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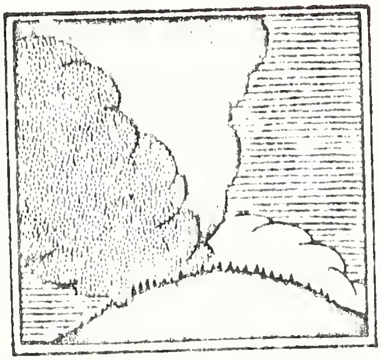

DIVISION OF FIRE RESEARCH
FOREST SERVICE
U. S. DEPARTMENT OF AGRICULTURE

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by

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Forest Service
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SUMMARY

In order to study the mechanics of wind action on trees, the induced resistance forces must be known. The principle wind resistance mechanism of trees arises from aerodynamic drag of the crown. This investigation was made to determine the aerodynamic drag of broadleaf crowns.

Eight species were tested, six in site class II or better, mixed hardwood stand in Pisgah National Forest, North Carolina, during the summer of 1952. The remaining species were tested in site class II or better, mixed conifer stand in Shasta National Forest, California, during the summer of 1950. A selected tree instrumented and mounted on the bed of a 1-ton truck with crown exposed above the cab was transported over a predetermined level, straight course at various steady speeds. Weight and moisture content of stem, branchwood and foliage, total height, crown length, and diameters at specified locations also were recorded.

The results are presented graphically by plotting drag force normalized with dry foliage weight against moment divided by dynamic pressure normalized with the cube of inside bark diameter at base of crown. Each species has its own curve although their general characteristics are the same.

The drag of two defoliated trees also was studied. Analysis reveals foliated trees offer 2 to 10 times greater aerodynamic drag.

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INTRODUCTION

The effect of wind on trees has been studied by many investigators interested in the physiological aspects of the problem. In order to study the mechanics of wind action, the induced resistance forces must be investigated in a manner which enables specification for trees of different size, crown structure, and/or species. These aerodynamic drag forces arise principally from the crown. The following is an analysis of crown drag measurements made on several broadleaf tree species.

One of the earliest investigations of wind action on trees was carried out by Metzger, who in 1893 proposed his mechanical stem form theory, which states that wind action on trees produces stems behaving as beams of uniform resistance. Since then, numerous workers such as Tirén (14,15),[1] Windirsch (17), and Jacobs (4) have studied the stem growth problem with Metzger's theory. Among those who disagree with Metzger's theory is Jaccard (2) who considers stem form the result not only of mechanical wind action but also of wind effect on transpiration and the force of gravity. Other workers have tried to discover the action of winds on root systems. Among the more recent is Pryor (8) whose studies on Monterey pine show that wind action stimulates growth in horizontal root systems but has little effect on vertical ones. Much literature devoted to the general problem of the action of wind on tree growth exists. Fritzsche (1), Jacobs (3), and more recently Merger (7) discussed the problem quite thoroughly; their discussions covered work done by other investigators not referenced here.

Despite the abundance of literature pertaining to wind action on trees, few workers attempted to measure the drag forces involved. Tirén attempted to estimate crown drag from conifer branch drag measurements made in a wind tunnel as part of his study on stem form. However, weighing the contribution to crown drag from different branch orientations is difficult. A recent crown drag study reported by Sauer (10) gives experimental results for entire conifer crowns rather than individual branches. Crown drag of saplings was measured in a wind tunnel; larger trees were tested by transporting specimens mounted on a truck bed. The data were correlated for each species with dimensionless parameters which permitted crown drag to be estimated from the dynamic pressure and tree characteristics.

Because of the differences in crown and foliage structure between broadleafs and conifers, it was believed that Sauer's conifer results would not apply. Therefore a study was made to determine the aerodynamic drag of several species of broadleafs under steady wind conditions.

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[1] For underlined numbers in parentheses, refer to Literature Cited, page 25.

EXPERIMENTAL PROCEDURE

This investigation was carried out in California and North Carolina. Full crown drag of eight species was studied (table 1); one each of American beech and scarlet oak was tested with defoliated crowns. Except for aspen and California black oak, specimens were selected from a site class II or better, mixed hardwood stand in Bent Creek Experimental Forest, Pisgah National Forest, North Carolina, elevation 2300 feet, in the summer of 1952. Aspen and black oak were selected from a site class II or better, mixed conifer stand in Shasta National Forest, California, elevation 4000 feet, in the summer of 1950. Individual trees were selected for good stem form, crown symmetry, and road accessibility. Foliage characteristics and availability were the basis upon which species were chosen. Test trees were felled in a manner to minimize crown damage.

The vehicle-test technique developed for the conifers study was used (10). Trees were instrumented with ring dynamometers and mounted on the bed of a 1-ton truck. Average velocity, moment force about the base of crown, and drag were measured by transporting these instrumented specimens at various steady speeds over predetermined level, straight courses. Upon completion of drag tests, weight and moisture content of stem, branchwood and foliage, total height, crown length, and diameters at specified locations were recorded for the specimen. These data were reduced and presented graphically in a manner similar to conifer results.

The North Carolina tests course was on highway 276 in the Pisgah National Forest. For the California tests, straight sections along highway 89 east of McCloud were used. Local effects were minimized by testing at the same velocities to and fro along the same course. Tests were performed during the early morning hours when surface winds and road hazards were at a minimum.

A range of speeds from 10 to 55 miles per hour (15 to 70 feet per second) at 5 m.p.h. intervals was used. Time was recorded from a stop watch with 0.002 minute least count. The lengths of test courses were chosen such that the velocity error was less than 2 percent.

The instrumentation system for the California trees was that used in the conifers study. Forces measured with ring dynamometers were recorded with a Foxboro SR-4 circular chart recorder. Readings from the circular charts had a least count corresponding to 10 pounds dynamometer load.

The above instrumentation was modified for the North Carolina tests (figure 1). The dynamometer at the base of crown measured the bending moment about the base of crown. The one close to the stem base, 5.16 below, connected in subtractive circuit with another matched dynamometer at the base of crown, measured the drag force. Measurements

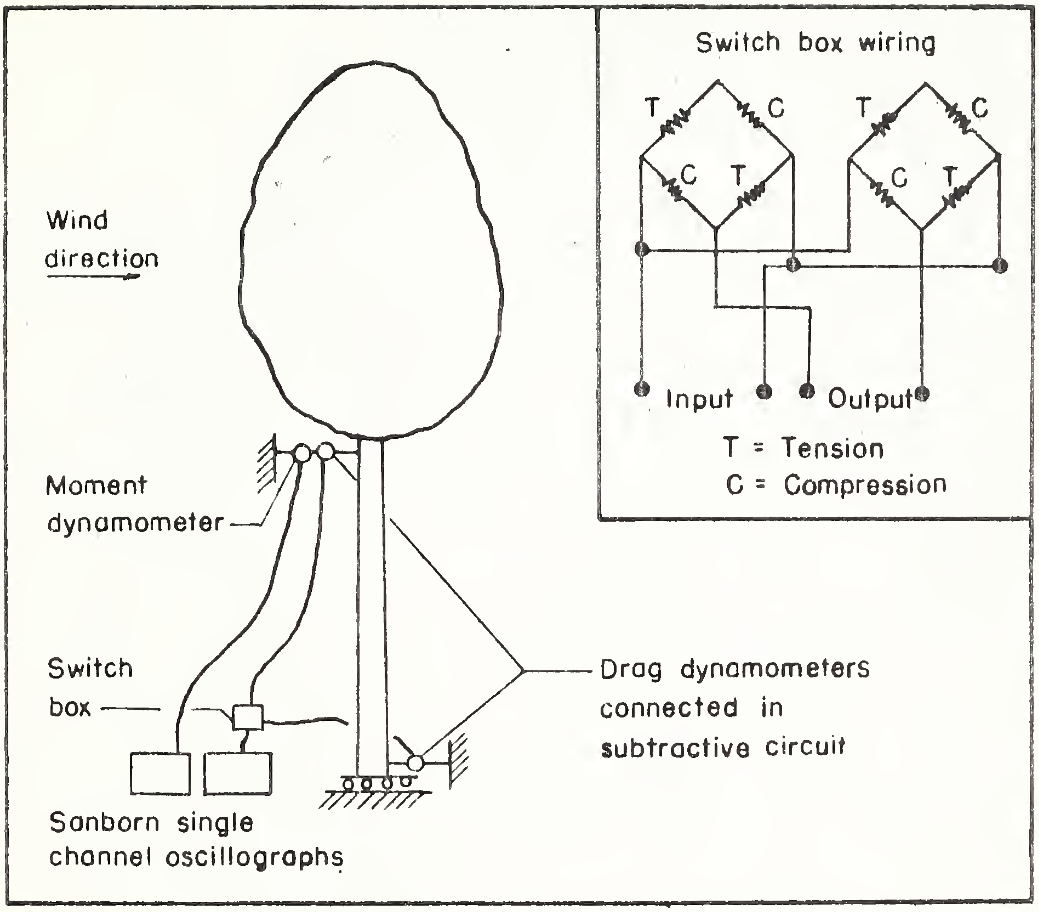

Figure 1.--Schematic diagram of instrumentation used for North Carolina tests

were recorded with single-channel Sanborn oscillographs operated off 24-V batteries through converters. This change in instrumentation allowed variable sensitivities which could not be obtained with the Foxboro recorder.

The least count of the oscillograph record is 1 millimeter. The least count of the reduced data varies with the gain and attenuation settings according to $K\frac{A}{D}$ where K is 31.4 pounds for drag measurements, and 20 pounds for moment measurements. An account of these least count variations is found in table 2 in Data and Results, under the heading "least count accuracy."

Table 1.- Foliage characteristics of test trees

Species	Leaf arrangement	Leaf shape	Leaf size range
Silver maple (Acer saccharinum L.)	Opposite, simple, deciduous	Circular-deeply palmately 5-lobed	6 to 7 in. diameter petioles 4 in. long
Sweet birch (Betula lenta L.)	Alternate, simple, deciduous	Ovate to oblong-ovate	2-1/2 to 5 in. long 1-1/2 to 2 in. wide petioles 1/2 to 3/4 in. long
Pignut hickory (Carya glabra Sweet)	Alternate, pinnately compound; 5 (rarely 7); sessile	Lance-shaped leaflets	8 to 12 in. long leaflets 4 to 6 in. long, 2 to 3 in. wide
American beech (Fagus grandifolia Ehrh.)	Alternate, simple, clustered at end of branchlets, deciduous	Oblong-ovate	2-1/2 to 5 in. long 1 to 2-1/2 in. wide petioles 1/4 to 1/2 in. long
Yellow-poplar (Liriodendron tulipifera L.)	Alternate, simple, deciduous	Tulip-like, usually 4-lobed with 2 lower broadest	4 to 6 in. long and wide
Quaking aspen (Populus tremuloides Michx.)	Alternate, simple, deciduous	Suborbicular to broadly ovate	1-1/2 to 2 in. diameter petioles 1-1/2 to 3 in. long
Scarlet oak (Quercus coccinea Muenchh.)	Alternate, simple, deciduous	Ovate or oblong-ovate	3 to 7 in. long 2 to 5 in. wide petioles 1 to 2-1/2 in. long
California black oak (Quercus kelloggii Newb.)	Alternate, simple, deciduous	Ovate or oblong-ovate	3 to 6 in. long about 2/3 length (width)

DATA AND RESULTS

The data have been correlated with dimensionless parameters that depend upon wind forces and tree characteristics (figures 2 to 5). These correlations are similar to the ones developed for conifers. The data are tabulated in table 2. Data for the defoliated trees are poor; hence no correlation is shown. Figure 6 shows the position of the center of pressure as a function of the dynamic pressure for several specimens tested. Estimation of an average center of pressure position may be obtained from figure 7 from tree parameters.

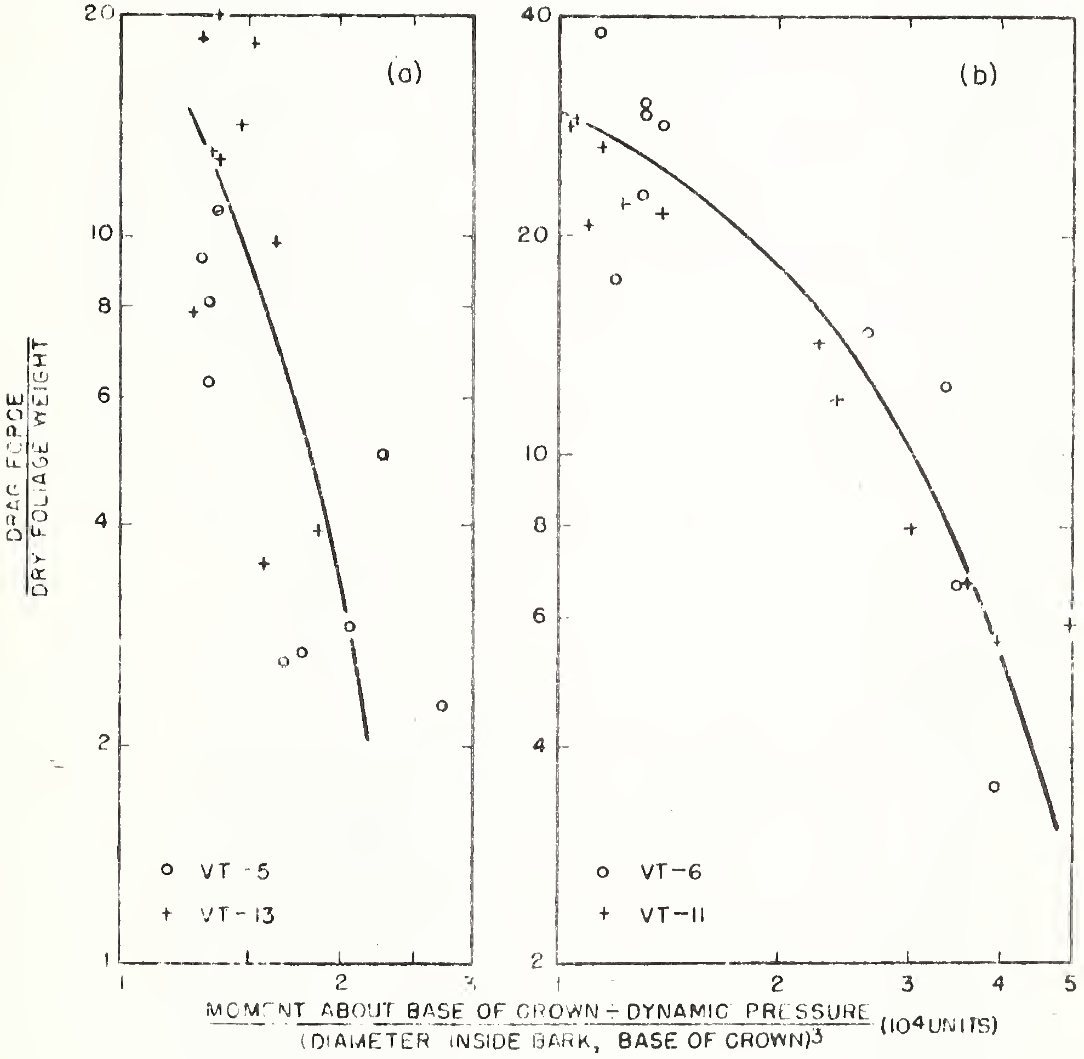

Figure 2.--Dimensionless correlation for (a) silver maple, and (b) sweet birch (full crown)

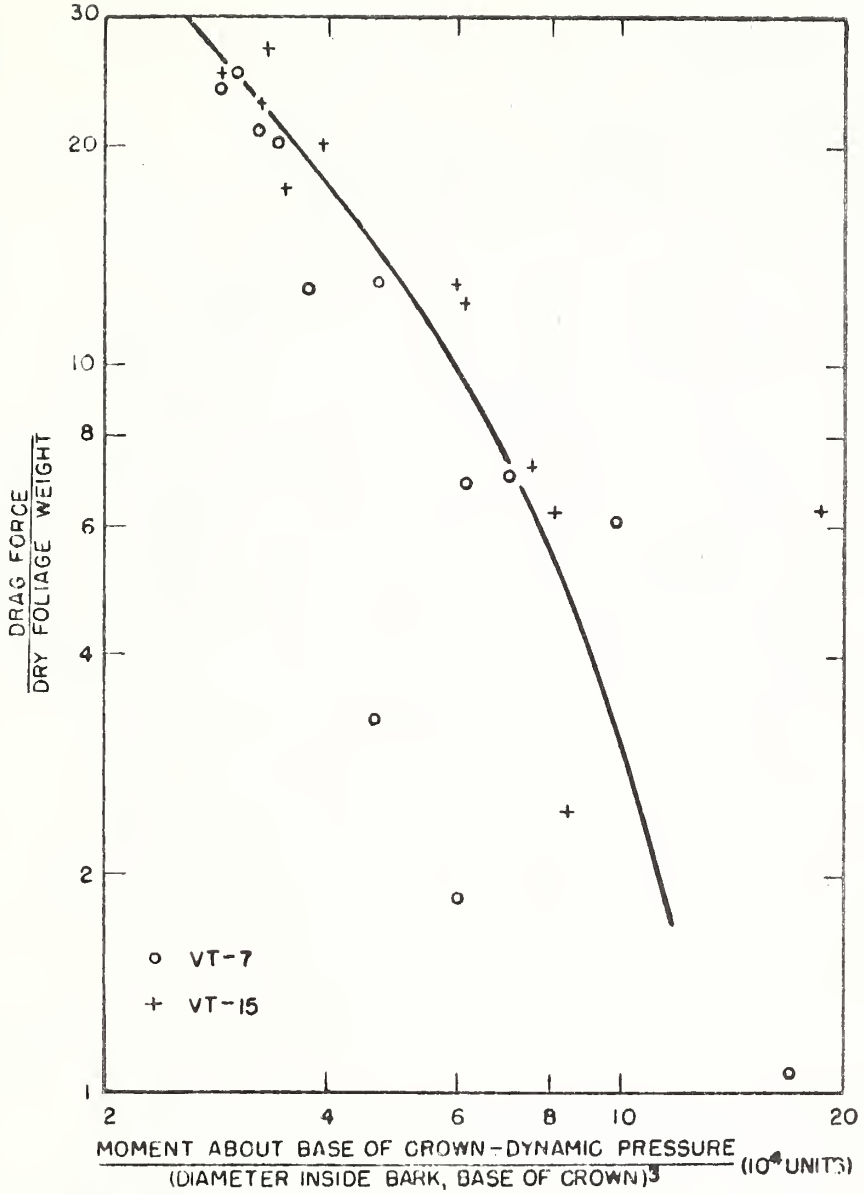

Figure 3.--Dimensionless correlation for pignut hickory (full crown)

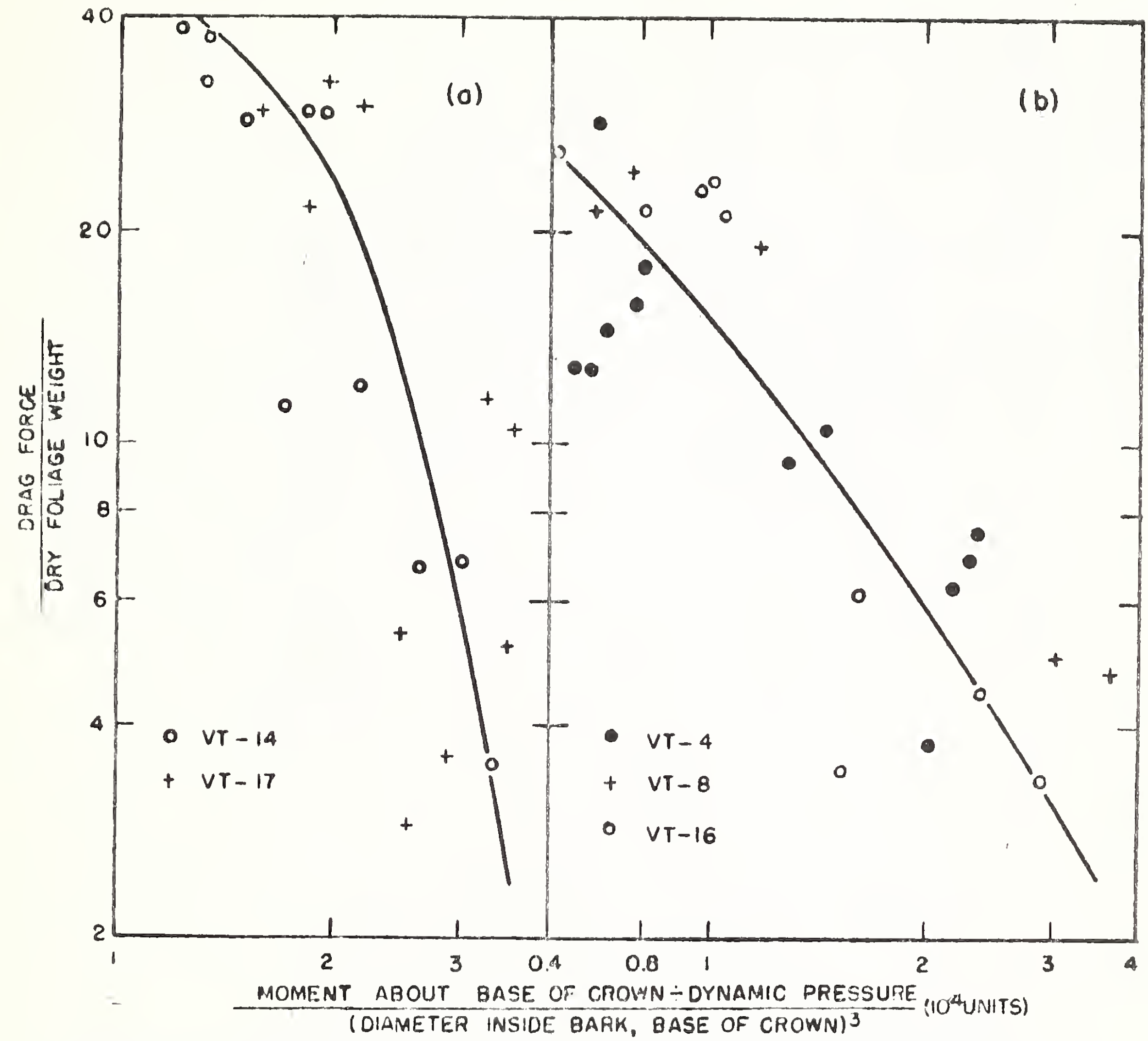

Figure 4.--Dimensionless correlation for (a) American beech, and (b) yellow-poplar (full crown)

DISCUSSION

Aerodynamic drag of a nonflexible body in submerged flow is a function of the geometry of the body, velocity, and fluid properties; specifically it is the product of drag coefficient, frontal area, and dynamic pressure. Drag coefficient is a function of Reynolds and/or Mach numbers. At low velocities, such as the range considered here, Reynolds number dominates.

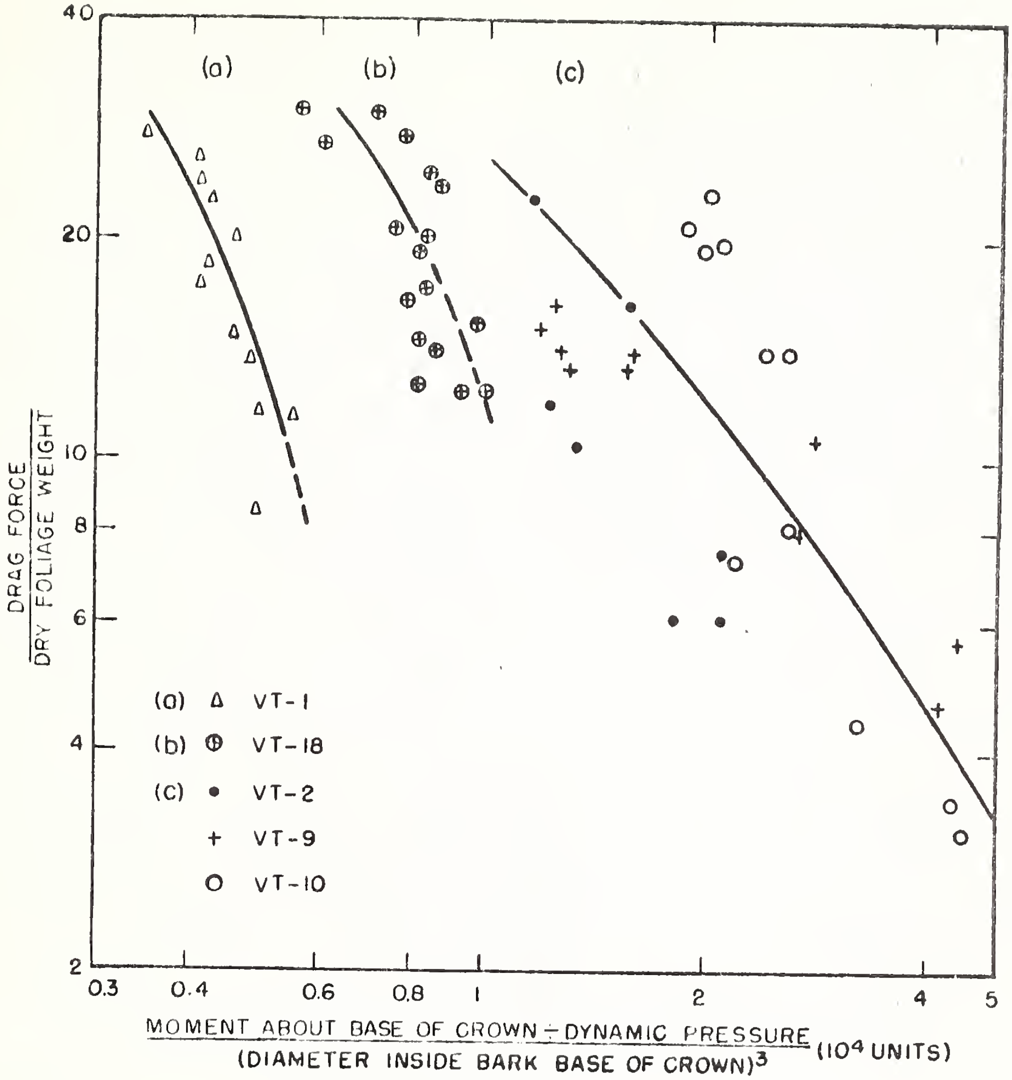

Figure 5.--Dimensionless correlation for (a) quaking aspen, (b) California black oak, and (c) scarlet oak (full crown)

For a flexible, porous body such as a tree crown, the area and porosity change constantly with dynamic pressure. These changes affect the drag coefficient and hence drag. Tirén (14,15) concluded that the exponent for the velocity is not constant with crown drag. Sauer (10) attributes the nonconformity of crown drag with rigid bodies to the change in drag coefficient and area. Since this study was patterned after the work of Sauer, the role of Reynolds number has been subjugated as was done for conifers. The above considerations indicate that crown drag coefficient and area must be represented with measurable tree crown characteristics.

Table 2.- Data for test trees

Species	Tree No.	Tree characteristics	[illegible]	[illegible]	T	[illegible]	Least count accuracy	M	Least count accuracy
			feet	minutes	°F	pounds	pounds	in.-lb.	in.-lb.
Silver maple (Acer saccharinum L.) $W_c = 102.758$ $W_{st} = 75.858$	[illegible] a	D_{bh} = 7.9 in.	500	.490	50	72.9	[illegible]	6,320	[illegible]
		d_c = [illegible] in.	"	[illegible]		76.3	[illegible]	6,350	4.0
			"	.368		61.7	[illegible]	16,300	[illegible]
		H_{bh} = [illegible] ft.	"	.364		[illegible]	[illegible]	14,[illegible]	[illegible]
		H_c = [illegible] ft.	"	.242		64.4	[illegible]	25,[illegible]	[illegible]
			500	.320		[illegible]	[illegible]	26,[illegible]	19.4
		W_{df} = [illegible] lb.	"	.268		171.0	[illegible]	[illegible]	[illegible]
			"	.270		[illegible]	7.0	[illegible]	20.8
		$\frac{W_{st}}{W_{df}}$ = [illegible]	1000	.302		[illegible]	[illegible]	48,600	22.2
$W_c = 83.904$	13 10 68.704	D_{bh} = [illegible] in.	500	.370	[illegible]	53.[illegible]	[illegible]	[illegible]	[illegible]
		d_c = [illegible]	"	.368		60.[illegible]	[illegible]	8,170	4.6
			"	.278		[illegible]	[illegible]	15,[illegible]	[illegible]
		H_{bh} = [illegible] ft.	"	[illegible]		[illegible]	[illegible]	18,100	7.7
		H_c = [illegible] ft.	800	.276		[illegible]	[illegible]	26,[illegible]	[illegible]
			"	.276		[illegible]	[illegible]	[illegible],600	[illegible]
		W_{df} = [illegible] lb.	"	.238		[illegible]	[illegible]	[illegible]	[illegible]
			"	.234		[illegible]	[illegible]	[illegible]	[illegible]
			"	[illegible]		283.0	[illegible]	[illegible]	[illegible]
		$\frac{W_{st}}{W_{df}}$ = [illegible]	"	.216		[illegible]	13.[illegible]	45,[illegible]	25.0
[illegible] $W_c = 35.266$	[illegible] 37.566	D_{bh} = [illegible] in.	500	.348	80	51.4	[illegible]	7,[illegible]	[illegible]
		d_c = 3.8 in.	"	[illegible]		27.0	[illegible]	[illegible]	[illegible]
			"	[illegible]		115.0	[illegible]	12,400	[illegible]
		H_{bh} = [illegible] ft.	"	.246		[illegible]	3.3	15,400	[illegible]
		H_c = [illegible] ft.	900	.230		135.0	[illegible]	15,900	9.8
			"	.200		[illegible]	[illegible]	23,[illegible]	11.9
		W_{df} = [illegible] lb.	"	[illegible]		[illegible]	6.2	20,700	[illegible]
			1000	.236		173.0	[illegible]	25,400	[illegible]
		$\frac{W_{st}}{W_{df}}$ = 3.58	"	[illegible]		[illegible]	7.2	26,[illegible]	[illegible]
			"	.216		[illegible]	7.1	26,[illegible]	[illegible]
$W_c = 47.045$	[illegible] 37.345 12	D_{bh} = [illegible] in.	500	.510	85	54.1	[illegible]	5,340	[illegible]
		d_c = [illegible] in.	"	.504		57.7	[illegible]	7,000	[illegible]
			"	.372		[illegible]	[illegible]	[illegible]	[illegible]
		H_{bh} = [illegible] ft.	"	.358		[illegible]	[illegible]	[illegible]	[illegible]
		H_c = [illegible] ft.	"	.226		[illegible]	[illegible]	[illegible]	[illegible]
			"	[illegible]		[illegible]	[illegible]	[illegible]	[illegible]
		W_{df} = 9.7 lb.	[illegible]	[illegible]		[illegible]	[illegible]	[illegible],500	[illegible]
			"	.233		[illegible]	[illegible]	[illegible],500	[illegible]
		$\frac{W_{st}}{W_{df}}$ = [illegible]	"	.212		[illegible]	[illegible]	[illegible],300	10.7
			"	[illegible]		[illegible]	[illegible]	[illegible],300	[illegible]
			1000	[illegible]		[illegible]	[illegible]	[illegible],600	[illegible]
			"	[illegible]		[illegible]	[illegible]	30,[illegible]	[illegible]
$W_c = 37.345$	[illegible] 37.345 12	D_{bh} = [illegible] in.	500	.276	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
		d_c = [illegible] in.	"	[illegible]		[illegible]	[illegible]	[illegible]	1.7
			"	[illegible]		[illegible]	[illegible]	[illegible]	[illegible]
		H_{bh} = [illegible] ft.	"	[illegible]		[illegible]	[illegible]	[illegible]	[illegible]
		H_c = [illegible] ft.	800	[illegible]		[illegible]	[illegible]	[illegible]	[illegible]
			"	[illegible]		[illegible]	[illegible]	[illegible]	[illegible]
		W_{df} = [illegible]	"	[illegible]		[illegible]	[illegible]	[illegible]	[illegible]
			1000	[illegible]		[illegible]	[illegible]	15,800	[illegible]
		$\frac{W_{st}}{W_{df}}$ = --	[illegible]	.184		[illegible]	[illegible]	[illegible]	[illegible]
			"	.188		[illegible]	[illegible]	[illegible]	[illegible]
			[illegible]	[illegible]		[illegible]	4.7	[illegible]	[illegible]
			"	[illegible]		[illegible]	[illegible]	[illegible]	[illegible]
Pignut hickory (Carya glabra Sweet) $W_c = 57.824$	7 43.924 12	D_{bh} = 6.5 in.	500	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
		d_c = [illegible] in.	[illegible]	[illegible]		[illegible]	[illegible]	[illegible]	[illegible]
		H_{bh} = [illegible] ft.	"	[illegible]		[illegible]	[illegible]	[illegible]	[illegible]
		H_c = [illegible] ft.	"	[illegible]		[illegible]	[illegible]	[illegible]	[illegible]
		W_{df} = [illegible] lb.	"	[illegible]		[illegible]	[illegible]	[illegible]	[illegible]
			800	[illegible]		[illegible]	[illegible]	[illegible]	[illegible]
		$\frac{W_{st}}{W_{df}}$ = [illegible]	"	[illegible]		[illegible]	[illegible]	[illegible]	[illegible]
$W_c = 62.006$	15 51.706 11	D_{bh} = [illegible] in.	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
		d_c = [illegible] in.	"	[illegible]		[illegible]	[illegible]	[illegible]	[illegible]
		H_{bh} = [illegible] ft.	"	[illegible]		[illegible]	[illegible]	[illegible]	[illegible]
		H_c = [illegible] ft.	"	[illegible]		[illegible]	[illegible]	[illegible]	[illegible]
		W_{df} = [illegible] lb.	800	[illegible]		[illegible]	[illegible]	[illegible]	[illegible]
		$\frac{W_{st}}{W_{df}}$ = [illegible]	"	[illegible]		[illegible]	[illegible]	[illegible]	[illegible]
American beech (Fagus grandifolia Ehrh.) $W_c = 64.555$	14 55.90 11	D_{bh} = 5.7 in.	500	[illegible]	50	[illegible]	1.7	[illegible]	[illegible]
		d_c = [illegible] in.	"	[illegible]		[illegible]	[illegible]	[illegible]	[illegible]
		H_{bh} = [illegible] ft.	"	[illegible]		[illegible]	[illegible]	[illegible]	[illegible]
		H_c = 25.3 ft.	800	[illegible]		[illegible]	[illegible]	[illegible]	[illegible]
		W_{df} = [illegible] lb.	"	[illegible]		[illegible]	[illegible]	[illegible]	[illegible]
		$\frac{W_{st}}{W_{df}}$ = [illegible]	"	[illegible]		[illegible]	7.5	[illegible]	[illegible]
$W_c = 108.609$	17 96.309 10	D_{bh} = [illegible] in.	500	[illegible]	50	[illegible]	[illegible]	[illegible]	[illegible]
		d_c = [illegible] in.	"	[illegible]		[illegible]	[illegible]	[illegible]	[illegible]
		H_{bh} = [illegible] ft.	"	[illegible]		[illegible]	[illegible]	14,300	[illegible]
		H_c = [illegible] ft.	"	[illegible]		[illegible]	[illegible]	[illegible]	[illegible]
		W_{df} = [illegible] lb.	800	[illegible]		[illegible]	[illegible]	[illegible]	[illegible]
		$\frac{W_{st}}{W_{df}}$ = [illegible]	"	.200		[illegible]	[illegible]	[illegible]	[illegible]

[a] For a [illegible] list of symbols, see Nomenclature, page [illegible].

[b] [illegible] atmospheric pressure for the summer was used, [illegible] in mercury.

[c] [illegible]

[d] [illegible]

Table 2.- Data for test trees (continued)

Species	Tree No.	Tree characteristics[1]	l[1]	t	T[2]	D	Least count accuracy	M	Least count accuracy
			feet	minutes	°F	---pounds---		---in.-lb.---	
Yellow-poplar (Liriodendron tulipifera L.) w_c = 24.3 16.2 12	[illegible]	[3]D_{bh} = 8.2 in.	500	.494	65	30.6	1.9	2,650	4.6
		[4]d_c = 4.[illegible] in.	"	.458		51.0	1.9	3,1[illegible]	4.8
		H_{bh} = 57.[illegible] ft.	"	.354		60.8	2.5	6,360	4.0
		H_c = 26.4 ft.	"	.360		56.3	2.0	6,120	2.7
		W_{df} = [illegible].1 lb.	"	.246		75.8	2.2	7,420	4.1
		$\frac{W_{db}}{W_{df}}$ = 2.00	"	.236		85.4	2.7	9,020	4.1
			800	.236		120.0	3.6	11,700	5.4
			"	.242		117.0	3.8	13,900	5.3
			"	.256		100.0	3.0	13,[illegible]	6.[illegible]
			"	.208		99.3	2.8	13,[illegible]	6.[illegible]
			1000	.206		211.0	11.4	19,[illegible]	20.0
			"	.222		230.0	11.8	19,400	20.1
w_c = 56.166 42.366 5	8	[3]D_{bh} = 9.2 in.	500	.406	70	68.8	2.2	9,210	5.1
		[4]d_c = [illegible].2 in.	"	.256		65.0	1.9	10,2[illegible]	4.9
		H_{bh} = 47.[illegible] ft.	1000	.201		262.0	9.7	25,2[illegible]	20.0
		H_c = 24.[illegible] ft.	500	.182		294.0	8.5	26,[illegible]	19.4
		W_{df} = 13.8 lb.	"	.194		333.0	9.2	34,[illegible]	25.6
		$\frac{W_{db}}{W_{df}}$ = 3.07							
w_c = 35.264 23.664 8	16	[3]D_{bh} = 6.9 in.	500	.472	74	39.0	2.0	6,750	3.1
		[4]d_c = 4.6 in.	"	.364		51.9	2.1	9,510	4.2
		H_{bh} = 34.7 ft.	"	.225		40.3	1.9	10,400	6.0
		H_c = 24.9 ft.	"	.234		70.6	2.1	15,[illegible]00	6.6
		W_{df} = 11.6 lb.	800	.206		224.0	7.7	33,300	22.7
		$\frac{W_{db}}{W_{df}}$ = 2.04	"	.196		274.0	7.7	35,200	22.[illegible]
			"	.152		247.0	7.8	32,400	18.9
			"	.186		264.0	7.9	35,100	18.1
Quaking aspen (Populus tremuloides Michx.) W_c = 30.784 25.584 2	1	[3]D_{bh} = 10.2 in.	1579	.730	58	42.8	10.0	4,940	659.0
		[4]d_c = 4.8 in.	2605	.854	51	74.9	"	9,160	"
		H_{bh} = 59.5 ft.	1348	.446	"	59.5	"	9,500	"
		H_c = 13.7 ft.	2344	.678	"	94.2	"	10,300	"
		W_{df} = 5.2 lb.	1604	.376	46	142.0	"	13,700	"
		$\frac{W_{db}}{W_{df}}$ = 4.92	1579	.432	"	121.0	"	12,300	"
			1579	.500	"	102.0	"	9,900	"
			2605	.396	42	58.8	"	7,390	"
			1348	.528	"	58.8	"	5,120	"
			2344	.674	"	98.8	"	11,000	"
			1604	.376	"	132.0	"	16,200	"
			1578	.420	"	116.0	"	13,100	"
Scarlet oak (Quercus coccinea Muenchh.) w_c = 46.62 36.12 7	2	[3]D_{bh} = 7.5 in.	500	.364	86	62.9	39.3	[illegible],530	48.8
		[4]d_c = 4.0 in.	"	.232		63.5	42.4	12,900	41.7
		H_{bh} = 46.4 ft.	"	.236		77.6	38.8	12,400	43.6
		H_c = 22.6 ft.	800	.230		109.0	45.5	21,500	40.2
		W_{df} = 10.6 lb.	"	.244		125.0	40.3	17,[illegible]00	37.4
		$\frac{W_{db}}{W_{df}}$ = 3.44	"	.220		170.0	16.7	27,[illegible]	30.[illegible]
			1000	.212		238.0	12.7	34,200	26.3
Scarlet oak (continued) 12 36 W_c = 36.12 12	3	[3]D_{bh} = 7.5 in.	500	.366	82	[illegible]	2.0	1,390	1.2
		[4]d_c = 4.0 in.	"	.234		75.7	2.2	4,880	5.6
		H_{bh} = 46.4 ft.	"	.208		32.7	1.9	5,030	5.2
		H_c = 22.6 ft.	800	.140		33.5	2.1	8,070	4.2
		W_{df} = 0.0	1000	.308		31.0	1.8	11,600	5.2
		$\frac{W_{db}}{W_{df}}$ = --	600	.222		49.5	1.5	8,[illegible]	5.2
			"	.216		65.9	1.8	9,070	4.1
			"	.206		62.4	1.8	12,100	4.6
			1000	.238		94.3	2.8	15,700	6.8
			"	.239		97.2	3.0	17,[illegible]	26.7
			"	.212		101.0	3.0	16,600	6.7
			"	.212		89.2	2.8	17,500	7.1
W_c = 58.05 45.15 10	9	[3]D_{bh} = 9.[illegible] in.	500	.350	85	72.8	2.1	14,300	6.4
		[4]d_c = 4.2 in.	"	.364		60.3	2.0	12,400	5.5
		H_{bh} = 56.9 ft.	"	.234		102.0	3.1	19,500	9.1
		H_c = 22.3 ft.	"	.228		137.0	4.5	21,400	9.6
		W_{df} = 12.9 lb.	800	.232		174.0	5.5	24,700	27.4
		$\frac{W_{db}}{W_{df}}$ = 3.50	"	.220		150.0	8.5	33,300	19.2
			"	.198		171.0	7.5	31,500	19.4
			"	.198		181.0	7.8	33,300	22.7
			1000	.228		209.0	8.7	37,600	21.3
			"	.225		195.0	6.0	36,100	19.[illegible]
W_c = 71.576 53.176 11	10	[3]D_{bh} = 9.6 in.	500	.500	85	62.5	2.1	8,310	4.6
		[4]d_c = 4.5 in.	"	.456		56.9	2.0	9,000	4.8
		H_{bh} = 49.8 ft.	"	.368		79.8	2.5	11,100	6.0
		H_c = 23.2 ft.	"	.224		134.0	4.4	20,[illegible]	10.0
		W_{df} = 18.4 lb.	"	.332		150.0	5.2	25,300	11.4
		$\frac{W_{db}}{W_{df}}$ = 2.89	800	.275		258.0	9.9	39,600	23.1
			"	.272		256.0	7.8	39,900	20.8
			"	.214		380.0	9.4	49,300	23.5
			"	.229		345.0	9.1	46,100	23.0
			"	.220		374.0	10.3	49,900	22.2
			"	.218		359.0	10.6	52,800	23.5
California black oak (Quercus kelloggii Newb.) 35.113 17 W_c = 42.413	18	[3]D_{bh} = --	1579	.450	58	123.0	10.0	15,000	659.0
		[4]d_c = 4.5 in.	2605	.930	"	91.0	"	11,700	"
		H_{bh} = --	1348	.490	"	101.0	"	11,700	"
		H_c = 13.5 ft.	1604	.380	"	215.0	"	18,500	"
		W_{df} = 7.3 lb.	1579	.440	"	194.0	"	14,300	"
		$\frac{W_{db}}{W_{df}}$ = 4.81	1579	.722	"	110.0	"	6,450	"
			2605	1.000	56	88.8	"	11,600	"
			1348	.526	"	88.8	"	12,000	"
			2344	.726	50	139.0	"	15,700	"
			1604	.774	"	214.0	"	24,200	"
			1579	.440	"	177.0	"	20,300	"
			1673	.474	"	150.0	"	15,600	"
			2605	.540	48	118.0	"	13,700	"
			1348	.446	"	104.0	"	13,300	"
			2344	.696	"	[illegible]	"	17,400	"
			1604	.396	"	196.0	"	23,400	"
			1579	.470	"	171.0	"	18,000	"

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[1] For definition of symbols, see Nomenclature, page 27.
[2] An average atmospheric pressure for the summer was used, 27.90 in mercury.
[3] Outside bark.
[4] Inside bark.

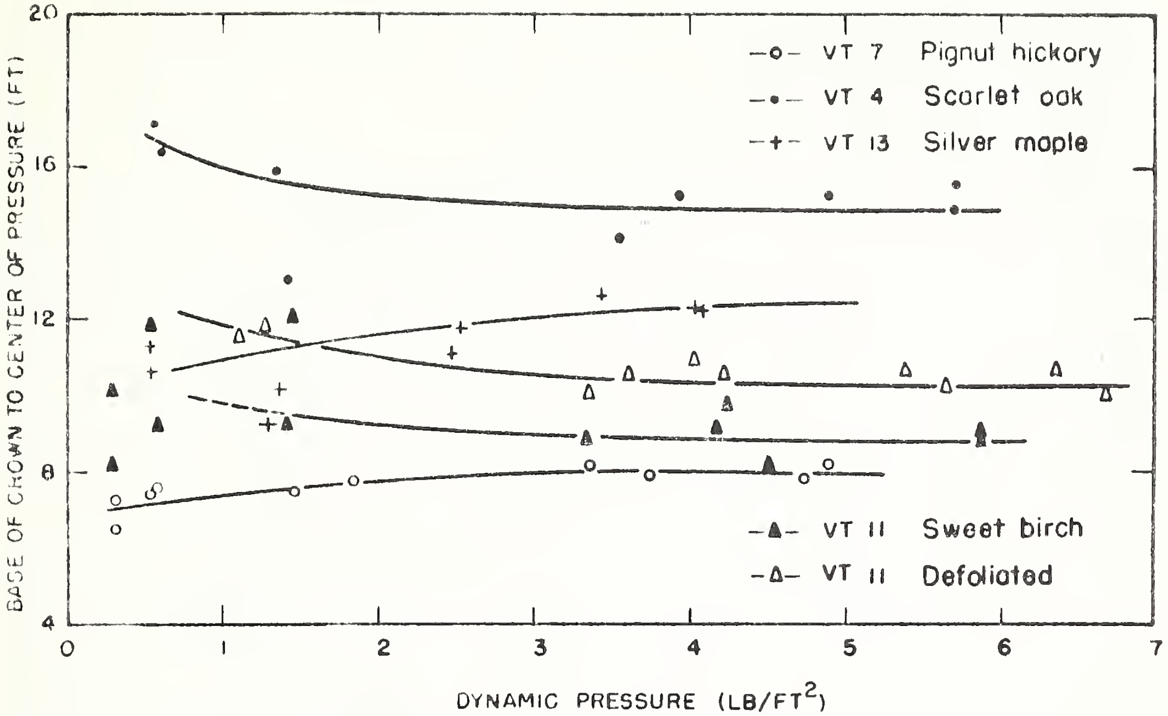

Figure [illegible].--Variation of center of pressure position with dynamic pressure

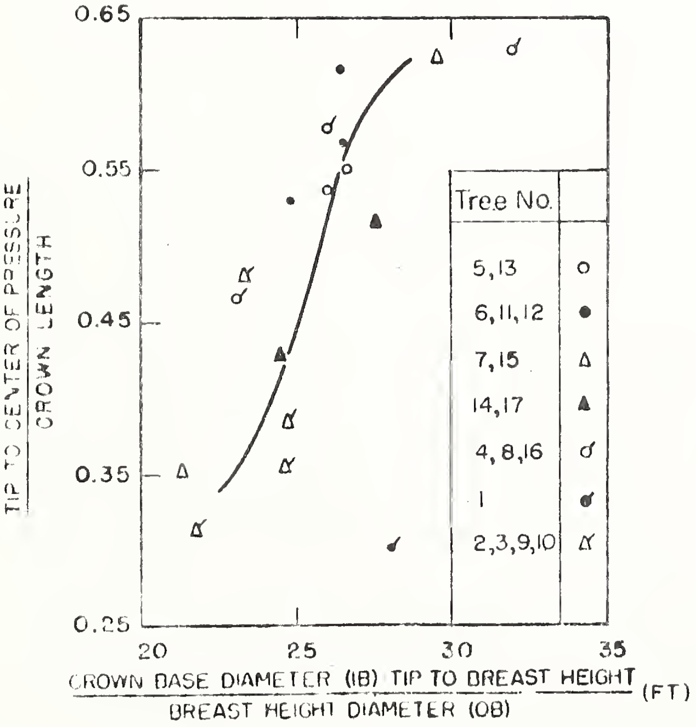

Figure 7.--Variation of average center of pressure position with tree parameters

The bending of tree crown and stem under the influence of wind forces results in a restoring couple, the magnitude of which is dependent upon the magnitude of the drag force and mechanical properties of the wood. This couple and drag force together with the dynamic pressure and tree characteristics must therefore combine to express the aerodynamic behavior of the crown.

Figures 2 to 5, inclusive, show the empirically correlated curves between drag force and moment about the base of crown normalized with dynamic pressure and tree parameters. These correlation groupings are similar to those used for conifers. The moment was chosen about the base of crown to indicate the degree of crown movement.

Comparison of raw data for conifers, North Carolina broadleafs, and California broadleafs indicates a greater variability for the North Carolina data. This variation cannot be reduced by correlation.

The tree characteristics used differ from those found to be important for conifers. Drag for conifers was normalized with dry crown weight. Broadleaf trees, unlike conifers, often do not exhibit a central stem. Their branchwood weights constitute the major portion of the crown weight (table 2). If drag per unit dry crown weight were used, the effect of foliage would be overshadowed. For this reason, the drag was computed on the basis of per unit dry foliage weight.

Dry branchwood to foliage weight ratio was shown to be important for conifers (10). Because of the size range of broadleaf trees, variations in this ratio were small in most cases. For specimens with large differences, scatter of the data hid its effect on the correlation. Because of this, the ratio was eliminated from consideration.

Two defoliated trees were tested with the same procedure. Unfortunately the data are too meager for correlation. Nevertheless, comparison of the raw data shows that presence of foliage increases the drag from two- to tenfold (figure 8). This fact was brought out quantitatively by Sauer (10).

The center of pressure position calculated from the data remained fairly constant for the most part over the dynamic pressure range studied (figure 6). Below a dynamic pressure of approximately 2 pounds per square foot, which is equivalent to about 44 feet per second wind velocity, the center of pressure position for some trees ascended, some remained substantially constant, while others descended. Quantitative considerations indicate variation in position of center of pressure with wind velocity depends upon combinations of stem and branch properties (table 3).

Branch and stem stiffness was not measured. Examination of figure 6 indicates a maximum change in location of the pressure center of about 20 percent. Since the data do not allow rectification of these changes, a plot of the average center of pressure position is given (figure 7).

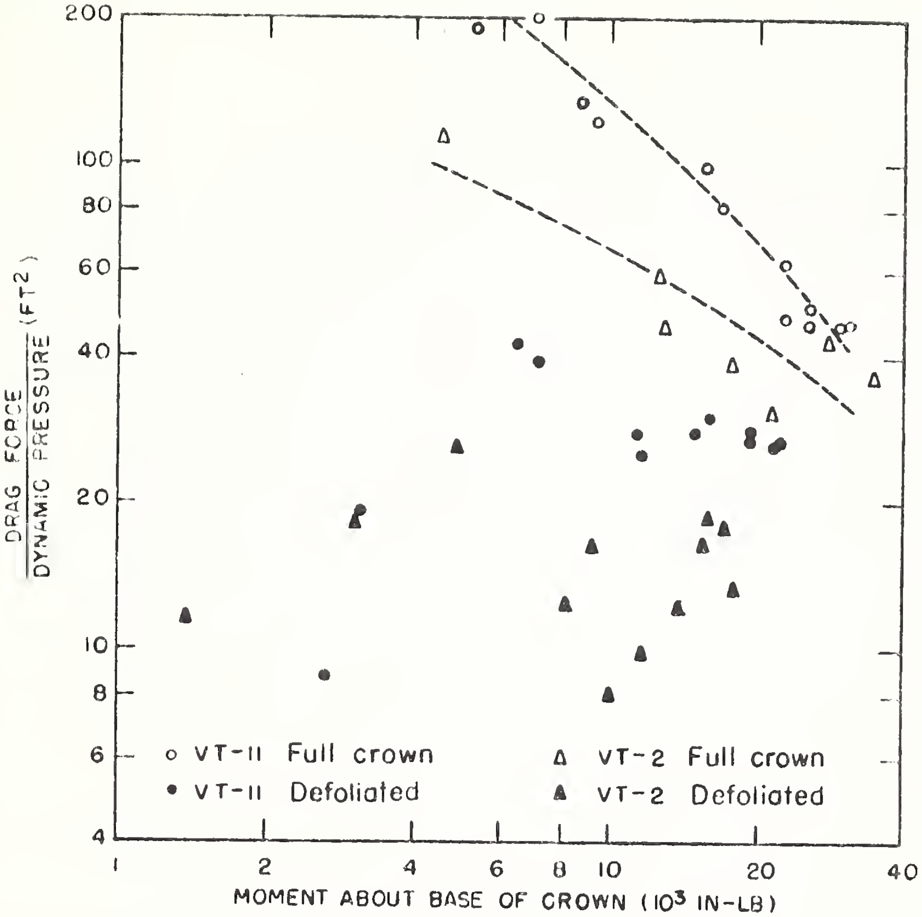

Figure 8.--Comparison of full and defoliated crown drag (VT-11 Sweet birch, VT-2 Scarlet oak)

Table 3.- Reaction of center of pressure position to increase in velocity

Branch	Stem	Reaction
stiff	stiff	remain constant
limber	stiff	ascend
limber	limber	descend

The mechanical properties of the stem, important from the standpoint of strength of materials, have been left out because their effect on the data does not justify complicating the correlation. The role of mechanical properties can be determined only by more experimentation.

A basic mechanical property which enters into stress determinations is the modulus of elasticity. Table 4 lists the average green modulus of elasticity for the various test specimens in descending order. The more supple, hence smaller modulus of elasticity, tree will bend more for a given dynamic pressure.[2] Therefore, the drag will be less and a higher dynamic pressure will be necessary to produce the same drag. Figure 9 shows that the order in the table follows approximately the order of the curves from right to left.

Table 4.-- Average modulus of elasticity for green wood determined with standard test specimens[1]

Species[2]	Modulus of elasticity of green wood (thousand psi)
Hickory, pignut	1650
Birch, sweet	1650
Oak, scarlet	1480
Beech	1380
Poplar, yellow	1090
Maple, silver	940
Aspen	860
Oak, California black	740

[1] Little is known about the modulus of elasticity of living trees

[2] See (5)

If the order of the curves were proportionally distributed, division of the independent variable by the modulus of elasticity to some power should bring the curves together. Since the order is not proportional, the curves cannot be brought together with the modulus of elasticity alone.

The influence of foliage characteristics on drag is inconclusive. However, it is interesting to note (figure 9) that hickory and aspen are at the two extremes of the band of curves. Table 1 shows that hickory has alternate pinnately compounded leaves 8 to 12 inches long while aspen has simple alternate leaves, 1-1/2 to 2 inches in diameter.

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[2] Tirén measured fir branch drag and found supple branches afford less resistance per given wind velocity.

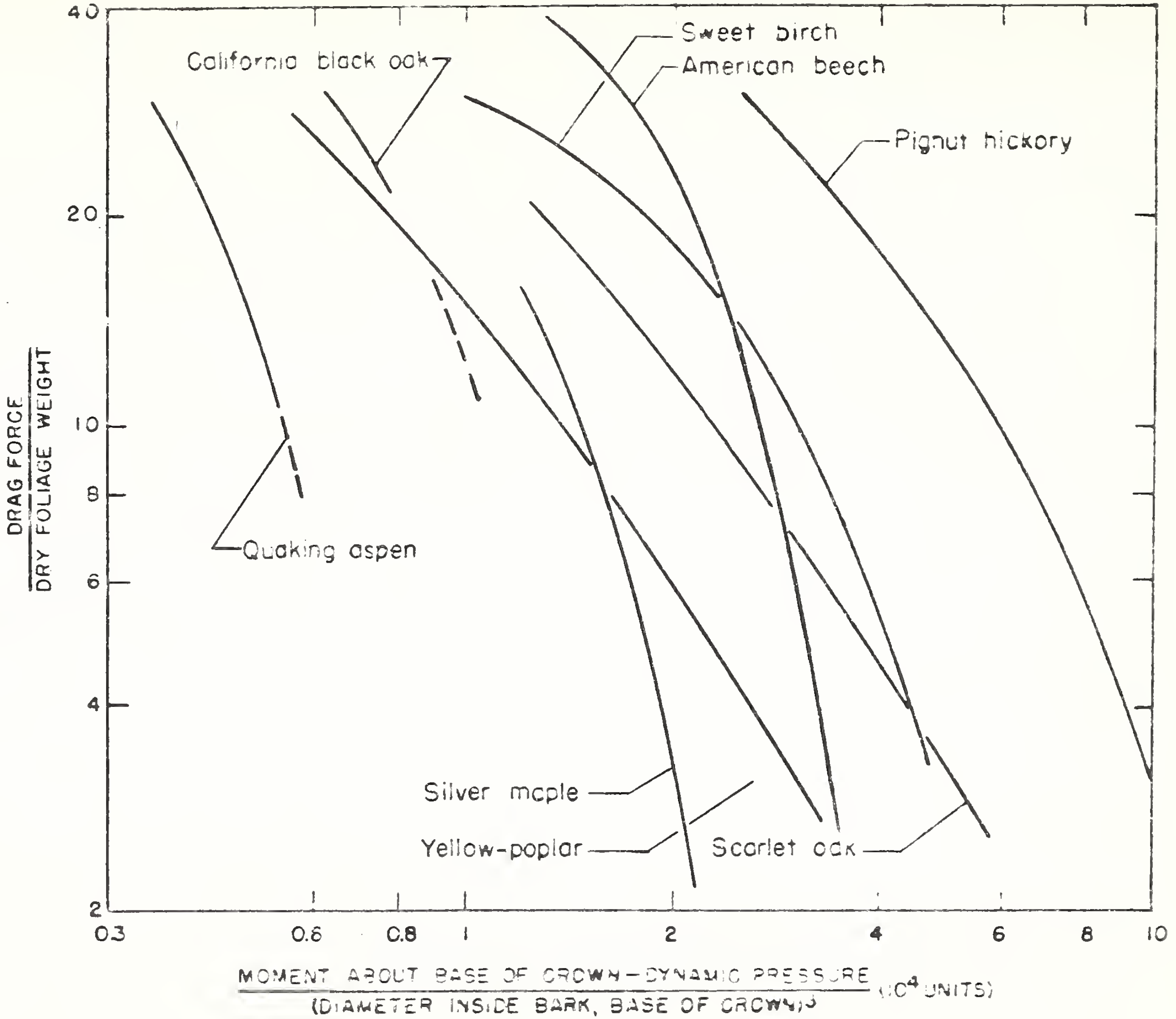

Figure 9.--Dimensionless drag correlation summary (full crown.)

It is known that transpiration continues after a tree is felled (6). The presence of wind and sunlight also increases the rate of transpiration (2; 9, pp. 170-174; 11). When sufficient water transpires, the leaves become flaccid and the wood becomes stiffer (the modulus of elasticity increases). The rate of change of modulus of elasticity with moisture content has been studied by Tiemann (12, 13) and Wilson (16). The rate of change of leaf strength with moisture content is not known, and requires further study.

Test specimens were felled and mounted the night before each run. Runs were started at about 6 a.m. and continued until all data were collected for a particular tree. At the completion of tests, observations showed that in all cases the leaves were flaccid. In many cases a small amount of leaves was torn off during the course of runs.

Moisture content samples were taken only at the end of each test. Therefore, the moisture loss of test trees is not known. Comparison of test trees with trees used for static breakage and crown analysis indicates a substantial loss of moisture in all North Carolina specimens (table 5). Comparable data for California black oak and aspen could not be found.

Due to limpness of leaves in flaccid crowns, their wind resistance will be less for the same dynamic pressure; also stiffer crown components will require less dynamic pressure for the same drag. Therefore, the experimental curves are less steep than they should be (figure 10).

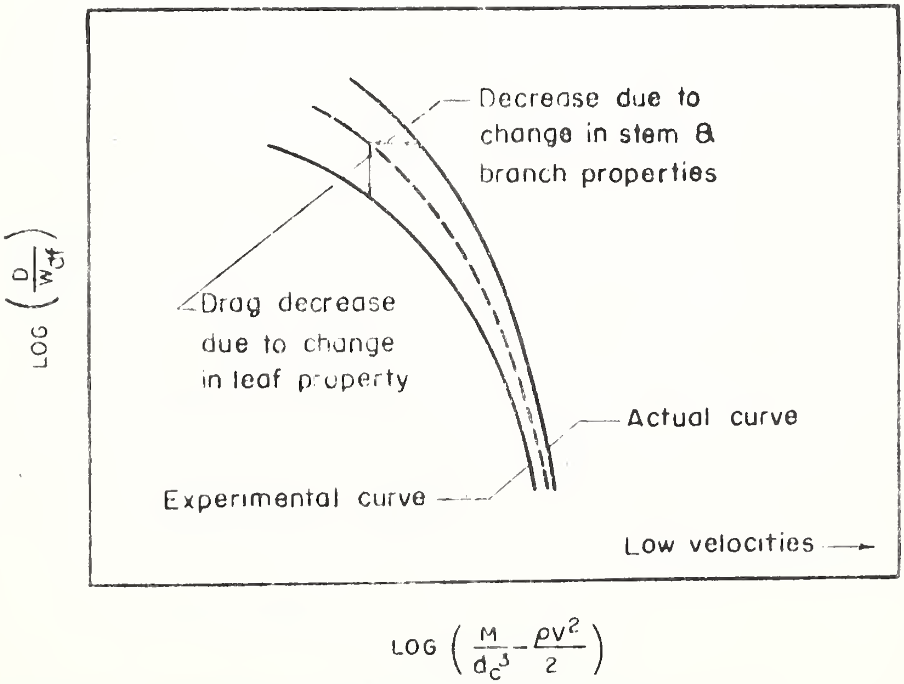

Figure 10.--Transpiration effect on drag curve

Table 5.-- Moisture content of drag test, static breakage, and crown analysis trees

Species	Moisture content					
	Vehicle-test trees[1]			Breakage-analysis trees[2]		
	Foliage	Branch	Stem	Foliage	Branch	Stem
	percent					
Silver maple	98.5	61.4	54.1	122.5	80.7	69.5
(Acer saccha-	108.6	62.7	76.0	151.8	70.9	66.3
rinum L.)				165.2	74.4	72.7
				195.6	72.5	56.9
				142.2	78.0	74.3
Sweet birch	122.9	60.2	56.4	177.8	69.1	71.6
(Betula lenta	105.2	54.8	52.2	158.9	68.6	71.4
L.)				132.0	87.1	71.4
				184.3	83.9	77.2
				135.4	79.8	58.9
Pignut hickory	133.2	57.1	59.6	168.0	64.1	53.2
(Carya glabra	118.0	68.2	59.2	144.5	67.8	70.5
Sweet)				225.7	72.6	58.7
				218.2	80.2	63.1
				201.5	68.5	49.5
American beech	75.6	66.2	66.5	142.1	74.8	73.2
(Fagus grandi-	83.5	50.9	77.8	151.3	93.2	80.3
folia Ehrh.)				121.4	70.6	75.0
				121.2	72.4	89.4
				131.1	66.3	81.0
Yellow-poplar	76.0	65.7	102.7	216.3	105.7	102.0
(Liriodendron	221.0	99.4	81.3	315.0	115.8	104.1
tulipifera L.)	142.5	80.3	132.6	255.9	128.2	130.7
				329.1	128.6	100.0
				311.4	115.3	106.2
Scarlet oak	84.1	55.2	68.5	154.1	83.1	84.4
(Quercus coc-	92.2	88.1	83.2	109.7	68.4	94.4
cinea Muenchh.)	92.4	62.1	76.1	127.0	62.4	67.6
				121.9	73.8	72.8
				145.4	66.3	93.8

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[1] These trees arranged in same order as in table 2. Moisture samples collected after completion of drag tests.

[2] Sample trees from "Crown Characteristics of Several Broadleaf and Palm Tree Species," T. G. Storey (in preparation), and trees used by W. Y. Pong for static breakage analysis.

Preliminary analysis by Storey[3] seems to indicate geometric similarity between young and mature broadleafs. In order to establish the general applicability of the empirical curves, dynamic similarity for broadleafs must be established as was done for conifers (10). This can be done by testing larger as well as smaller trees.

Table 2 shows the restricted number and size of test species. The limited samples also indicate the necessity for further experimentation. A larger size range of test trees will reveal also the role of dry branchwood to foliage weight ratio.

The preceding discussion has brought out many interesting points which have not been studied adequately. To recapitulate, influence of foliage characteristics, crown geometry, strength properties of leaves, branches, and stem, and change of moisture content should be investigated for complete understanding of the broadleaf aerodynamic crown drag mechanism.

CONCLUSIONS

1. Empirical curves based on wind forces and tree parameters have been developed for the prediction of aerodynamic drag of foliated crown for several species of broadleaf trees.

2. Each species has its own curve although the general characteristics of all curves are similar.

3. Foliage contributes a major portion to crown drag. For the trees tested, a difference of two- to tenfold exists between defoliated and full crowns.

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[3] Storey, T. G., Crown characteristics of several broadleaf and palm tree species--relation between weight of crown, branchwood and foliage, and stem diameter (In preparation).

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NOMENCLATURE

A = oscillograph attenuation setting

d_{bh} = outside bark diameter at breast height, in.

d_c = inside bark diameter at base of crown, in.

D = drag force, lb.

H_{bh} = stem length above breast height, ft.

H_c = length of crown, ft.

$\overline{H}_{cp}$ = stem length from tip to center of pressure, ft.

IB = inside bark

K = dynamometer constant, lb.

L = length of test course, ft.

M = moment about base of crown, in.-lb.

OB = outside bark

t = time, min.

T = temperature, $^{\circ}F$

V = velocity, ft./sec.

W_{db} = total weight of dry branchwood, lb.

W_{df} = total weight of dry foliage, lb.

ρ = mass density of air, lb.-sec.^{2}/ft.