Silva Fennica 1993, Vol. 27 N:o 2: 113–126

Swaying of trees as caused by wind: analysis of field measurements

Heli Peltola, Seppo Kellomäki, Alpo Hassinen, Matti Lemettinen &
Jorma Aho

TIIVISTELMÄ: TUULEN AIHEUTTAMA PUUN HUOJUNTA: KOKEELLISEN AINEISTON ANALYYSI

Peltola H., Kellomäki, S., Hassinen A., Lemettinen M. & Aho, J. 1993. Swaying of trees as caused by wind: analysis of field measurements. Tiivistelmä: Tuulen aiheuttama puun huojunta: kokeellisen aineiston analyysi. Silva Fennica 27(2): 113–126.

Measurements of wind and subsequent swaying of two Scots pines (*Pinus sylvestris*) were made at stand edge conditions. The horizontal windspeed was measured ten meters outside of the stand edge for four heights using cup anemometers. The compass directions were determined using a directional vane placed above the canopy. Tree swaying was measured by accelerometers at xy-coordinates. The shape of the wind profile at the stand edge varied to some degree depending on windspeed, but the form was a logarithmic one. Swaying of trees increased along with increasing windspeed. Furthermore, swaying was more or less irregular in relation to xy-coordinates, but it occurred, however, mainly perpendicularly to the direction of mean windspeed. The maximum bending of trees to the direction of mean windspeed varied also only little for various gusting windspeeds (average windspeed of 20 seconds) and dynamic wind loads. These maximum bendings of trees were also in most cases less or equal to those predicted on the basis of static wind loads, when the mean windspeed for static wind load is taken as equal to the gusting windspeed.

Kahden erikokoisen männyn (*Pinus sylvestris*) huojuntaa suhteessa tuulen nopeuteen ja puuskaisuuteen mitattiin metsikön reunassa. Tuulta mitattiin metsikön reunassa neljältä eri korkeudelta anemometreillä ja tuulen suuntaa mitattiin suunta-anturilla latvuston yläpuolella. Puun huojuntaa mitattiin kohtisuoraan toisiaan vastaan olevilla kiihtyvyysantureilla (venymäliuska-anturit), jotka antoivat puun liikkeen xy-koordinaatein. Tuuliprofiilin muoto vaihteli jossain määrin metsikön reunassa tuulen nopeuden suhteen, mutta profiilin muoto säilyi logaritmisena. Puiden huojunta lisääntyi tuulennopeuden kasvaessa, mutta huojunta oli enimmäkseen keskituulennopeuden suunnan suhteen poikittaista. Keskituulennopeuden suuntainen puiden maksimitaipuma vaihteli myös hyvin vähän eri tuulennopeuksilla ja dynaamisilla tuulikuormilla. Puiden maksimitaipumat olivat useimmissa tapauksissa pienempiä tai yhtäsuuria kuin vastaavasti staattisilla tuulikuormilla ennustetut taipumat, joiden ennustamiseen on käytetty keskituulennopeutena 20 sekunnin puuskatuulen keskiarvoa.

Keywords: wind, windspeed, wind loads, dynamic loads, trees.
FDC 181.2

Correspondence: Seppo Kellomäki, University of Joensuu, Faculty of Forestry, P.O. Box 111, FIN-80101 Joensuu, Finland.

Accepted September 1, 1993

Symbols and definitions

(Standard international units: m, kg, Pa, S)

Symbol	Explanation	Dimension	Value
$A(z)$	Projected area of the crown and stem against wind at height z	m^2	
C_d	Drag coefficient	-	0.29
$d_{1.3}$	Diameter at breast height	m, cm	
h	Tree height	m	
E	Modulus of elasticity	MPa	7000.0
F_s	Total static load due to wind	N	
z	Height along stem	m	
$F_s(z)$	Static wind load at height z	N	
I	Area moment of inertia of the stem	m^4	
k	von Karman's constant	-	0.41
p	Air density	kgm^{-3}	1.2226
$U(z)$	Mean windspeed at height z	ms^{-1}	
U_o	Friction velocity	ms^{-1}	
$x(z)$	Horizontal displacement of the stem from the upright position at height z	m	
Z_o	Roughness length parameter	m	0.20
$l(z)$	Distance from the tree top	m	
b	Distance from the crown centre to the tree top	m	
a	Distance from ground level to the crown centre	m	
$F_d(z)$	Dynamic wind load at height z	N	
Φ	Gust factor	-	
ψ	Peak factor	-	
φ	Exposure factor	-	
k_1	Background turbulence factor	-	
k_2	Gust resonant factor	-	
A_d	Streamlined diameter of the crown at the height of the crown centre	m	
k_3	Size reduction factor	-	
k_4	Gust energy ratio	-	
ι_a	Aerodynamic damping	-	
ι_m	Mechanical damping	-	0.2
f_o	Natural frequency	s^{-1}	
P	Natural period	s	
m_x	Mean mass per unit length	kgm^{-1}	
m_t	Total green mass of tree above ground	kg	
R_t	Upward displacement of tree in space and in time	m	
$R_{t'}$	Upward displacement of tree in space and in time after the trend removal	m	
$\Sigma(x_t)$	Sum of stem deflections at time in terms of x-coordinate	m	
$\Sigma(y_t)$	Sum of stem deflections at time in terms of y-coordinate	m	
$corr_x$	Correction parameter	m	
$corr_y$	Correction parameter	m	

1 Introduction

About 20 million cubic meters of timber have been lost in Finland due to wind-induced damage since the early 1950s and up to the early 1980s (Laiho 1987). Wind-induced damage is most frequent at stand-edge conditions around clear cut areas. In these conditions windthrow and stem breakage are processes that are mainly controlled by the properties of the wind, i.e. speed, duration, and gustiness. The wind field is quite dynamic resulting in swaying of trees with consequent short-term vibration or oscillatory motions of the stems (Papesh 1974, Mayer 1987, 1989), which can exceed the strength of roots or stem and lead to windthrow or stem breakage. For example, Hutte (1968) suggested that even normal winter storms without strong gusts make the spruces to swing to such an extent that they finally get uprooted, especially trees having a flat root system on wet soils are in danger. This view is also supported by Hintikka (1972), who observed that wind breaks roots of trees even during natural swaying, which might finally cause a failure. The danger of stem breakage or uprooting is much increased when the frequency of gusts is in resonance with the oscillation of tree stems.

Wind-induced damage is also related to the stand properties and properties of individual trees; i.e. tree species composition, stand density, height and diameter of trees, crown length, and rooting of trees (e.g. Fraser 1962a, 1962b, 1964, Raymer 1962, Walshe and Fraser 1963, Fraser and Gardiner 1967, Mayhead 1973a, 1973b, Oliver and Mayhead 1974, Papesh 1974, Savill 1976, Petty and Worrel 1981, Petty and Swain 1985, Mayer 1985, Coutts 1986). Furthermore, the site conditions, such as soil texture, moisture and soil frostness, influence the stability of trees (Fraser 1962a, Fraser and Gardiner 1967, Mayer 1985, Coutts 1986, Laiho 1987). In particular, the height of trees in relation to their breast height diameter seems to be one of the single most important factors determining stem deflection and the strength of the tree in relation to the properties of the wind (Peltola and Kellomäki 1993).

The shape of tree sways can be analyzed, if a tree is affected by a single, brief force, which may be an artificial force or a wind gust. Usually, the first approach has been used (e.g. Mayhead 1973b, White et al. 1976, Holbo et al. 1980, Antmann 1986, Mayer 1987, 1989). When studying tree response, i.e. swaying of trees, as a result of dynamic wind load (e.g. Holbo et al. 1980, Mayer 1985, Amtmann 1986), it should be taken into consideration also the turbulent character of the windload as well as the stationary effect (Mayer 1989).

The aim of this study was to analyze wind measurements at the stand edge conditions and the subsequent swaying of two Scots pines (*Pinus sylvestris*). Maximum bending of trees at the direction of mean windspeed was studied with regard to the dynamic wind load, which was estimated on the basis of wind measurements and tree characteristics as tree height, diameters of tree stem at breast height and crown. Furthermore, these maximum bendings of trees were compared to the theoretical bending as caused by static wind load, when the mean windspeed for static wind load is taken as equal to the gusting windspeed for dynamic load.

2 Measurements

Wind measurements and measurements of the swaying of trees were carried out close to Mekrijärvi Research Station of the University of Joensuu (62°47' N, 30°58' E, 145 m a.s.l.) in the autumn of 1989. The wind measurements represent the conditions about 10 m outside two Scots pine stands facing south, i.e. the stands were side by side in an east-west direction. Wind had main access into the stands from the south, i.e. from over a large open bog, allowing the measurement of the wind profile from an open area during southerly winds. During northerly winds (exactly from west to southeast) the stands obstructed the windblow, i.e. wind blowing from the direction 0–135 and 270–360 degrees. Only records representing the wind from southeast to west were, thus, included in the analysis (direction 135–270 degrees). The mean height of the

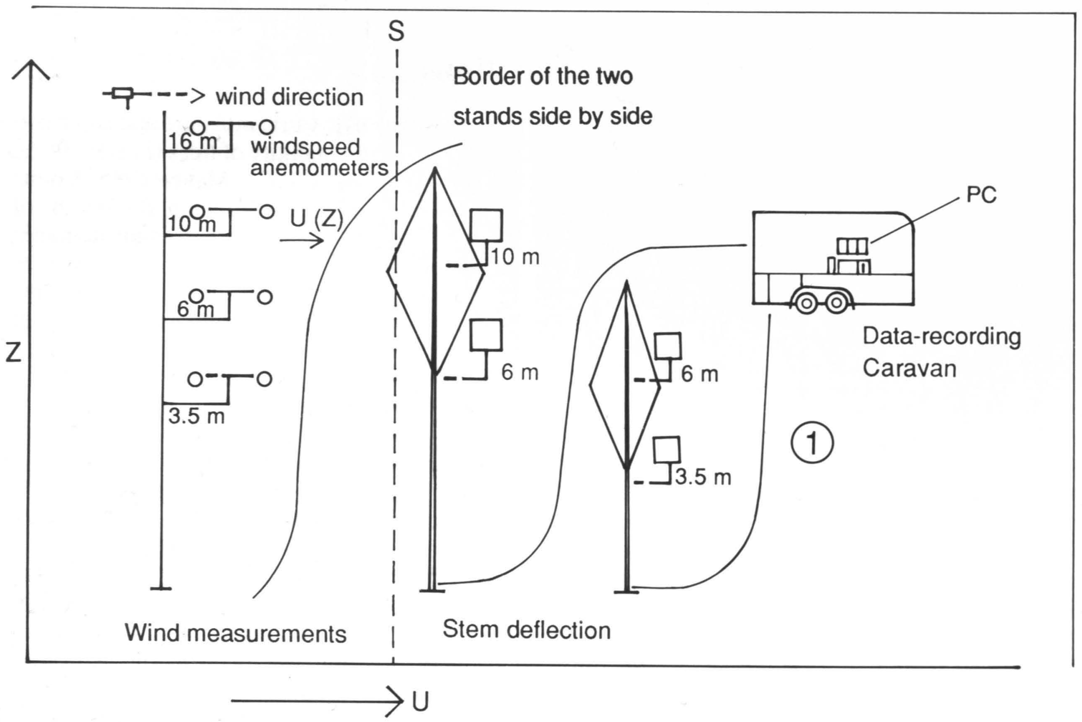

Fig. 1. Layout of the measuring system.

Table 1. Empirical measurements of tree characteristics, windspeed and tree swaying.

Measurements	Tree 1	Tree 2
Height, m	13.5	9.5
$d_{1.3}$, cm	24.0	16.0
Height/$d_{1.3}$	1:60	1:60
Crown length, m	7.5	6.0
Crown max width, m	4.0	2.0
Wind direction (degrees), at height, m	16.0	16.0
Windspeed, ms^{-1} at heights	6.0, 10.0, 16.0	3.5, 6.0, 16.0
Tree swaying, m at heights	6.0, 10.0	3.5, 6.0

taller stand was 18–20 m and its density was 350–400 stems ha^{-1}. The mean height of the smaller stand was 6–8 m and its density was about 2700 stems ha^{-1}, respectively.

Windspeed was measured with the help of cup anemometers (model SMA-300-NA) at heights of 3.5 m, 6 m, 10 m, and 16 m, and wind direction was measured at a height of 16 m with the help of directional vane (model SMA-300-SA) (Fig. 1). Swaying of two Scots pines (heights 13.5 m and 9.5 m) was measured simultaneously with wind measurements with the help of two accelerometers (strain gauges, model Kyowa). They were mounted perpendicularly on the stems of two Scots pines at heights of 10 m and 6 m, and 6 m and 3.5 m, respectively. These measurements represented the stem below the crown and the stem close to the centre of the crown (Table 1). The measuring accuracy of the wind measurements was ± 5 % for horizontal windspeed ranging from 0.8 to 30 ms^{-1}, and ± 5 % for wind direction ranging from 0 to 360 degrees. The measuring accuracy of accelerometers was ± 2 % for tree motion obtained as xy-coordinates. The measuring system for acceleration was adjusted so that the acceleration due to gravity has been taken as a measuring standard at the beginning of each measuring period.

Electrical pulses from the sensors for windspeed, wind direction and accelerometers were interfaced with a computer through a multipurpose A/D-interface card (model Metrabyte DASH 16) using an amplifier. The accelerometers emitted signals at sampling frequency of 90 Hz. Measurements at this high frequency included irrelevant vibrations and other types of noise connected to stem deflection. Therefore, the averages of ten consecutive samples were calculated and stored in a file in order to reduce the noise, i.e. the average acceleration was logged at the frequency of 9 Hz. Furthermore, the measurements were made only during three-minute subperiods representing wind gusts arbitrarily selected by the person operating the measuring system in order to limit measurements that would otherwise exceed the available storing capacity. The measurements were repeated during 26 subperiods in November and December, 1989.

3 Analysis of the measurements

3.1 Mean windspeed and wind gustiness

Wind properties were represented using mean windspeed and wind gustiness at the given height. The *mean windspeed* was calculated for heights of 10 m, 6 m, and 3.5 m in relation to windspeed at the height of 16 m. The logarithmic profile agreed quite well with the measurements (Fig. 2) given in classes of 0–2 ms^{-1}, 2–4 ms^{-1} etc. (Table 2), i.e.

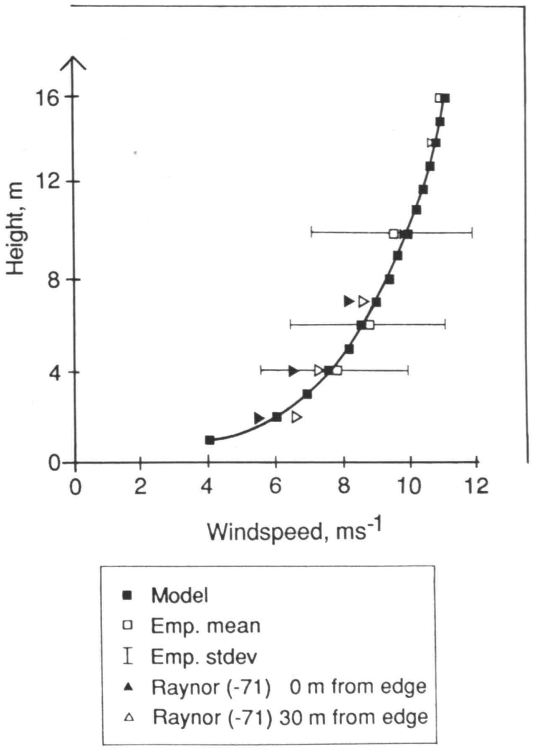

Fig. 2. Theoretical logarithmic profile with the measured profile at the pine stand edge referred to that of Raynor (1971).

$$U(z) = (U_o / k) \cdot (\log(z / Z_o)) \tag{1}$$

where U(z) is the mean windspeed [ms^{-1}] at height z [m], k von Karman's constant (0.41, [dimensionless]), U_o the friction velocity [ms^{-1}], and Z_o [m] the roughness length parameter (see e.g. Gloyne 1968, Oliver 1974) with value 0.20 m.

Gustiness of wind was studied by analysing fluctuations of the windspeed. The gusting windspeed was defined as the mean windspeed for gusting period. It was selected as twenty seconds, because that length of time period was found adequate to make the comparison of bendings as caused by static and dynamic wind loads relevant (in shorter periods as, for example, five to ten seconds, the tree itself may add the dynamic response significantly). To calculate the gusting windspeeds the three-minute measuring periods were reduced into twenty-second subperiods. The resulting gusting speeds at the heights of the crown centres were then used for the analysis of the subsequent deflections of the trees at the same heights. The maximum windspeed averages of fourty-seconds, one minute, and one and a half minute were also compared to the averages of windspeeds of three-minutes periods.

3.2 Wind load

Dynamic windload was used to predict the maximum deflections of trees in the direction of the mean windspeed. It was estimated using height, diameter, and crown properties of the tree in

Table 2. Mean relative wind profiles (measurements at the heights of 3.5, 6.0 and 10 m above ground) at various windspeed classes with the mean standard deviation (std), minimum and maximum relative wind value. Total number of observations was 55 500 during 26 different 3-minutes period.

Windspeed class, ms^{-1}		Windspeed, % of the speed at 16 m						
				Height				
		10 m	(std)	6 m	(std)	3.5 m	(std)	Percentage of total obs.(%)
0–2	Mean	142	(21)	121	(38)	92	(23)	0.8
	min	91		43		39		
	max	186		221		130		
2–4	Mean	96	(24)	87	(23)	75	(21)	35.9
	min	25		19		23		
	max	170		204		198		
4–6	Mean	87	(20)	80	(20)	70	(17)	39.0
	min	25		6		23		
	max	178		176		142		
6–8	Mean	80	(20)	70	(19)	65	(15)	18.5
	min	20		12		25		
	max	164		146		126		
8–10	Mean	85	(20)	66	(21)	68	(12)	4.1
	min	22		16		39		
	max	141		123		91		
10–12	Mean	80	(18)	60	(19)	-		1.1
	min	23		15		-		
	max	119		104		-		
12–14	Mean	83	(14)	59	(14)	-		0.5
	min	52		28		-		
	max	111		88		-		
14–16	Mean	78	(14)	53	(9)	-		0.1
	min	52		40		-		
	max	102		77		-		
Average 2–10	Mean	87	(22)	80	(21)	71	(19)	
	min	20		6		23		
	max	186		221		198		100.0

relation to the wind profile (Eq. 1) representing windspeed values of 2–10 ms^{-1}. Dynamic wind load at height z was assumed to be a combination of the *gust factor* and *static wind load* as determined by Eq. (2) (Davenport and Surry 1974, Sachs 1978, RIL 144 1990), i.e.

$$F_d(z) = \Phi \cdot F_s(z) = \Phi \cdot (0.5 \cdot C_d \cdot p \cdot A(z) \cdot U(z)^2) \quad (2)$$

where $F_d(z)$ is the dynamic windload at height z [N], $F_s(z)$ is the static wind load [N], Φ is the gust factor [dimensionless], C_d the drag coefficient ([dimensionless], value of 0.29 for Scots pine by, e.g., Mayhead (1973a)), p is the air density (1.2226 [kgm^{-3}]), A(z) is the projected area of the crown and stem [m^2] against wind at height z, and U(z) the mean windspeed [ms^{-1}], which equals 0.85 times gusting speed (mean speed of twenty second).

Gust factor Φ was calculated using Eq. (3),

$$\Phi = 1 + \psi \cdot \varphi \cdot \sqrt{k_1 + k_2} \quad (3)$$

where ψ is the peak factor [dimensionless], φ the exposure factor [dimensionless], k_1 is the background turbulence factor [dimensionless], and k_2 is the gust resonant factor [dimensionless] (see RIL 144 1990).

Peak factor ψ depends on the natural frequency of the structure, i.e. it increases as a logarithmic function of natural frequency of the structure. Exposure factor φ increases logarithmically as a function of the height of the structure. It is, however, also affected by the exposedness of the area (see Appendix 1, e.g. Sachs 1978, RIL 144 1990).

Background turbulence factor k_1 equals to $0.66–0.11 \cdot A_d / h$, $h < 30$ m, where A_d is the streamlined diameter of the crown against wind [m] at height of the crown centre, h is the height of the tree [m]. It takes into account the correlation between wind gusts, which affect on various parts of the structure. Gust resonant factor k_2 takes into account the vibration of the smallest frequency of the structure (due to the wind gusts). It equals Eq. (4),

$$k_2 = (\pi^2 \cdot k_3 \cdot k_4) / (2 \cdot (\iota_a + \iota_m)) \quad (4)$$

where k_3 is the size reduction factor [dimensionless], k_4 is the gust energy ratio [dimensionless], ι_a is the aerodynamic damping [dimensionless] and ι_m is the mechanical damping [dimensionless].

Size reduction factor k_3 depends logarithmically on the natural frequency and height of the structure, and mean windspeed, i.e. it increases when the natural frequency or height increases and decreases when mean windspeed increases. Gust energy ratio k_4 depends similarly on the natural frequency of the structure and mean windspeed. However, it depends also in some degree on the height of the structure (see Appendix 1, e.g. Sachs 1978, RIL 144 1990). Mechanical damping ι_m is assumed to be 0.2 (RIL 144 1990). Aerodynamic damping equals Eq. (5)

$$\iota_a = F_s(z) / (f_o \cdot m_x \cdot U(z)) \quad (5)$$

where $F_s(z)$ is the static wind load [N] at the height of the crown centre, f_o the natural frequency [1/P], where P is the natural period, [s^{-1}], m_x is the mean mass per unit length [kg/m], and U(z) is the mean windspeed [ms^{-1}] at height z.

The approach to calculating the *natural period* is based on the assumption that tree responses to windload like a uniform metal rod (Mayhead 1973b). The natural period was expressed as a function of tree height, total green mass of tree above ground and diameter at breast height, i.e.

$$P = 0.86 + \frac{(0.74 \cdot h \cdot \sqrt{m_t \cdot h})}{d_{1.3}^2} \quad (6)$$

where P is the natural period [s], h the tree height [m], m_t the total green mass of tree above ground [kg] and $d_{1.3}$ the diameter at breast height [m].

The stem mass is a sum of one-meter-long stem segments, the mass of each segment being the product of the segment volumes and the density with respect to the position of the segments along the stem (Tamminen 1962, Laasasenaho 1982, Kilkki 1989, Peltola 1990). The projected area of the stem was estimated with the help of mid diameter of the segments. The segment diameter at different heights was calculated using the method developed by Laasasenaho (1982).

The green mass of the crown was assumed to be 30 % of stem mass. Its vertical distribution was estimated on the basis of the model developed by Oker-Blom et al. (1988) and measured ratio of crown, which was found to be 0.60 of the total tree height. The projection area of the crown envelope was assumed to be formed by two triangles having a common base representing the maximum diameter of the crown. The crown area was assumed to streamline about 20 % of that for still air at windspeeds less than 10 ms^{-1} (Peltola and Kellomäki 1993).

3.3 Analysis of tree swaying

Swaying of a tree depicts the displacement of a tree from the upright position at a given moment, i.e.

$$R_t = \sqrt{(((\sum x_t) - corr_x)^2 + ((\sum y_t) - corr_y)^2)} \quad (7)$$

where R_t is the upright displacement of tree [m] in space and in time. The term $\sum(x_t)$ sums the stem deflections at a moment in time in terms of x-coordinate ($x_t = 0.5 \cdot a_x \cdot t^2$, where x_t is the stem deflection in x-coordinate [m] at time t [s], a_x is the acceleration in the direction of the x-coordinate [ms^{-2}],) just as the term y_t sums does regarding the y-coordinate. The terms $corr_x$ and $corr_y$ are the correction parameters for circuit zero output voltage settings; i.e. averages for the signals from the channels for acceleration converting channel output into real displacement values.

In calculating the upward displacement of a tree by double integration from acceleration values, drift was a problem causing the linear trend to apply to the displacement observations. The trend due to drift was eliminated from the displacement observations with the help of the linear trend filter (see e.g. Box and Jenkins 1976); i.e.

$$R_{t'} = R_{t+1} - R_t \quad (8)$$

where $R_1 \ldots R_n$ is the original series after double integration, and $R_{1'}...R_{(n-1)'}$ the series after the linear trend removal.

3.4 Analysis of effect of wind properties on tree swaying

The effect of wind on tree swaying was analyzed by comparing the theoretical and measured deflection of stems at the direction of the mean windspeed. *Measured* deflection was assumed to be directly proportional to the dynamic wind load. The dynamic wind load was calculated on the basis of mean windspeed of twenty-second period (gusting windspeed). *Theoretical* deflection indicated stem bending due to static windload at the direction of the mean windspeed, which was taken as equal to the gusting windspeed for dynamic load.

Theoretical deflection was calculated in relation to the static wind load as (Pennala 1980),

$$x(z) = \frac{F_s \cdot a^2 \cdot h \cdot (3 - a/h - 3 \cdot l(z)/h)}{6 \cdot E \cdot I} \quad z \geq a \quad (9)$$

$$x(z) = \frac{F_s \cdot a^3 \cdot (2 - 3 \cdot (l(z) - b)/a + (l(z) - b)^3/a^3)}{6 \cdot E \cdot I} \quad z < a \quad (10)$$

where x(z) is in Eq. (9) horizontal displacement of the stem from the upright position at height z [m] between the crown centre and the tree top, and in Eq. (10) it is the same but below the crown centre [m]. F_s is the total static wind load acting on the tree [N] at the direction of the mean windspeed, l(z) is the distance from the tree top [m], h is the height [m] and E is the modulus of elasticity [Pa]. I is the area moment of inertia of the stem [m^4] depending on the shape of the stem cross-section and equals to $\pi \cdot d_{1.3}^4 / 64$ for a solid cylinder (Jones 1983). Parameter a is the distance from ground level to the crown centre [m] and b equals the distance between the crown centre and the tree top [m]. In the computations, E was assumed to be 7000 [MPa] in green wood elasticity for Scots pine (Sunley 1968, Lavers 1969, Petty and Worrel 1981).

Whenever a tree was already swaying at the beginning of the measurement, stem deflection was *corrected* assuming that the doubling of windspeed will result in a quadrupling of stem deflection. This correction was done, because the measured amplitude of the deflection was calculated from the distance between the upright position and the position from the upright, where the measuring point at the onset of the measurement was. The resulted value is later named as corrected stem deflection.

4 Results

4.1 Wind properties and wind profile

The wind blew mainly from the south and southwest, i.e. the directional distribution of windblow was 7 % for the direction of 0–90 degrees, 2 % for the direction of 90–180 degrees, 62 % for the direction of 180–270 degrees, and 29 % for the direction of 270–360 degrees based on the total number of measurements during the 26 subperiods. The mean wind direction was 261 degrees with a standard deviation of 23 degrees. Windspeeds for the southern and southwestern directions were systematically higher than those of the other directions because the wind blew over an open field.

The windspeed at the edge of the stand varied substantially at different heights regardless of the wind direction (Figs. 3, 4), but the variability within the crown canopy followed quite closely that above the canopy. Windspeed varied from 1.3 ms^{-1} to 15.8 ms^{-1} at a height of 16 m above ground and mean speed was 4.9 ms^{-1} with a standard deviation of 1.8 ms^{-1}. Only occasionally did windspeed exceed 14 ms^{-1}. Consequently, gusting wind also varied substantially, but even the maximum gusting windspeed (mean speed of twenty seconds) was quite small; it equals only 10 ms^{-1}. To demonstrate the relationship between gusting speeds averaged over different times t and measurement periods, we got that the maximum mean windspeed of twenty-second period was about 1.53 times greater than the 3-minutes average, mean ratio being subsequently about 1.39 and standard deviation 0.12 (Table 3).

Table 3. Ratio of probable maximum speed averaged over time t to that averaged over 3 minutes.

	t = 3 min	1.5 min	1 min	40 sec	20 sec
Max ratio	1.0	1.23	1.30	1.49	1.53
Mean ratio	1.0	1.09	1.14	1.26	1.39
St dev	-	0.05	0.09	0.12	0.12

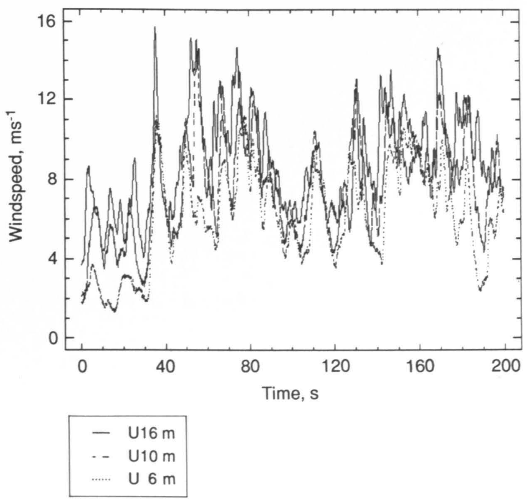

Fig. 3. Example of variation on windspeed at levels of 16 m, 10 m and 6 m during a 3-minute period. Maximum windspeed at 16 m in height was 15.7 ms^{-1}, mean 8.8 ms^{-1}. Measurements were made 3th December at 15.30 p.m. in 1989.

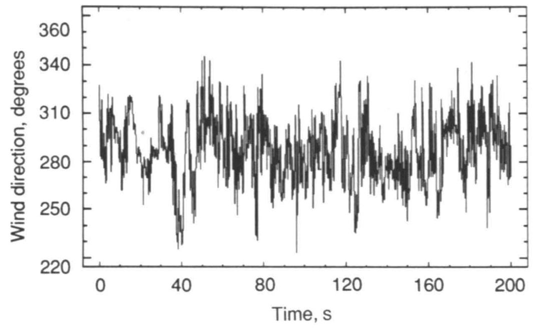

Fig. 4. Example of variation on wind direction during the same 3-minute period as in Fig. 3.

Wind turbulence was found to increase in pace with mean windspeed, i.e. the standard deviation of windspeed increased with increasing speed. The shape of the mean wind profile for different windspeeds varied to some degree, but the form of the wind profile was generally near a logarithmic one. The wind profile this near the stand edge is, however, in some degree affected by the stand edge conditions, which could be seen in Fig. 2 (see Raynor 1971).

4.2 Tree swaying

Swaying of trees increased along with increasing windspeed, but swaying was more or less irregular in relation to xy-coordinates. It also occurred mainly perpendicularly to the direction of mean windspeed (Fig. 5). The length of *calculated* natural periods for the tree 9.5 m in height was 1.89 s and for the tree 13.5 m in height it was 2.2 s (Eq. 6). Furthermore, the stems never seemed to come back to the upward position during gusts, i.e. the stems were bending constantly more or less into the direction of the prevailing wind.

The maximum bending of trees to the direction of mean windspeed varied only little for various gusting windspeeds (average windspeed of 20 seconds) and dynamic wind loads (Fig. 6). The swaying was very slight, i.e. the tree of 13.5 m in height bent at the level of crown centre (10 m in height) less than 5 cm for windspeeds ranging from 4 ms^{-1} to 8 ms^{-1} at the same height. For the tree of 9.5 m in height the maximum deflection for the same windspeeds was 2 cm at the level of crown centre of 6 m in height (deflec-

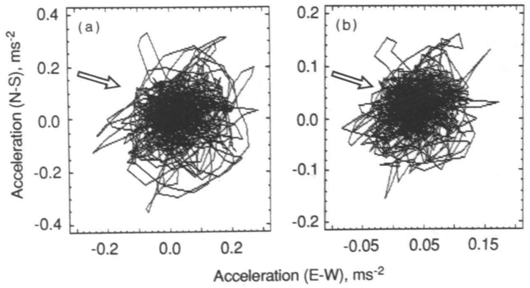

Fig. 5. Damped bending motions of Scots pine tree 13.5 m in height due to dynamic windloads. It was illustrated by the acceleration in N–S and E–W-directions at (a) height of 10 m and (b) 6 m during the same period as in Fig. 3 (time intervals of 0.1 s). Mean windspeed at 10 m in height was 7.8 ms^{-1} and maximum 14.5 ms^{-1} (maximum gust speed of 20 s was 10.3 ms^{-1}). The arrors indicate the mean wind direction during that 3-minutes period (287 degrees).

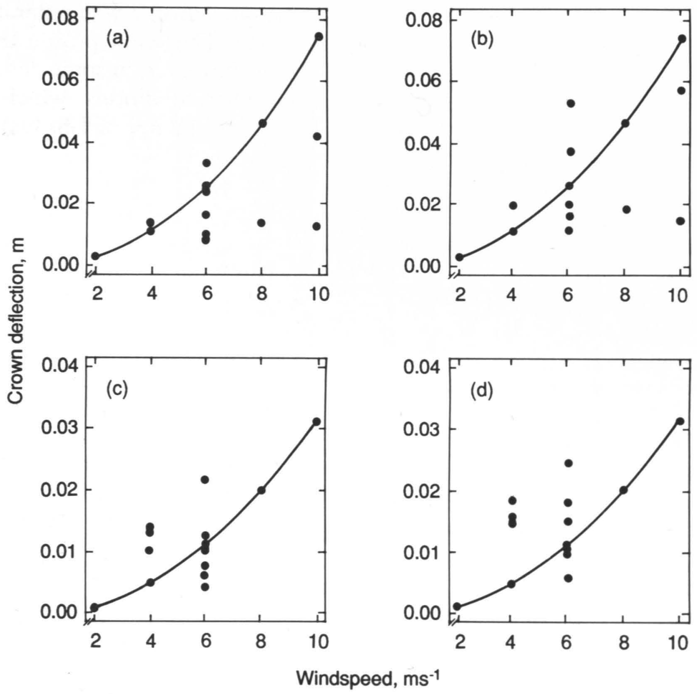

Fig. 6. Maximum deflection of two Scots pines with regard to mean windspeed of twenty-seconds at the direction of mean windspeed: (a) measured values and (b) corrected values for tree 13.5 m in height, (c) and (d) same for tree 9.5 m in height. Maximum deflection and windspeed are indicated at the same heights of crown centres (10 m and 6 m, respectively). The point indicates empirical results and line indicates model results.

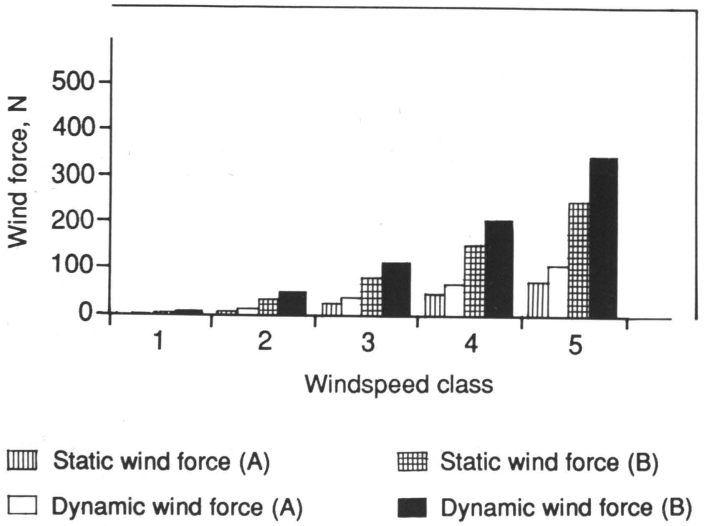

Fig. 7. Estimated static and dynamic windloads for two trees studied for various windspeed classes, i.e. 0–2 ms^{-1}, 2–4 ms^{-1} etc. (A) tree 9.5 m in height, (B) tree 13.5 m in height.

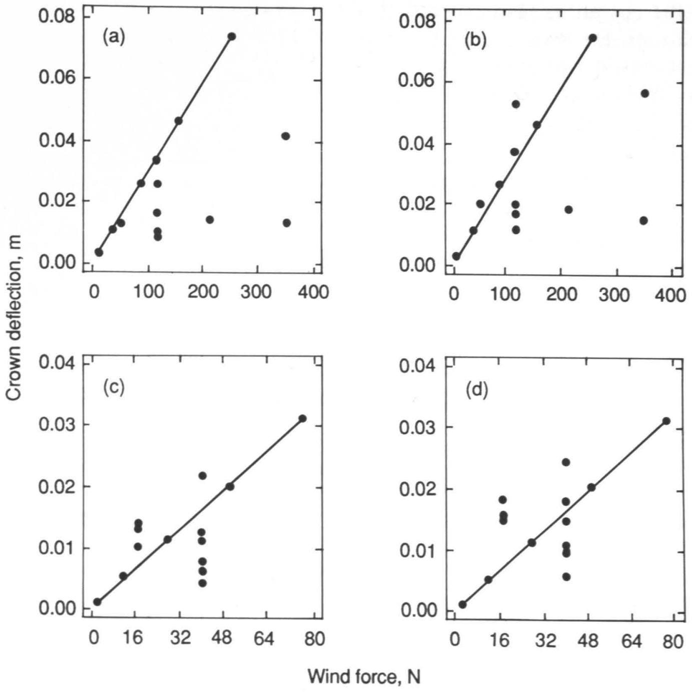

Fig. 8. Maximum deflection of two trees with regard to dynamic and static wind load for mean windspeed of twenty-seconds at the direction of mean windspeed: (a) measured values and (b) corrected values for tree 13.5 m in height, (c) and (d) same for tree 9.5 m in height. Maximum deflection and windspeed are indicated at the same heights of crown centres. The point indicates deflection as caused by dynamic wind load (empirical results) and line deflection as caused by static wind load (model results).

tions at the level of the stem below crown are not discussed here, because they were very little). Furthermore, these maximum bendings of trees were also in most cases less or equal to those predicted on the basis of static wind loads, when the mean windspeed for static wind load is taken as equal to the gusting windspeed. This was the fact especially for the tree of 13.5 m in height, although the dynamic windload (Eq. 1, 2) is found nearly 1.5 times as great as the static windload regardless of windspeed (Fig. 7, Fig. 8). The results were quite similar even in the case where the stem position at the starting point of measurements was considered. However, corrected stem deflection exceeded in the most of the cases the bendings caused by static loads, especially, for the tree 9.5 m in height.

5 Discussion and conclusions

The swaying of trees in this study was measured in field conditions, where trees are continuously subjected to dynamic windloads. Consequently, the tree swaying recorded in this study differed substantially from that observed in experiments where trees are made to sway artificially (White et al. 1976, Mayer 1989). Artificially applied forces make a tree sway in an elliptical pattern, this swaying pattern being mostly affected by soil conditions (Mayer 1989). This pattern was not supported by the current measurements; this indicates that although the swaying of trees as caused by wind increased along with increasing windspeed, it was still more or less irregular as found also by Mayer (1989). Likewise, swaying was more pronounced in the direction perpendicular to the mean windspeed as was also found by Mayer (1985, 1989) and Amtmann (1986). The differences in swaying between the x-coordinates and y-coordinates with regard to the dynamic wind load are, however, found typical for trees not in contact with neighbouring trees (White et al. 1976, Holbo et al. 1980).

The discussion of maximum bendings of the stems in this study considered only the cases where bendings occurred to the direction of mean windspeed, because all the equations discussed are derived only for the wind loads acting to the direction of the mean windspeed. The maximum bending of trees varied only little with regard to the variability in gusting windspeed and the subsequent windload. The swaying was also very slight. Furthermore, these maximum bendings of trees differed also very little from those predicted on the basis of static wind loads, although the dynamic windload was nearly 1.5 times as great as the static windload for same windspeeds.

The results were quite similar even in the case where the stem position at the starting point of measurements was considered. Corrected stem deflection exceeded, however, in the most of the cases the bendings caused by static loads, especially, for the tree 9.5 m in height. The results of theoretical stem bendings, which based on Eqs. (9) and (10) might also underestimate the stem deflection to some degree. This is because they do not precondition any taper in the stem shape. In addition, the contribution from the overchanging branch mass is not included and this has been found to lead to underestimate of bending of up to 20 % at least in spruce plantation (Gardiner and Wood 1992). However, the crown area and its distribution were taken into account in calculation of the wind load on tree, and this may compensate for the above underestimation.

A signal from the accelerometers was obtained when windspeed exceed 2 to 4 ms^{-1} at 16 m in height, in particular in the case the tree 13.5 m in height. It is obvious that the current results underestimate the tree bending, because the trees were displaced in some degree in the direction of wind already before measurements commenced. We observed stem deflections, which were only some centimeters at the crown centre, even though the inclination of the stem in relation to the prevailing wind direction was considered. For example, Oliver and Mayhead (1974) have found during gusts of up to 17.5 ms^{-1} that a 16-metres tall Scots pine deflected about 2 m at the top of the tree for some seconds. In this study gusting wind speeds were very small ones and that kind of deflections could not be expected.

Furthermore, the small deflections of our experimental trees are quite to be expected due to the great stiffness of the stem with large taper ($d_{1.3}$/h 1:60) and rather small size of trees which reduced the swaying of the trees. The measuring point was also at the centre of the crown, thus giving smaller values than those reported at the tree top as, for example, by Oliver and Mayhead (1974). The results of this study are similar to those observations of White et al. (1976), who found the low value for height/breast height diameter ratio of a tree to increase substantially the resistance of tree against the dynamic windload.

Acknowledgements: This study is funded by the Academy of Finland within the Finnish Research Programme on Climatic Change (Silmu). The support of the Faculty of Forestry, and the Mekrijärvi Research Station, the University of Joensuu, is also acknowledged. We also wish to extend our special thanks to Dr. Tuomo Kärnä (Technical Research Centre of Finland), for his valuable comments concerning the manuscript. Thanks are also to Dr. Hans Odin and Dr. Esko Elomaa, who have rechecked the manuscript and have given valuable comments and criticism. Furthermore, we thank Riitta Honkanen for drawing the figures of this study, and Erkki Pekkinen for revision of the English text.

References

Amtmann, R. 1986. Dynamische Windbelastung von Nadelbäumen. Forst. ForschBer. Münch. 74.

Box, G. E. P. & Jenkins, G. M. 1976. Time series analysis: forecasting and control. Holden-Day, San Francisco. 575 p.

Coutts, M. P. 1986. Components of tree stability in Sitka spruce on peaty gley soil. Forestry 59(2): 173–197.

Davenport, A. C. & Surry, D. J. 1974. The pressures on low rise structures in turbulent wind. Canadian Structural Engineering Conference 1974.

Fraser, A. I. 1962a. The soil and roots as factors in tree stability. Forestry 35(2): 117–127.

— 1962b. Wind tunnel studies of the forces acting on the crowns of small trees. Annual Research Report for year ended March 1962. For. Comm. p. 178–183.

— 1964. Wind tunnel and other related studies on coniferous trees and tree crops. Scott. For. 18(1): 84–92.

— & Gardiner, J. B. H. 1967. Rooting and stability in Sitka spruce. For. Comm. Bull. 40: 1–28.

Gardiner, B. A. & Wood, C. J. 1992. Measuring and modelling the static and dynamic characteristics of conifers. Presented to Society for Experimental Biology Meeting, Lancaster, UK, April 1992.

Gloyne, R. W. 1968. The structure of the wind and its relevance to forestry. Forestry (suppl.) 99: 7–19.

Hintikka, V. 1972. Wind-induced root movements in forest trees. Commun. Inst. For. Fenn. 76(2). 56 p.

Holbo, H. R., Corbett, T. C. & Horton, P. J. 1980. Aeromechanical behavior of selected douglas-fir. Agric. Met. 21: 81–91.

Hutte, P. 1968. Experiments on windthrow and wind damage in Germany; site and susceptibility of spruce forests to storm damage. Forestry (suppl.) 41: 20–27

Jones, G. 1983. Plants and microclimate. A quantitative approach to environmental plant physiology. Cambridge University Press. 323 p.

Kilkki, P. 1989. Metsänmittausoppi. Silva Carelica 3. 238 p. [In Finnish].

Laasasenaho, J. 1982. Taper curve and volume functions for pine, spruce and birch. Seloste: Männyn, kuusen ja koivun runkokäyrä-ja tilavuusyhtälöt. Commun. Inst. For. Fenn. 108. 74 p.

Laiho, O. 1987. Metsiköiden alttius tuulituhoille Etelä-Suomessa. Summary: Susceptibility of forest stands to windthrow in Southern Finland. Folia Forestalia 706. 24 p.

Lavers, G. M. 1969. The strengh properties of timbers. For. Prod. Res. Lab. Bull. 50. 2nd edition. HMSO, London. 62 p.

Mayer, H. 1985. Baumschwingungen und Sturmgefährdung des Waldes. Wiss. Mitt. Met. Inst., Münch. 51.

— 1987. Wind-induced tree sways. Trees 1. p. 195–206.

— 1989. Windthrow. Phil. Trans. R. Soc. Lond. B 324: 267–281.

Mayhead, G. J.1973a. Some drag coefficients for British forest trees derived from wind tunnel studies. Agr. Met. 12: 123–130.

Mayhead, G. J. 1973b. Sway periods of forest trees. Scott. For. 27(1): 19–23.

Oker-Blom, P., Kellomäki, S., Valtonen, E. & Väisänen, H. 1988. Structural development of Scots pine stands with varying initial density: a simulation model. Scand. J. For. Res. 3: 114–129.

Oliver, H. R. 1974. Windspeed modification by a very rough surface. Met. Mag. 103: 141–145.

— & Mayhead, G. J. 1974. Wind measurements in a pine forest during a destructive gale. Forestry 47(2): 185-194.

Papesh, A. J. G. 1974. A simplified theoretical analysis of the factors that influence windthrow of trees. 5 th. Australaisian Conference on Hydraulics and Fluid Mechanics. Univ. Canterbury, New Zealand. p. 235–242.

Peltola, H. 1990. Model computations on the critical windspeed for windthrow and stem breakage of Scots pine. Thesis for the degree of licentiate of science in agriculture and forestry. University of Joensuu, Faculty of Forestry. 63 p.

Peltola, H. & Kellomäki, S. 1993. A mechanistic model for calculating windthrow and stem breakage of Scots pines at stand edge. Unpublished manuscript. 15 p.

Pennala, E. 1980. Lujuusopin perusteet 407. Otakustantamo, Espoo. 355 p. [In Finnish].

Petty, J.A. & Worrel, R. 1981. Stability of coniferous tree stems in relation to damage by snow. Forestry 54(2): 115-128.

— & Swain, C. 1985. Factors influencing stem breakage of conifers in high winds. Forestry 58(1): 75–85.

Raymer, W. G. 1962. Wind resistance of coniferous. NPL Aero Rep. 1008: 1–20.

Raynor, G.S. 1971. Wind and temperature structure in a coniferous forest and a continuous field. For. Sci. 17: 351–363.

RIL 144. 1990. Rakenteiden kuormitusohjeet. Suomen Rakennusinsinöörien liitto. RIL r.y. 171 p. [In Finnish].

Sachs, P. 1978. Wind forces in engineering. Second edition. Pergamon Press. 400 p.

Savill, P. S. 1976. The effect of drainage and ploughing of surface water gleys on rooting and windthrow of Sitka spruce in Northern Ireland. Forestry 49(2): 133–141.

Sunley, J. G. 1968. Grade stresses for structural timbers. For. Prod. Res. Bull. 47: 1–18.

Tamminen, Z. 1962. Fuktighet, volymvikt mm. hos ved och bark. I Tall. Summary: Moisture content, density and other properties of wood and bark. I Scots pine. Rapp. Uppsats. Instn. Virk. Skogshögsk. 41. 118 p.

Walshe, D. E. & Fraser, A. I. 1963. Wind tunnel tests on a model forest. NPL Aero Rep. 1078. 41 p.

White, R. G., White, M. F. & Mayhead, G. J. 1976. Measurement of the motion of trees in two dimensions. Institute of Sound and Vibration Research, Southampton University, and Forestry Commission. 22 p.

Total of 41 references

Appendix 1. Estimation of some model parameters (see e.g. Sachs 1978, RIL 144 1990).