PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY B BIOLOGICAL SCIENCES

Windthrow [and Discussion]

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Windthrow

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The factors that influence storm damage in forests are summarized and the four kinds of storm damage in forests are presented. Two equations for the estimation of windloads are explained including the problems that their use involves. By use of wind-induced bending moments of trees the occurrence of windbreakage or windthrow is discussed.

The response of trees to windloads is mostly in form of damped bending sways. Based on artificial force effects, their shapes are shown to be dependent on soil conditions. If trees are continually exposed to dynamic windloads the shape of their sways is irregular at first sight.

During strong winds and storms, the most important load on trees is generally stochastic and can be analysed by the spectral method. Based on this method, results from experimental investigations on wind-induced sways of tall spruce trees within a stand are shown, including power spectra of Reynold's stress as measure of windload, stem accelerations as measures of tree response, and magnitudes of mechanical transfer functions. The main result is that conifers such as spruce trees can be compared to a narrow bandpass filter, i.e. they can take in energy from the turbulent wind field only at a certain frequency range.

1. Introduction

Windthrow as a kind of storm damage in forests is a serious problem in British forestry as well as in other European countries because storm damage in forests is a major source of economic loss (Rottmann 1986). The types of storm damage to woodland and non-woodland trees are known from numerous observations and photographs (see for example, Quine 1988).

Storm damage in forests generally depends on the following factors (see Coutts 1986; Mayer 1985; Petty & Worrell 1981; Petty & Swain 1985; Savill 1976).

1. Meteorological conditions, especially storms with reference to wind speed, duration, and gustiness as well as the precipitation sums for soil moisture.
2. Site and soil type.
3. Terrain.
4. Stand characteristics, such as stand height, composition of tree species, stand density, diameter at breast height, and crown length,
5. Physical condition of trees, including diseases such as 'red ring rot'.

2. Kinds of storm damage in forests

In principle, there are four kinds of storm damage in forests (Mayer 1985) (figure 1): (1) stem breakage; (2) stock (base of stem) breakage; (3) root breakage; and (4) tree throw.

It is sometimes difficult to distinguish between these different kinds of storm damage. For example, in many cases root breakage cannot be distinguished from tree throw unless the root

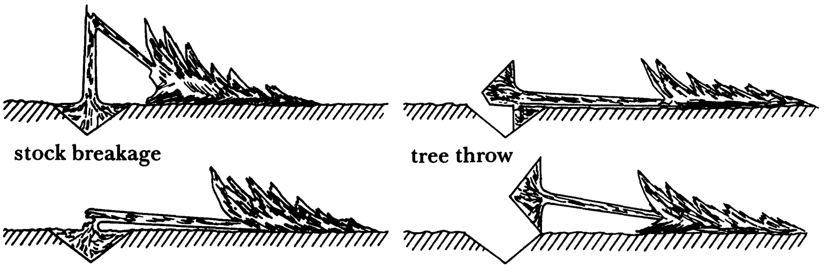

FIGURE 1. Types of storm-induced damage in forests (Mayer 1985).

system has been analysed. Therefore the only distinction usually made is between wind breakage (namely stem breakage and stock breakage) and windthrow (namely root breakage and tree throw).

Literature concerning physical threshold values of storm damage in the form of wind breakage or windthrow and their relation to tree species, stand and site is lacking (Mayer 1987). Such threshold values should consider the factors that influence storm damage in forests, listed above.

The following observations arise from mapping of storm damage in forests (Mayer 1985).

1. Stock breakage and stem breakage occur after brief windloads of great force, such as during tornadoes or thunderstorms where the windload is greater than the breaking stress of wood.

2. Tree species, such as fir or pine, with vertical roots or main roots that extend deeply, are damaged mainly by stock breakage or stem breakage.

3. If the soil is frozen or very dry, storm damage mostly occurs in the form of stem breakage or stock breakage.

4. Storm damage in the form of tree throw or root breakage mainly occurs in trees with shallow prop roots, such as spruce, whereby the trees bend with damped swaying motion before damage occurs.

5. The moister the soil the greater is the probability of storm damage in the form of tree throw or root breakage; swaying with damped motion precedes damage. It is evident that swaying of trees is of great importance for windthrow.

3. WINDLOAD ON TREES

The principal requirement for predicting wind-induced tree swaying is to know the windloads, which can generally be estimated by use of a physical equation or an empirical formula. The starting point for the physical equation is the assumption that in the simplest case a free-standing coniferous tree changes the streamlines because it is effective as an obstacle to air flow. The wind force acting on the tree, the windload K_1, then is:

$$K_1 = \tfrac{1}{2}\rho_L C_D u^2 A, \quad (1)$$

where ρ_L is the air density, C_D is the drag coefficient, u is the wind speed and A is the projection area of the crown perpendicular to the air flow.

In principle, C_D, u, A and K_1 depend on the height, z. Problems involved with the experimental estimation of C_D are explained in detail by Mayhead (1973*a*). Among other factors he determined the dependence of C_D on windspeed u in the range $u \geqslant 10$ m s^{-1}. The regression lines in figure 2 show that drag coefficients of trees decrease with increasing u. In addition, C_D shows considerable variability between different tree species and remarkable variability even within the same tree species (Mayer 1987).

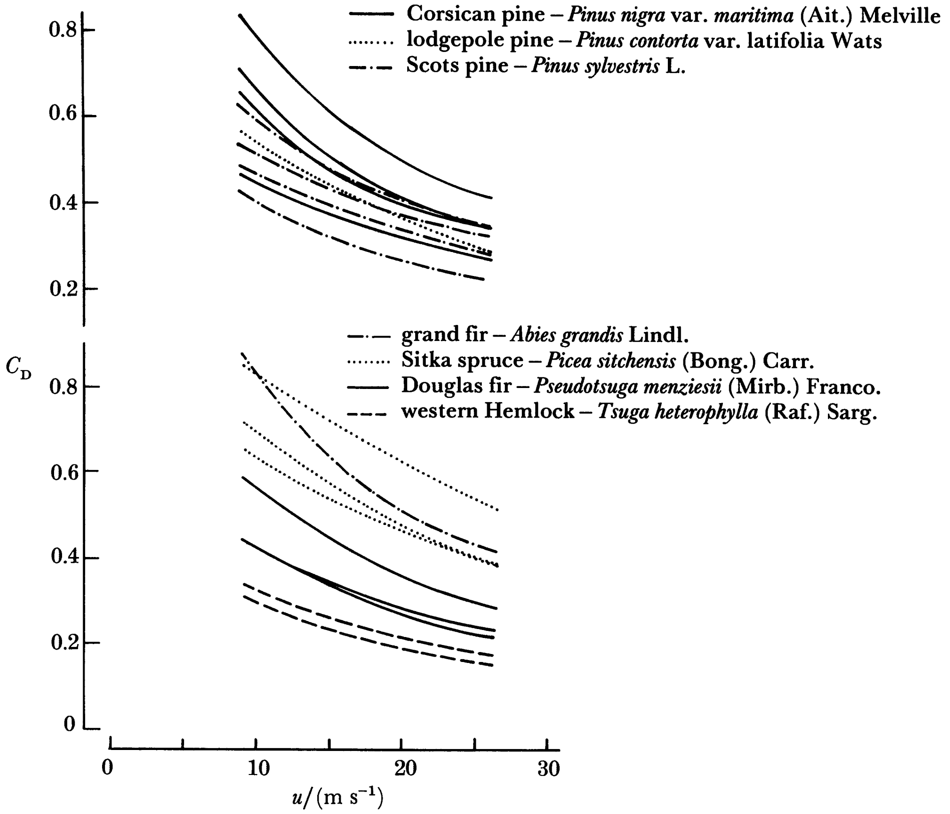

FIGURE 2. Dependence on wind speed, u of drag coefficients C_D for different tree species. (Mayhead 1973*a*).

However, it must be pointed out that for practical purposes it is nearly impossible to make use of equation (1) for calculating the windload because the actual values of C_D and A are not known.

An empirical formula for the windload on trees was found by Fraser (1964). Working on environmental factors that influence storm damage in forests, he experimented with a wind tunnel to analyse the relation between the effect of wind speed and windloads on conifers. In his investigations he assumed that the terms C_D and A are closely correlated with the tree mass. For wind speed not less than 10 m s^{-1} he found the following empirical relation between windload, K_1 (in Newtons), and wind speed, u (in metres per second), and tree mass, m (in kilograms):

$$K_1 = 12.46u + 0.552\,um - 3.22m + 33.06. \tag{2}$$

This equation has the advantage that the actual values of C_D and A are not needed. The disadvantage, however, of equation (2) is that this relation has been derived only for stationary windloads. Assuming the windload acts at the centre of gravity of the crown (figure 3), a bending moment, M_W, owing to the windload is generated, which can be calculated by:

$$M_W = K_1 h_k, \tag{3}$$

where h_k is the height of the centre of gravity of the crown above the tree base. Assuming that K_1 is constant, M_W decreases with increasing crown deflection because h_k becomes lower.

If the stem is deflected by the windload, a second bending moment, M_B, owing to the crown weight, K_2, is induced:

$$M_B = K_2\, y, \tag{4}$$

where y is the stem deflection.

The third bending moment, not illustrated in figure 3, is the bending moment, M_S, owing to the mass of the bent tree stem. M_S can be obtained by dividing the stem into segments and calculating the product of mass and horizontal deflection for each segment. The sum of these products gives the total moment M_S. The mass can be estimated from the known stem volume and the value for wood density.

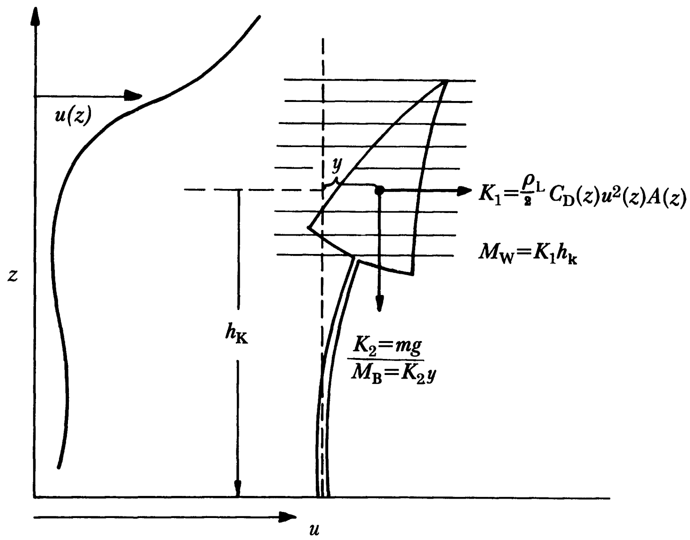

FIGURE 3. Schematic illustration of the windload on a tree and the resulting bending moments; for explanation of symbols see text (Mayer 1985).

The bending moment M_B contributed by the crown can be exactly calculated in a similar manner, if the distribution of mass in the crown is known.

By addition of M_W, M_B and M_S the total applied bending moment caused by the wind is obtained. This applied bending moment increases with increasing stem deflection. The greatest portion of the applied bending moment is M_W, the bending moment due to the windload, but the contributions of M_B and M_S are far from negligible (Petty & Swain 1985). Mayer (1985) gives an example for pine where M_W is equal to 100%, M_B 18.2% and M_S 21.3%.

The 'swaying tree' system has some resistive parts that include stem stiffness, the support given to the crown of a tree by contact with its neighbours, and root anchorage (Mayer 1985; Amtmann 1986). A measure of the stem stiffness is the elasticity of the wood. The more a tree bends, the greater the resistive bending moment owing to the elasticity of the wood becomes. If the applied bending moment of a tree exceeds the maximum value of the resistive bending movement due to the stem stiffness, wind breakage may occur. If the applied bending moment exceeds the maximum value of the resistive bending moment due to anchorage, windthrow may occur. This maximum value varies, depending on soil conditions.

4. Tree sways

The response of trees to windloads occurs frequently in form of swaying. In principle, conifers at great risk in storms, such as spruce or Douglas-fir, can essentially sway in four ways: (1) bending sways; (2) torsion sways; (3) longitudinal sways and (4) superposed sways. With trees swaying as a result of dynamic windloads, damped bending sways are most important (Amtmann 1986; Holbo *et al.* 1980; Mayer 1985).

The shape of damped bending tree sways can be analysed if a tree is affected by a single, brief force, which may be a wind gust or an artificial force. Extensive investigations on tree sways have been done in a British research programme in the past 20 years (see, for example, Mayhead 1973*b*) as well as by Amtmann (1986), Holbo *et al.* (1980) and Mayer (1985). In the investigations by Amtmann (1986) and Mayer (1985), stem accelerations have been chosen as measure of tree sways, and these accelerations can be recorded in a simple, but more exact, manner than stem deflections (Amtmann 1985). Stem deflections can be derived from stem accelerations by use of the Duhamel integral (Amtmann 1986).

Figures 4 and 5 contain examples of the shape of damped bending sways of a tall dominant spruce tree within the Ebersberger Forest near Munich, illustrated by the course of the orthogonal components a_1 and a_2 of the horizontal stem acceleration vector (Mayer 1985). The measuring height was not chosen arbitrarily but deliberately because, by physical modelling of damped beam sways, the measuring height in both figures was located near the node of the first harmonic.

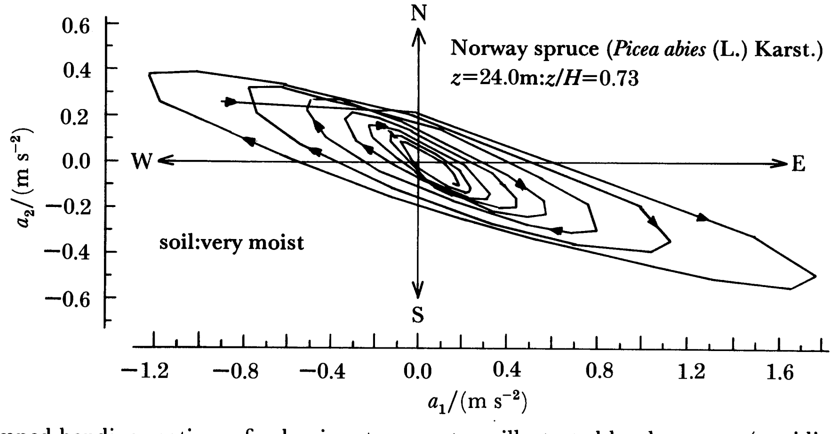

FIGURE 4. Damped bending motions of a dominant spruce tree, illustrated by the course (equidistant time intervals of 0.2 s) of the orthogonal components a_1 and a_2 of the horizontal stem acceleration vector; z, measuring height; H, stand height; very moist soil conditions (Mayer 1985). Ebersberger Forest, 21 June 1979.

The main difference between both tree pulling experiments lies in the soil conditions: one in a very moist soil (figure 4) and the other in a dry soil (figure 5). From both figures it can be concluded that the experimental tree showed damped bending sways in an elliptical form. Mayhead (1973*b*) and Mayer (1987) found this shape results from four factors.

1. Eccentricity of the crown or crown mass.

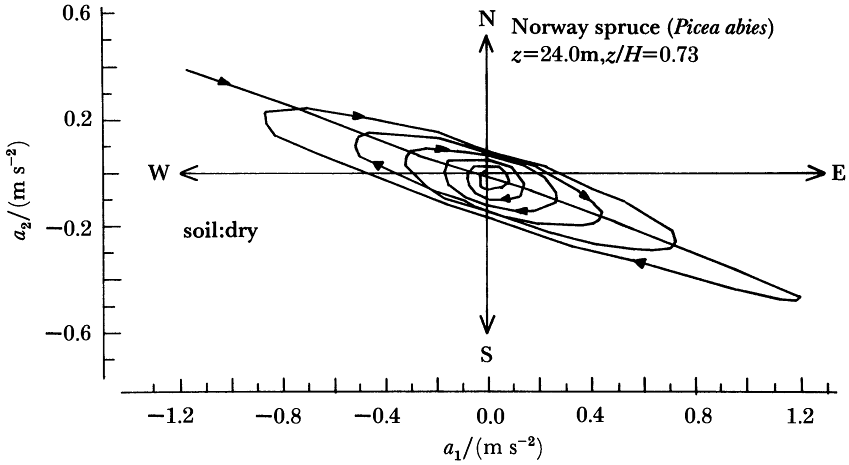

FIGURE 5. As for figure 4, but dry soil conditions (Mayer 1985). Ebersberger Forest, 25 July 1979.

2. Asymmetrical rooting of the spruce in the soil.
3. Deviation of the actual stem's sectional area from a circle.
4. Damping conditions of the spruce tree including wood elasticity, friction between crown and surrounding air as well as between roots and soil.

Also, figures 4 and 5 show that the artificially induced bending sways occurred without contact with neighbouring trees. When trees within a stand are swaying due to windloads, however, they frequently come into contact with neighbouring trees, which have a supporting effect, i.e. the swaying amplitudes become limited.

Summing up the results for the swaying period in figures 4 and 5, it can be stated that, in moist soil, tree swaying is marked by lower friction resistance of the roots than in dry soil: the tall dominant Norway spruce tree on a very moist soil had a 10% higher sway period than on a dry soil where the sway period was about 5.0 s.

The tree sway in figures 4 and 5, were caused by a brief artificial force. During strong winds or storms, however, trees are continually exposed to dynamic windloads. In principle, there are three possible types of tree response to windload resulting from a wind gust.

1. The tree does not sway. Then, because of a wind gust, a dynamic windload arises which induces damped tree swaying.

2. The tree sways in the direction of the acting dynamic windload, whereby an additional impulse on the tree motion is produced. In this way, the tree deflection can be enhanced considerably by a comparatively small windload.

3. The tree sways against the direction of the acting dynamic windload, whereby an additional, often abruptly arising, damping of the sway is produced. Subsequently, the tree often sways in the direction of the windload.

These rather generalized descriptions of wind-induced tree motions are modified in reality by temporal and spatial irregularities of the turbulent wind flow and other factors that determine tree motions (Amtmann 1986; Mayer 1985). The real response of a tall Norway spruce tree within a stand to windloads due to strong winds is illustrated in figure 6. Here, the shape of the tree motions is not as regular as in figures 4 and 5.

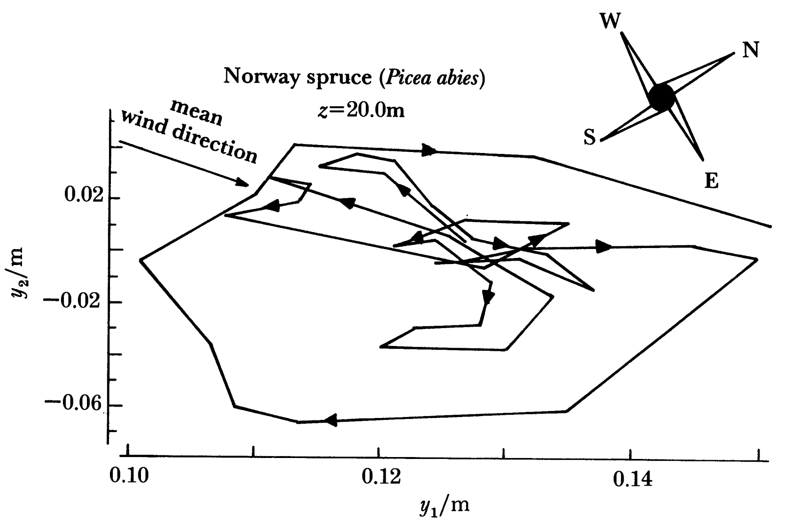

FIGURE 6. Damped bending motions of a Norway spruce tree due to dynamic windloads, illustrated by the course (equidistant time intervals of 0.4 s) of the orthogonal components y_1 and y_2 of the horizontal stem deflection vector; z, measuring height (Amtmann 1986). Forstenrieder Park, 30 May 1984.

5. Physical fundamentals for investigations on wind-induced tree motions

To analyse wind-induced damped bending motion of trees, physical modelling of tree oscillations is very useful. It is based on the assumption that trees with linear oscillations, which means conifers such as spruce or Douglas fir, can be treated as elastic one-sided fixed beams. In analogy to investigations in building aerodynamics (Försching 1974), measurements of wind-induced tree sways of different spruce trees have shown (Amtmann 1986; Mayer 1985) that their deflections due to gusty wind were irregular and that sways occurred in, and perpendicular to, the wind direction. Any investigation of tree response to windloads should therefore also take into consideration the turbulent character of the windload as well as the stationary effect. The most important load on trees due to strong winds and storms is generally stochastic and can be analysed by statistical methods (Försching 1974).

In principle, tree response to turbulent windloads can be estimated by use of either the time-course method or the spectral method (Mayer 1985). The time-course method supplies the temporal course of a response parameter, such as the stem acceleration in figure 7, to a pretended load function. The exact physical base is a differential equation for wind-induced tree oscillations (Finnigan & Mulhearn 1978; Mayer 1985) containing the drag coefficient, C_D, and the actual width, b, of a tree at the height, z. But for practical purposes it is nearly impossible to make use of that equation because the actual values of C_D and b again are not known.

Therefore the spectral method (figure 8) is more useful, where the power spectrum of tree response results from a frequency analysis of the wind speed with respect to windload (Amtmann 1986; Holbo *et al.* 1980; Mayer 1985):

$$P_Y(f) = |H_m(if)|^2 P_K(f), \qquad (5)$$

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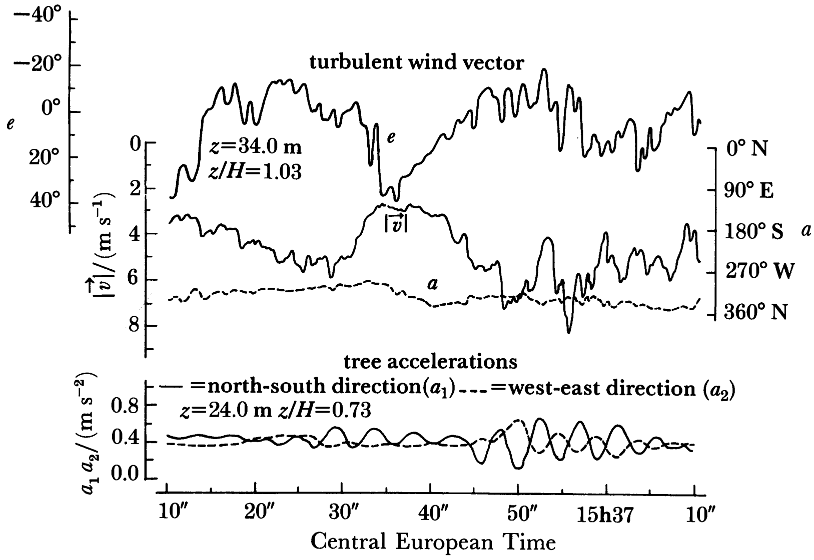

FIGURE 7. Time-courses of elevation angle, e, azimuth angle, a, and amount $|\vec{v}|$ of the turbulent wind vector near the top of a tall Norway spruce forest, as well as components a_1 and a_2 of the horizontal stem acceleration vector of a dominant spruce tree within the stand; z, measuring height; H, stand height (Mayer 1985). Ebersberger Forest, 10 May 1979.

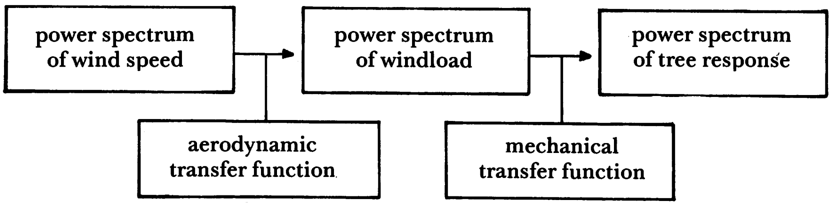

FIGURE 8. Schematic illustration of the spectral method (Mayer 1987).

where $P_Y(f)$ is the power spectrum of tree response, f is the frequency, $P_K(f)$ is the power spectrum of windload, $H_m(if)$ is the mechanical transfer function and i is the imaginary unit $((-1)^{\frac{1}{2}})$.

For practical purposes, in investigations on wind-induced tree motions, it is useful to apply the Reynold's stress τ as a measure of windload (Amtmann 1986; Holbo *et al.* 1980; Mayer 1985). τ is the turbulent vertical flow of impulse in the longitudinal direction and comprises normal and tangential pressures. τ can be calculated by use of the fluctuations of the longitudinal and vertical components of the turbulent wind vector.

6. Results from investigations on wind-induced tree motions

In the following, some results of experimental investigations on wind-induced motions of spruce trees are presented: these were done by the Lehrstuhl für Bioklimatologie und Angewandte Meteorologie der Universität München. The objective of these investigations was the analysis of the energy transfer from the turbulent wind field to the swaying spruce tree system. Most of these experiments were done at the meteorological measuring site within the Ebersberger Forest, a 33 m tall Norway spruce forest about 25 km east of Munich (Mayer 1985). Measurements of the three-dimensional wind speed were done by a tower-mounted Gill anemometer bivane. As characteristics of tree motions, the horizontal stem acceleration vectors have been measured at three heights (Mayer 1985): near the lower fixed point (mostly 2 m above the forest floor); at the height of the antinode of the first harmonic; and at the height of the node of the first harmonic.

The sampling rate of the measuring systems was 0.2–0.4 s for the stem acceleration as well as for the wind speed. The physical basis for analysing data has always been the spectral method.

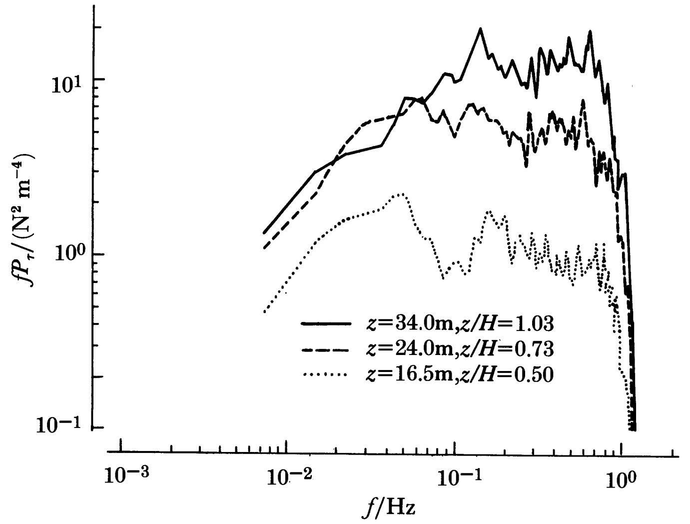

FIGURE 9. Power spectra of Reynold's stress τ $(=fP_\tau(f))$ during strong winds above and within a tall Norway spruce forest; z, measuring height; H, stand height. Ebersberger Forest, 15 December 1982.

An example of the power spectra of Reynold's stress, τ, is shown in figure 9. From this figure and other analogous results, the general shape of power spectra of τ above tall spruce forests can be described as follows (Mayer 1987).

1. Spectral variance densities of τ increase in the frequency range between 0.01 and 0.08 Hz.

2. In the frequency range between 0.08 and 0.7 Hz, the spectral variance densities of τ have some maxima that are not separated from each other by marked gaps. Within this range spectral variance densities of τ are approximately constant.

3. For frequencies of f greater than 0.7 Hz, spectral variance densities of τ decrease rapidly.

Based on wind measurements in a pine forest during a destructive gale, Oliver & Mayhead (1974) evaluated windloads that were smaller than expected from the use of an equation for the stationary windload and comparison of the induced bending moment with the maximum resistive bending moment. The explanation of their discrepancy is that, for storm damage in forests, dynamic wind conditions are more important than stationary windloads. One consequence of dynamic windloads is the so-called 'pump effect' of trees, especially of spruce, which can reduce considerably the amount of windload necessary to cause storm damage because of lower friction between roots and soil. The pump effect of trees is the process whereby the root plates at the luff lose weight owing to wind-induced free motions.

In contrast to the power spectra of τ, the power spectra of the longitudinal stem acceleration

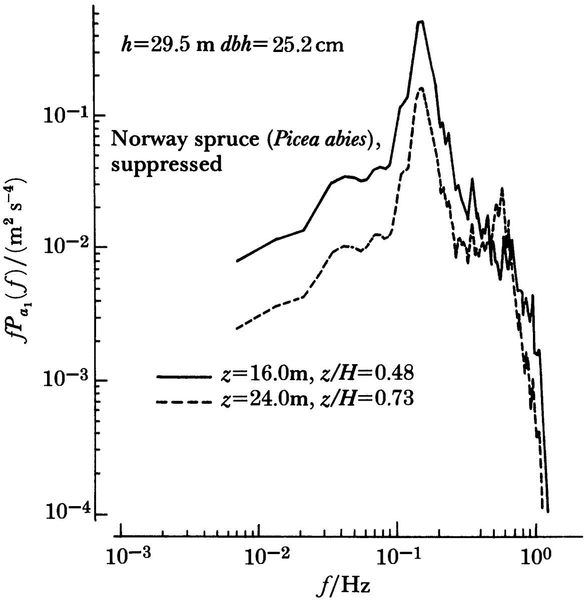

FIGURE 10. Power spectra of longitudinal stem acceleration, a_1, of a suppressed Norway spruce tree within the stand; z, measuring height; H, stand height; h, tree height; dbh, diameter at breast height (Mayer 1985). Ebersberger Forest, 16 December 1982.

a_1 of a suppressed spruce tree within the stand show distinct maxima at the two heights illustrated in figure 10 for $f = 0.16$ Hz; that means the sway period was 6.3 s. Identifying the frequency of the maximal spectral variance density of a_1 with the characteristic frequency of the primary sway of the experimental tree, the importance of the primary sway becomes clear.

In addition, figure 11 contains the power spectra of a_1 for a dominant and a suppressed spruce tree within the stand. The measuring heights were at the level of the sway antinode of the first harmonic. This figure shows that tree classes may have an influence on the characteristic frequencies of the primary motions and first harmonics as well as on the spectral variance densities. As an indicator of tree classes, the value of h/d can be chosen where h is the tree height and d is the diameter at breast height. In figure 11 the suppressed spruce tree has a value of h/d equal to 117 and the dominant spruce tree has a value of h/d equal to 78. From this figure and other analogous power spectra for tree motions it can be concluded for spruce trees within a stand that the characteristic frequencies of the primary motions and the first harmonics increase as the value of h/d decreases (Mayer 1985). The higher the value of h/d of a spruce tree, the greater its spectral variance densities with the result that its resistance to dynamic windloads decreases.

As mentioned above, the transfer of energy from the turbulent wind field to a tree can be analysed by use of the mechanical transfer function $H_m(if)$. $|H_m(if)|$ can be calculated by equation (5) if the power spectra of Reynold's stress τ and characteristics of tree motions are known. Based on the power spectrum of τ from the relative height $z/H = 1.03$ (i.e. near the top of the stand), and power spectra of the longitudinal (equal to a_1) and lateral (equal to a_2) stem accelerations of a spruce tree at the relative height $z/H = 0.73$ (i.e. near the centre of the crown space), figure 12 contains the spectral densities of $|H_m(if)|$ for both directions of the horizontal stem acceleration vector. From these results and from all other analogous spectra

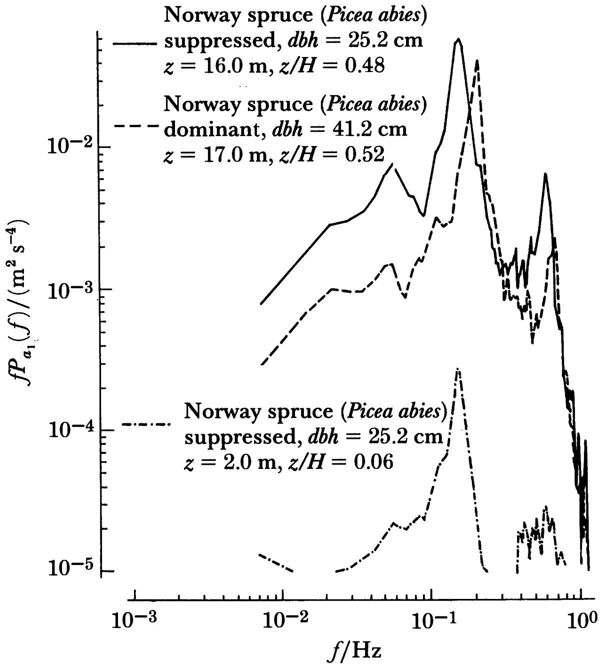

FIGURE 11. Power spectra of longitudinal stem acceleration, a_1, of a dominated and a dominant spruce tree within the stand; *z*, measuring height; *H*, stand height, *dbh*, diameter at breast height (Mayer 1985). Ebersberger Forest, 16 December 1982.

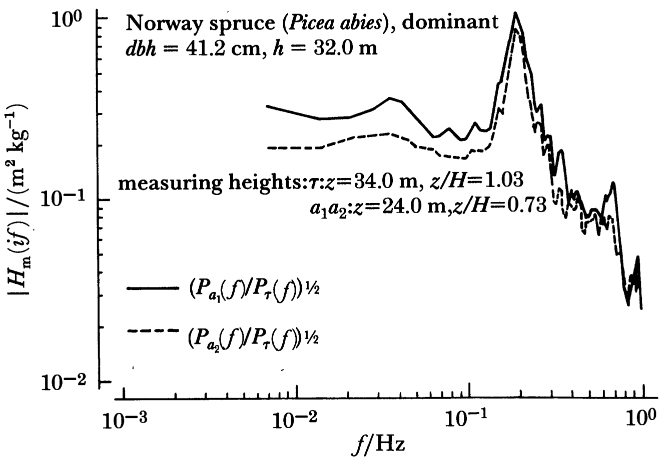

FIGURE 12. Power spectra of the amount of the mechanical transfer function ($= |H_m(if)|$) of a dominant Norway spruce tree within the stand based on power spectrum of τ at the relative height $z/H = 1.03$ and power spectra of a_1 and a_2 at the relative height $z/H = 0.73$; *z*, measuring height; *H*, stand height; *h*, tree height, *dbh*, diameter at breast height (Mayer 1985). Ebersberger Forest, 15 December 1982.

(Amtmann 1986; Mayer 1985), it can be seen that all spectra in general reproduce the course of the power spectra of the longitudinal and lateral components of the horizontal stem acceleration vector. Thus all spectra of $|H_m(if)|$ have a distinct maximum at a frequency corresponding to the characteristic frequency of the primary sways.

In addition, for all investigated conifers, only small differences between the spectral densities of $|H_m(if)|$ for both components of the horizontal stem acceleration vector can be seen. The reasons for these small differences may be the asymmetrical distribution of branches within the crown, the root anchorage, which depends on the mean wind direction, and the bending strength, which depends on the development of the root collar.

For wind-induced motions of conifers it follows from all spectra of $|H_m(if)|$ (Amtmann 1986; Mayer 1987) that (1) outstanding importance has to be assigned to the primary motions of trees; and (2) energy of the turbulent windfield can be absorbed best by a swaying conifer in the frequency range of its primary motion. Therefore swaying conifers can be compared with a bandpass filter, i.e. they can take in energy from the turbulent windfield only at a certain frequency range.

7. Conclusions

The question of how the results of investigations on wind-induced tree motions can be used in practice is often posed. First, it must be said that, according to information in the literature (see, for example, Mayer 1985), no tree species can survive violent storms (with mean wind speeds over a period of 10 min higher than 30 m s^{-1}) without any damage. This threshold value for wind speed is referred to the height near the top of a forest stand. Taking the results of the spectral method as a basis for the reduction of storm risk of vital conifers, necessary silvicultural action must be as follows.

1. To influence the amount and frequency distribution of the windload in such a way that its sphere of action becomes unsuitable for inducing tree motions.

2. To raise the characteristic frequencies of the primary motions of trees, because then the effective windload takes on lower values due to the narrow-band energy transfer.

Numerous sylvicultural methods for achieving these objectives, such as cutting off the tops of the crowns or chaining trees together, are described in literature about forests (Rottmann 1986).

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Discussion

M. R. Raupach (*CSIRO Centre for Environmental Mechanics, Canberra, Australia*). A comment and a question: the comment concerns the interaction of tree resonance (at a particular frequency set by the tree structure) with the turbulent wind spectrum. Coherent eddies over canopies are observed to have a more or less well-defined shape (like a double roller) with a length proportional to the canopy height. As these eddies are advected past a point, the peak in the turbulent frequency spectrum will shift to higher frequencies with wind speed increase. The wind speed at which breakage occurs may be determined partly by the coincidence of tree resonance frequencies and peak turbulent frequencies, as well as by the more obvious influence of direct drag.

The question: what mechanisms influence observed treethrow patterns, including streaky damage patterns (with the streaks aligned with the wind), and observations of damage initiation just behind a leading edge rather than at the edge itself?

H. Mayer. Dr Raupach's very interesting question was not included in our investigations on windthrow. From memory of maps of storm damage in forests in the F.R.G., the storm risk at open edges of forests seems to be greater than just behind an edge. However, storm damage within a stand or just behind an edge can sometimes be observed. Here the reasons may be: effects of atmospheric micro down-bursts, effects of topography, effects of storm direction (during growth a tree becomes adapted in its stability to the mean wind direction only), and silvicultural effects characteristic of a forest stand, including the air flow above the stand. In principle, windthrow depends on many different factors. So it is hardly possible to choose only one factor as responsible for some kind of storm damage in forests.

W. Kohsiek (*KNMI, P.O. Box 301, 3730 AE De Bilt, The Netherlands*). Firstly, instead of using the spectral distribution of the Reynold's stress to calculate the windload on a tree, the spectrum of $u^2C_D A$ is to be preferred because the Reynold's stress can not give the friction of an individual obstacle. Why was $u^2C_D A$ not used?

Secondly, in measuring the Reynold's stress, the instrument (propeller bivane here) should be positioned well above the tree tops to avoid effects of local obstacles. At what level was the propeller bivane placed?

H. Mayer. Firstly as u^2 as well as C_D and A are time functions, a Fourier transformation of $u^2C_D A$ results in spectra of u^2, C_D and A. In our investigations the spectral variance densities of C_D and A could not be determined. The power spectrum of Reynold's stress was therefore used as first approximation for the spectral distribution of $u^2C_D A$.

Secondly, the three-dimensional wind vector has been measured near the tree tops at the relative height $z/H = 1.03$ (z, measuring height; H, stand height), because these measurements should be used for estimating the windload acting on a single tree within the stand. The power of Reynold's stress presented here cannot be compared with descriptions of Reynold's stress in the literature, of course. The objectives of our investigations, however, have not been to supply meteorologically comparable results for Reynold's stress above a forest, but to approximate the windload acting on a single tree within a stand as well as possible.

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B. Gardiner (*Forestry Commission, Northern Research Station, Roslin, U.K.*). I should like to pick up on a point Dr Mayer raised, namely that wind energy can only be absorbed at the resonant frequency of the tree. Actually, energy will be absorbed at all frequencies but with lesser efficiencies. Therefore, because the turbulent spectrum has most energy at frequencies lower than the tree resonant frequencies, it may be that it is the low-frequency gusts that are the most important.

H. Mayer. The entire windload on a tree can be subdivided into a dynamic and a stationary part. Regarding the sum of these two parts, the low-frequency gusts load a tree more, of course, than high-frequency gusts, which only make a contribution to dynamic windloads. The portion of energy from the low-frequency gusts that contributes to the dynamic windload on a tree, however, is smaller than the portion of energy from the high-frequency gusts in the range of the resonant frequency of a tree.

J. A. Clarke (*School of Agriculture, Nottingham University, U.K.*). Dr Mayer has described tree failure by stem breakage and root failure. A third case may occasionally be observed in thin trees, which is permanent bending of the trunk without actual breakage, rather like lodging in cereal crops. Are the dynamics of this mode of failure likely to be significantly different from those of the mechanisms he has considered?

H. Mayer. The long-term bending of a trunk without breakage is attributed to the effect of stationary windloads and not to the effect of dynamic windloads. However, it is conceivable that the cells of a trunk are damaged as a result of dynamic windloads on one side only, so that a tree can grow lop-sidedly.

R. Amtmann (*German Military Geophysical Office, Mont Royal, F.R.G.*). I have two comments to make.

Firstly, assuming that trees can be treated as elastic one-sided fixed beams, which perform only linear bending sways, the peaks in their swaying spectra can be associated with the harmonic modes of the swaying tree. At the frequencies of these modes, the swaying tree works like a bandpass filter and takes in the kinetic energy of the wind field best. As the kinetic energy in the wind field is greatest near the frequency of the first mode compared with higher modes, the first mode of the swaying tree is the most important mode describing dynamic windloads on a tree.

Secondly, for the calculation of windloads on a tree, the centre of gravity of a tree crown has to be estimated. It was assumed that A (the projection area of a crown perpendicular to the air flow) of *Picea abies* can be described by a triangle with two equal sides and the third (the smallest) side coincident with the crown base. This assumption agrees with the work done by Burger (1939). In addition it should be pointed out that this so-called centre of gravity is only a substitution to make the calculations of windloads more convenient. To determine the centre of gravity exactly, the distribution of needles and branches as well as the acting windforces has to be taken into account.

Reference

Burger, T. S. 1939 Baumkrone und Zuwochs in zwei hiebsreifen Fichtenbeständen. *Mitt. schweiz. Anst. forstl. VersWes.* **21**, 5–57, 147–176.

J. M. Crowther (*Department of Physics and Applied Physics, University of Strathclyde, U.K.*). I should like to ask about the linearity assumption which Dr Mayer made in his transfer function estimation for relating tree sways to turbulent atmospheric flows. The data he showed on drag coefficient of different tree species exhibit a clear windspeed dependence, and it is also probable that the projected areas will also be windspeed dependent. Has he combined this type of information in his equation $K_1 = \frac{1}{2}\rho_L u^2 C_D A$ to determine whether the power law dependence of K_1 on u is indeed linear, or close to linear? If the relation is nonlinear it is possible that resonant oscillations of the tree stem may be stimulated by harmonics of lower-frequency components in the turbulent air flows. Could he please comment on these points?

H. Mayer. Measurements by Ylinen (1952) have shown that for strong winds and storms the dependence of K_1 on u is close to linear. However, his measurements were made in a wind tunnel without any consideration of dynamic windloads on tall trees, which have the greatest storm risk. In other respects see the first comment by Dr R. Amtmann.

Reference

Ylinen, A. 1952 Über die mechanische Schaftformtheorie der Bäune. *Silva Fennica*, **76**.

P. G. Jarvis (*Department of Forestry and Natural Resources, University of Edinburgh, U.K.*). I should like to ask how Dr Mayer determines the 'centre of pressure' in the crowns of his experimental trees? In an early diagram he showed an exact spot that was assumed for the purpose of calculation. I ask this because we have recently mapped the distribution of leaf area density within the crowns of radiata pine (*Pinus radiata* D. Don) and Sitka spruce trees. The average value through the crown was *ca.* 2 m^2 m^3, but the range is from 0 to 20 m^2 m^3. The peaks of the distribution are at rather different locations for spruce and pine, and for pine that has been irrigated and fertilized compared with pine that has not. I wonder also how sensitive his calculations were to the location of the centre of pressure.

H. Mayer. I have not determined the centre of pressure in the crowns of the experimental trees because I do not need this parameter in my calculations. I have mentioned the centre of gravity of the crown only in a schematic diagram, drawn to show the bending moments acting on a coniferous tree as a result of windloads. Otherwise, see the comment by Dr R. Milne and the second comment by Dr R. Amtmann.

R. Milne (*Institute of Terrestrial Ecology. Penicuik, U.K.*). I should like to reply to Professor Jarvis's comment on variation of leaf area density within conifers.

If the canopy of a tree is divided into vertical layers that coincide with the branching nodes (which can easily be done for a spruce), then the drag forces generated by the wind on the needles in each layer will act as bending forces at the point where the branches join the mean stem. Averaging across the layer is then not as dangerous as Professor Jarvis may have suggested. His comment does not of course minimize the problem of measuring needle areas in forest canopies.

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