 10H. Also the wind drag forces can double on the shelter system with more side width. As increased shelterbelt porosity rises from 0% to 100% the shearing process and isotach divergence reduces. Mean winds within shelter systems are reduced by 1/3 to 1/5 of their upwind values at mean crop height, Raine and Stevenson, (1977).

Air turbulence at crop height is produced where there is shear or relative motion between adjacent air layers upwind. Shelterbelts add shear and produce new eddies of greater rotational speeds and smaller sizes. These small eddies have more kinetic energy closer to crop natural periodicity. This eddy production starts just 'upwind' and slightly below mean shelterbelt height and continues for about 2½-3H downwind of each shelterbelt. This high frequency turbulence generation is supplemented at each successive downwind shelter barrier, Cionco, (1983). The eddies traverse downwind with the bulk flow producing enough high frequency eddies to cause large crop sway motions. If the air filters through a porous shelter system, which for both artificial and natural shelter depends on the shelterbelt gaps or hole sizes, crop sway reduces.

Acceleration and deceleration of adjacent air layers through an array of shelterbelts (a shelter system) will continually create turbulent eddies. This alters the spectra shapes within shelter systems with higher kinetic energy components in the inertial region producing still larger shelterbelt and plant sway motions. Wind forces due to the turbulent eddy velocities even though they are of the same instantaneous magnitude as equivalent mean wind forces, can now induce much higher crop sway motions. Shear caused by artificial barriers may be more severe and the eddies formed may be more even in size and may rotate faster. This may give 'discrete' band widths of kinetic energy, perhaps concentrated at the crop natural frequency or the support structure frequency. Gusts with wavelengths similar to the shelter system row spacings, may become trapped and produce devastating crop damage.

Seginer (1972) and Raine and Stevenson analysed winds through single shelterbelts. Counihan (1971) has extended measurements to more complex systems. It appears that increases in space between forested trees do not produce a gradual reduction in turbulence levels. Also, in shelter systems a critical spacing of each shelterbelt could generate more turbulence even though mean wind speeds were lowered. A peak in 'aerodynamic' roughness and turbulence occurs for element spacings near half of roughness mean height to space ratio (Counihan, Fig.2).

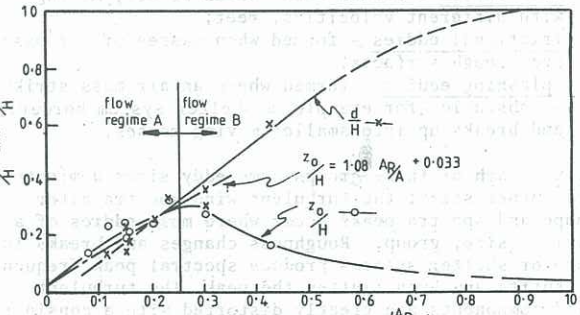

Fig.2: Roughness and zero plane displacement v spacing

Similarly, Shaw and Pereira (1982) by modelling, Maitani (1979) over maize, Holbo (1980) in a conifer forest and Papesch (1984) in full scale and model forests, relate resonant components of crop sway motion to increments in the spectra caused by crop density changes, Papesch and Miller (1986), Fig.3.

Increases in aerodynamic damping caused by large leaves or plant stems and fruit mass may cause large reductions in the resonant frequencies of the plants, reducing sway motion, Finnegan and Mulhearn, Fig.4.

Shelterbelt studies by Raine et al depicted wind

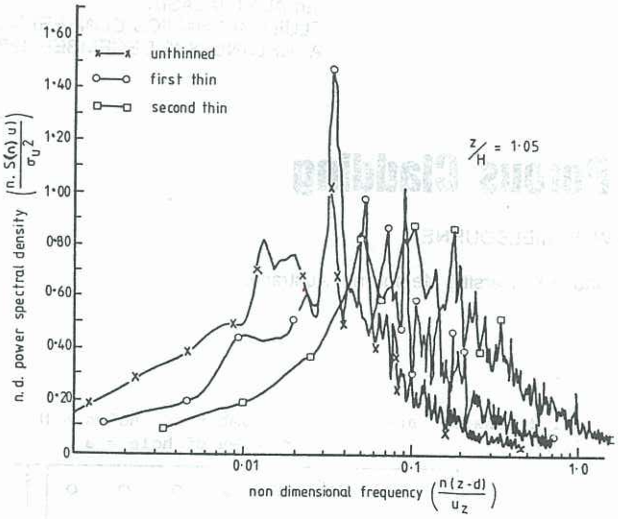

Fig.3: Full scale wind spectra at mean forest height.

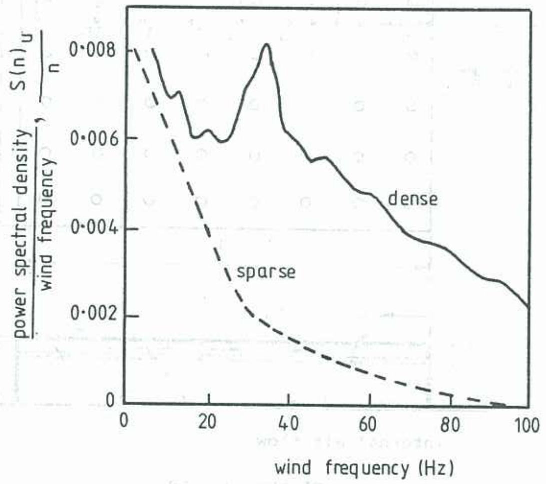

Fig.4: u'- power spectra in two aeroelastic model canopies of different densities.

energy spectral distribution shifts to higher frequencies behind a single barrier. In a shelter system, additional shelterbelts downwind must, because of additional shear, generate even higher eddy energy levels with higher frequencies. The advantage of reducing the mean wind speed is lost because turbulent winds are able to sway the crops more readily. Also, tall crops stretching above the mean canopy height of the crop transmit motions to the plant and support systems and may produce the secondary effect of fruit wind rub.

Wind damage to crops such as Kiwifruit plants is affected by the spacings of the individual barriers in shelter systems composed of both artificial and natural shelterbelts. The highest wind damage occurs upwind and in front of the natural shelter barriers and behind the lower height artificial barriers. This may be because of trapped vorticity, McAneney and Judd (1984).

CONCLUSIONS

To reduce wind damage to crops within shelter systems research must:

- balance mean and r.m.s. sway movement of plants projecting above the mean crop height;
- reduce the absolute values of both mean and turbulent wind speeds that are economically practical without affecting other ecological processes which hinder fruit productivity;
- optimise shelterbelt height, porosity, hole size, spacing, flexibility and mass distribution;
- alter genetically plant size and shape to maximise aerodynamic and mass damping;
- engineer plant support systems to reduce crop effective length;
- balance the use of artificial and natural shelter systems to reduce high concentrations of vorticity in localised areas within shelter systems;

There is a place for both artificial and natural shelterbelts on horticultural farms provided they are complimentary and do not reinforce wind turbulence causing higher wind damage to the cash crops. Natural shelter should be the primary means of sheltering crops, while artificial shelter should be used with discretion in localised secondary areas, at corners or breaks in the shelter system. Horticulture shelter systems whether composed of artificial or natural barries, will provide physical protection from wind damage for high value, less hardy crops such as Kiwifruit and citrus plants provided their geometry is made optimum.

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