Forestry Commission

Occasional Paper 24

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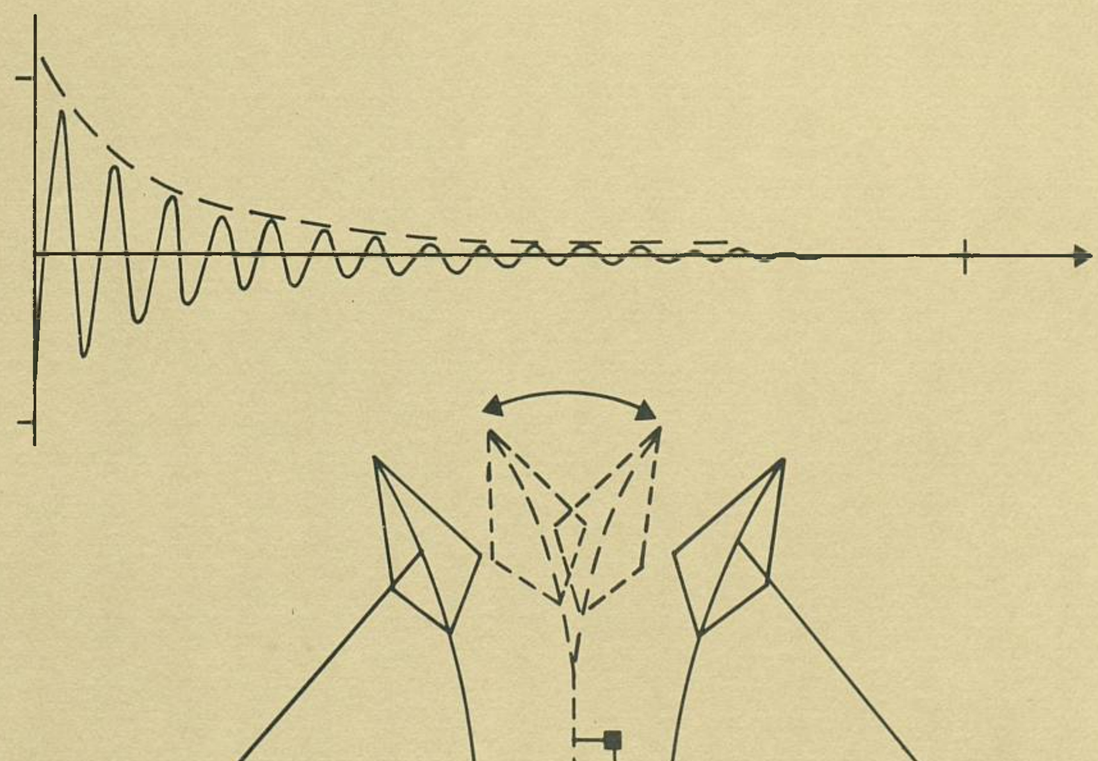
B.A. Gardiner



FORESTRY COMMISSION
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First published 1989

ISBN 0 85538 235 X

ODC 421:181.232:174.7 *Picea sitchensis* : (411)

Keywords: Tree mechanics, Wind, Forestry

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MECHANICAL CHARACTERISTICS OF SITKA SPRUCE

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Abstract

A series of tests has been carried out on 10 Sitka spruce trees about 15 metres tall in order to determine their mechanical characteristics. Such information is necessary for the design of model trees for use in wind-tunnel studies of airflow over forests.

Background

The Forestry Commission is collaborating with the University of Oxford Wind Engineering Research Group in an investigation of the airflow over a model forest as part of wider research into forest stability, partly funded by the EEC. The model trees are at a scale of 1:75 and are designed to represent 15 m tall Sitka spruce planted at approximately 3600 stems per hectare. To design the model trees it is necessary to know certain characteristics of full-size trees. This Paper describes mechanical tests which were carried out on 10 Sitka spruce trees in the Lauder and Rivox Forests in southern Scotland to meet this requirement. In addition, the stem shapes, distribution of stem mass with height, branch masses and branch lengths were determined. Tests were carried out between July and September under calm conditions. The forest blocks used for the tests were planted on single mouldboard ploughing in 1962 and have a yield class of between 14 and 16.

Objectives

To determine the physical and mechanical characteristics of a 'standard' Sitka spruce. Specifically these were described by:

a. the breast height diameter (dbh);

b. stem density;

c. the Young's Modulus – this provides a measure of the stem stiffness and the amount the tree bends under a specific load;

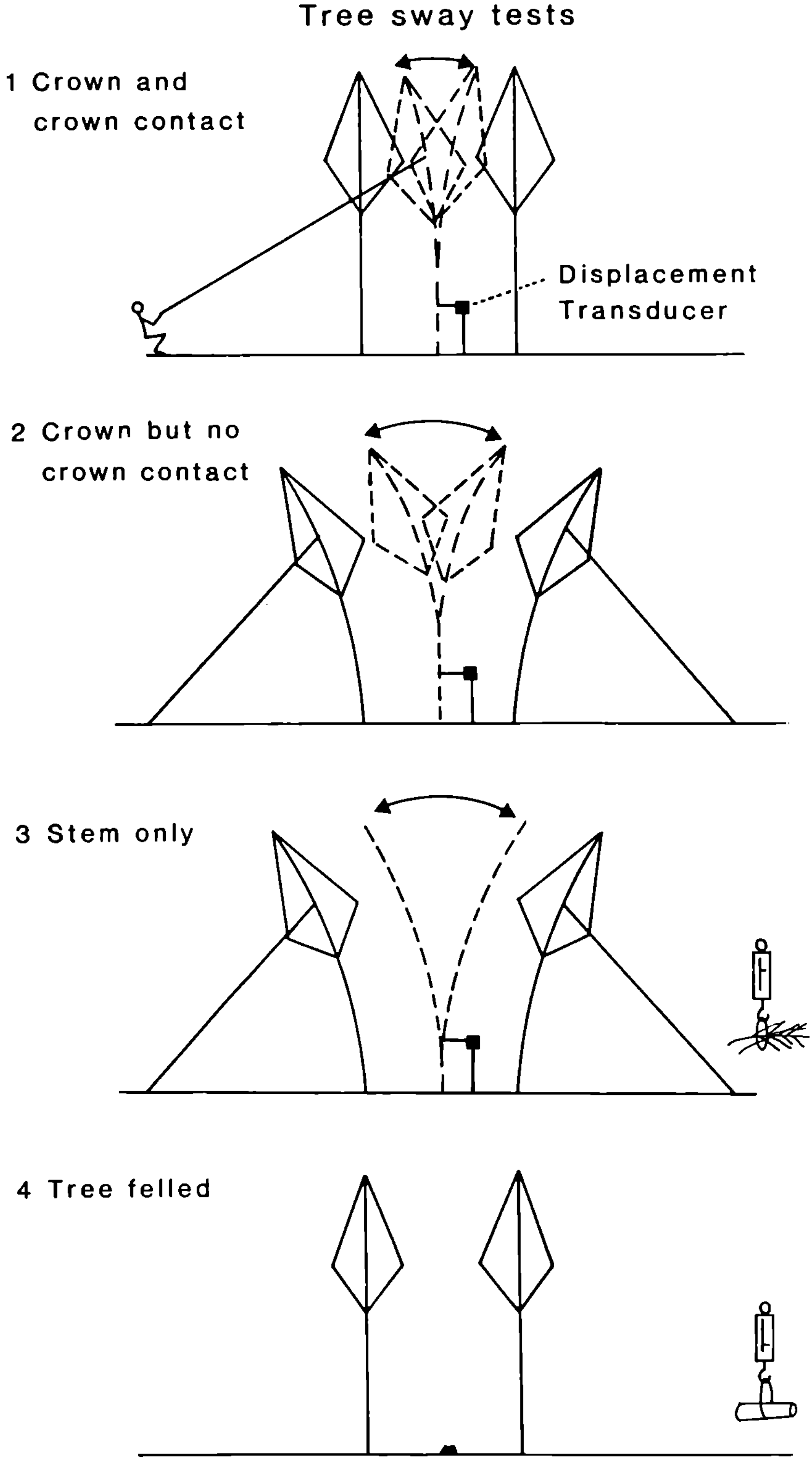

Figure 1. Schematic illustration of tree sway tests.

d. the natural vibration frequency of the whole tree and of the stem only;

e. the damping ratio of the whole tree both when in contact and when not in contact with its neighbours – this determines how quickly the motion of the tree dies out;

f. the stem shape;

g. the total stem and branch masses and their distribution with height.

Method

Sway tests

Figure 1 illustrates the method of carrying out the sway tests. A tree of height close to 15 m was selected and a displacement transducer on a 3 m post was attached to the stem of the tree. The tree was then made to sway by pulling on an attached rope and letting go. The movement of the tree was recorded on a logger for just over a minute The swaying was carried out with the tree in contact with the surrounding trees, with the surrounding trees pulled out of the way, and with the branches removed. In each case the tree was swayed three times along and three times across the direction of ploughing. Figure 2 shows an example of the tree oscillation, firstly with its crown but with no neighbour contact and secondly for the stem only. Such information allows the whole tree and stem vibration frequencies and damping ratios to be determined.

When the branches were removed for the final section of the sway tests the branches attached to each metre of the stem were weighed. The tree was finally felled and the length, diameter at breast height and diameter and weight for each metre of stem were measured.

Bending tests

Stem sections, 3 metres in length, from four trees were supported at each end and loaded in the centre (see Figure 3). The deflection at the centre was measured for different loads and this provides a means of calculating the Young's Modulus of the stem section using the expression (Cannell and Morgan, 1987):

$$E = \frac{PL^3}{48 I_A \delta}\left[\frac{2S^2}{L^2}\left\{\frac{3+KS}{(1+KS)^3} - \frac{1}{2(1+KL/2)^2}\right\}\right] \qquad (1)$$

where:

δ = deflection (m), P = load (kg), L = section length,
$I_A = \frac{\pi r_A^4}{4}$(Second Moment of Area),
$S = \frac{L}{1+(r_A/r_B)^{1/3}}$ $K = \frac{r_B - r_A}{r_A L}$,
r_A & r_B are the radii of the stem section at the thin and thick ends respectively.

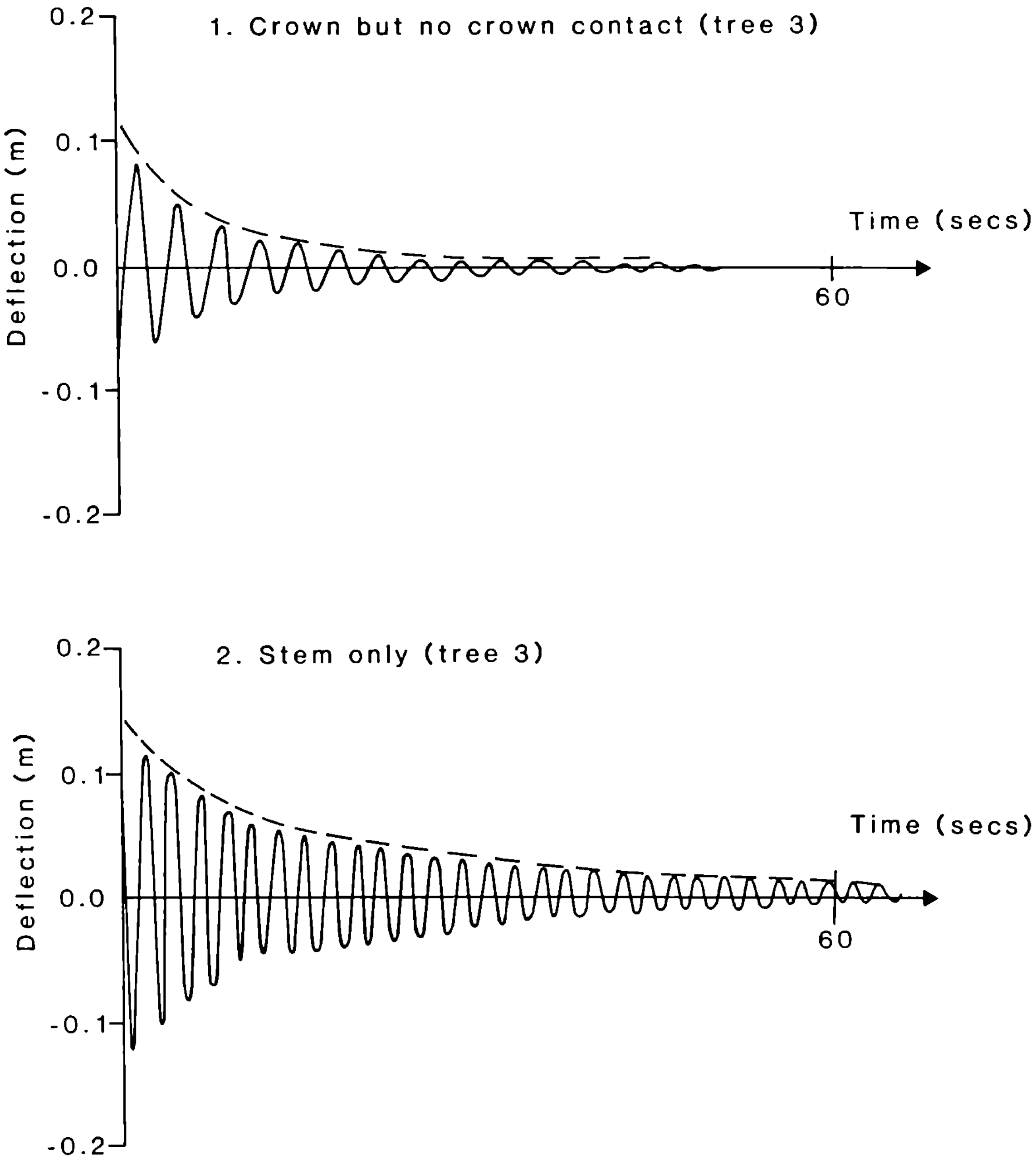

Figure 2. Oscillation of Tree 3 following pulling. The first trace is for the tree with its canopy but with no neighbour contact, the second trace is for the stem only.

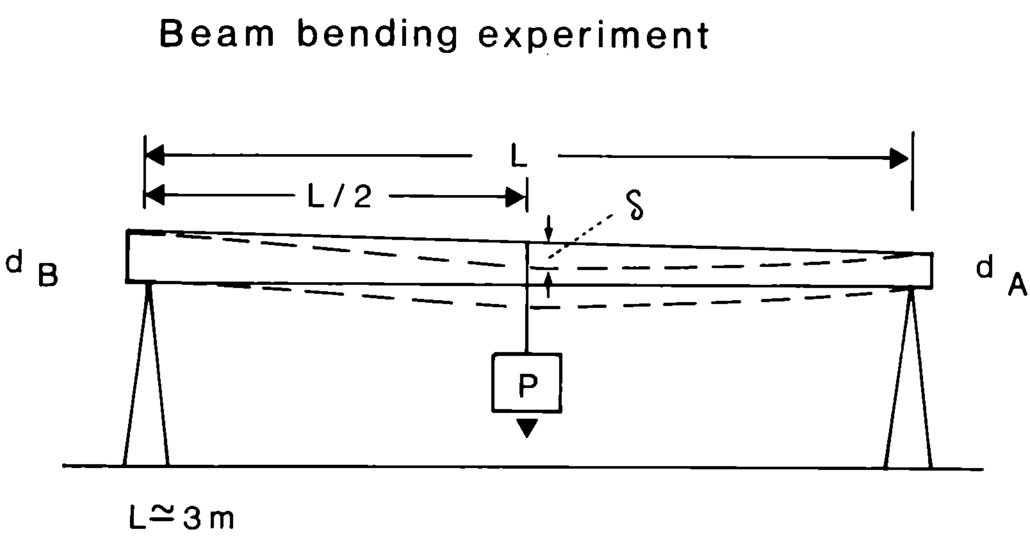

Figure 3. Schematic illustration of bending tests.

Results

A summary of parameters determined for each tree and for the 'standard' tree is presented in Table 1. The method of determining each of the 'standard' tree parameters is set now described.

a. *Height:* defined to be 15 metres.

b. *Diameter at breast height (DBH):* the DBH for each test tree was plotted against its height and from a best fit to the data the DBH for a tree of 15 metres height was obtained.

c. *Stem density:* derived from the average density of the 10 test trees. Individual densities were obtained by dividing the total stem mass by the total stem volume.

d. *Branch and stem mass:* a plot of the individual stem masses against tree height^2 × DBH showed a linear relationship. The stem mass of the 'standard' tree was obtained from this relationship using the height and DBH as defined above.

The branch mass for each tree showed a linear dependence on stem mass, so knowing the 'standard' tree stem mass allowed the 'standard' tree branch mass to be determined.

Table 1. Characteristics of 10 sample trees and 'standard' tree.

Characteristic	*Tree number*										*Standard*
	2	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*	*tree*
Height (m)	17.05	14.0	13.35	16.2	15.05	16.05	14.6	15.4	14.0	15.7	15.0
DBH (cm)	20.6	13.0	16.3	19.8	18.1	16.0	14.5	16.3	13.8	18.6	16.5
Stem weight(kg)	256.8	74.82	143.77	227.57	190.37	172.07	122.87	154.67	115.45	214.55	162.3
Branch weight(kg)	61.7	15.27	47.57	71.45	54.62	51.12	31.25	48.57	32.75	56.67	49.5
Density (kg m^{-3})	892.14	810.2	893.52	856.87	900.71	927.67	880.46	916.79	961.88	903.74	894.4
Resonant frequency(Hz)											
a.Stem only	0.53	0.49	0.70	0.57	0.60	0.43	0.49	0.52	0.51	0.51	0.54
b.Whole tree	0.33	0.32	0.43	0.36	0.37	0.26	0.30	0.30	0.30	0.29	0.33
Damping ratio											
a.With crown clashing	-	0.056	0.071	0.047	0.072	0.075	0.059	0.068	0.088	0.076	0.068
b.No crown contact	-	0.041	0.049	0.039	0.052	0.051	0.051	0.054	0.051	0.046	0.048
c.Stem only	-	0.013	0.015	0.013	0.013	0.020	0.016	0.014	0.018	0.015	0.015
Young's Modulus (GPa)											
a.Frequency method											5.67
b.Bending method	8.43	7.71		3.83	6.33						6.57
Drag (kg) at 20 m s^{-1} windspeed											161.8

e. *Damping ratios:* Derived from the average of the damping ratios for the individual trees. Individual damping ratios were obtained from the exponential decay of the amplitude of the tree sway as illustrated previously in Figure 2. The damping ratio (ζ) is defined by:

$$\zeta = \frac{1}{2\pi n} \ln\left(\frac{A_0}{A_n}\right) \tag{2}$$

where A_0 is the initial amplitude and A_n is the amplitude n cycles later.

No systematic variation of damping across and along the ploughing direction was discovered.

f. *Vibration frequencies:* from Figure 2 it is apparent that a resonant frequency can be derived for the whole tree and for the stem only. To obtain such frequencies for the 'standard' tree it is necessary to be able to define frequency in terms of the characteristics of the tree. Beginning with the stem only and treating it as a tapered cantilever beam, an analytic solution is possible if the stem shape can be described by the following function:

$$r_x = r_B\left(\frac{x}{L}\right)^n \tag{3}$$

where:
r_x is the radius at a point x metres from tip
r_B is the radius at the base
L is the tree length in metres
and $0.0 < n < 1.0$.

Figure 4 shows a plot of normalised height versus diameter normalised to the DBH for the 10 trees. (DBH was used in preference to base radius as the latter is influenced by buttressing.) The line through the points represents an equation of the form given above with $n = 0.6$. This provides a reasonable description of the stem shape, and solving for the resonant frequency we obtain:

$$\text{freq} = \frac{6.98 r_B}{4\pi L^2}\sqrt{\frac{E}{\rho}} \tag{4}$$

where E = Young's Modulus and ρ = density.

Assuming E and ρ are reasonably constant from tree to tree then the frequency should be proportional to $\frac{r_B}{L^2}$. Figure 5 is a plot for the 10 trees of frequency against $\frac{r_B}{L^2}$ (r_B has been calculated from DBH using equation 3 above). The relationship holds well both for the stem only and for the whole tree. Knowing the DBH and height of our 'standard' tree we can, therefore, obtain a value for both the stem only and the whole tree resonant frequencies.

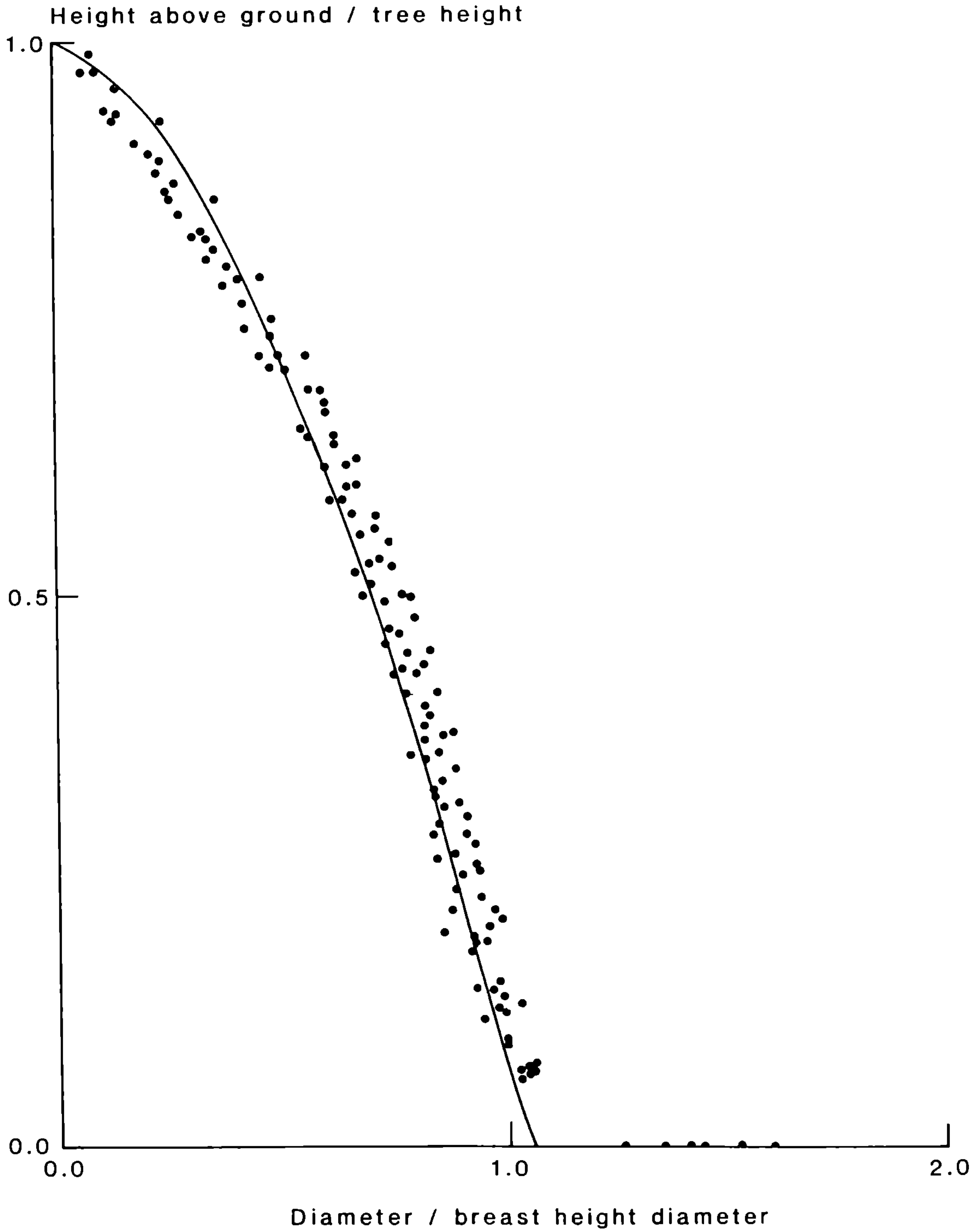

Figure 4. Normalised height versus normalised diameter for all 10 test trees. The solid line represents an equation of the form described in equation 3 with $n = 0.6$.

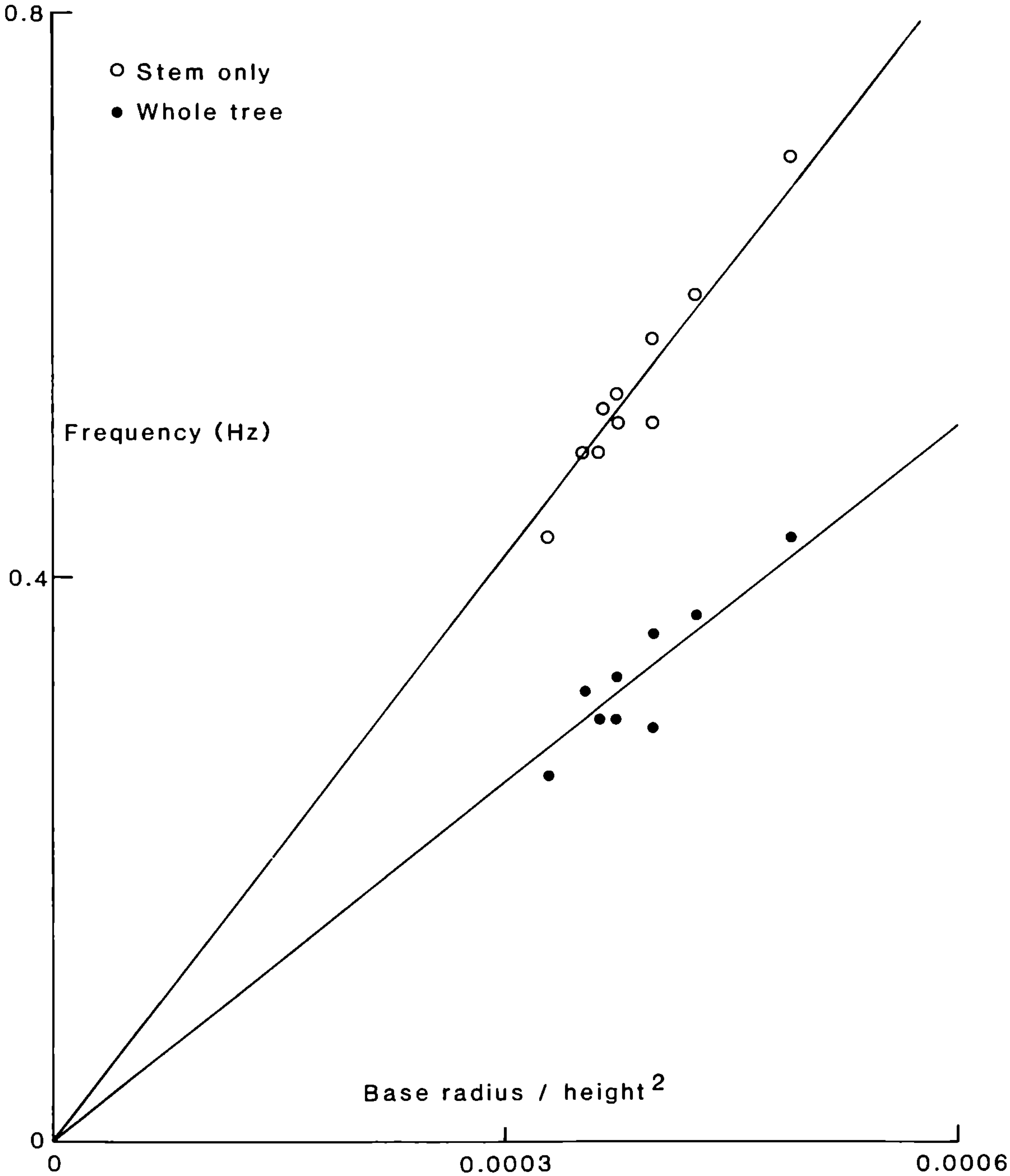

Figure 5. Stem and whole tree frequencies plotted against base radius/height^2. The solid lines represent least squares fits forced through the origin. (The base radius was estimated from the DBH using equation 3 and putting $x = L - 1.3$)

Again, no systematic difference in values obtained across and along the ploughing direction was discovered.

g. *Young's Modulus:* equation 4 also provides a method of obtaining Young's Modulus. The slope of Figure 5 is equal to $\frac{6.98}{4\pi}\sqrt{\frac{E}{\rho}}$. Since we already know ρ (see 5c above) the only unknown is E. A least squares fit on the stem only data in Figure 5 for a line forced through the origin gave a slope of 1393 and hence a value for $E = 5.67$GPa. This is similar to values quoted in Cannell and Morgan (1987).

The bending tests described on page 3 provide a direct measurement of Young's Modulus through the use of equation 1. The value obtained by performing bending tests on sections from four trees was 6.57±2.03GPa, which is in reasonable agreement with the result obtained using the frequency method.

h. *Stem shape under loading:* for a single point load acting at right angles to the stem and assuming the stem shape obeys a relationship of the form given in equation 3 it is possible to provide an analytic solution for the dislacement of the stem from the vertical (y). Taking n in equation 3 as 0.6 again, we obtain:

$$y = 2.98\frac{PL^3}{EI_B}\left[0.56 + 0.84d + 0.84\left(\frac{x}{L}\right) - 0.24d\left(\frac{x}{L}\right) - 0.6d\left(\frac{x}{L}\right)^{-0.4} - 1.4\left(\frac{x}{L}\right)^{0.6}\right] \quad (5)$$

where:

P = applied force, E = Young's Modulus, L = tree length,
$I_B = \frac{\pi r_B^4}{4}$, r_B = base radius, x = distance from tip and
d = distance from tip of applied load/length of tree.

This equation only describes the stem shape between the base and the load point, and is only valid for y less than approximately 1/10th the tree length (small displacements).

i. *Drag:* no new measurements were made and the estimate of drag was based on work by Mayhead, Gardiner and Durrant (1975). From wind-tunnel experiments they showed that the drag (kg) for Sitka spruce is given by:

$$D = 0.04436u^2m^{2/3}e^{-0.0009779u^2} \quad (6)$$

where m = live branch mass (kg) and u = windspeed m s^{-1}.

Determination of the live branch mass of the 'standard' tree is described in paragraph d on page 6.

Summary

A series of tests has been carried out on 10 Sitka spruce trees. This has enabled the characteristics of a 'standard' tree to be obtained, where the 'standard' tree seeks to represent the average characteristics of 15 metre trees grown at a density of approximately 3600 stems per hectare. Such information is necessary in the design of model trees for wind-tunnel studies and also in determining the response of full-size trees to wind loading.

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Typeset from computer text files
at the Forest Research Station, Alice Holt Lodge.

Printed and published by the Forestry Commission
231 Corstorphine Road, Edinburgh EH12 7AT
October 1989