

ALIGNING FORCES ON WOOD PARTICLES IN AN ELECTRIC FIELD

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ABSTRACT

Electrostatic alignment affords a promising route to improved mechanical properties in anisotropic particleboards aimed at competition with sawn lumber in structural uses. A quartz-fiber torque balance was used to measure the aligning torque exerted on elongated wood particles by DC and AC fields over a range of wood moisture content, field intensity, and frequency. Approximate predicting equations relating aligning torque to relevant process parameters have been developed, which should aid the process designer. The dynamics of free-falling particles in an electric field favors small slender particles and high field intensity for best alignment. However, slender particles have long charge relaxation times and thus require high moisture content for effective alignment in a field of a given frequency.

INTRODUCTION

Parallel orientation of the grain direction of wood particles in particleboards affords a promising route to materials able to serve in structural applications now dominated by plywood and sawn lumber. Early attempts at particle orientation were based on mechanical means and required rather long particles of uniform length and shape. More recently, to avoid this limitation, J. D. Logan¹ and J. W. Talbott have experimented with an electrical orientation concept. During this work, it was observed that the degree of particle alignment (as inferred from measured board properties) afforded by a 60 Hz AC field was very sensitive to field strength, to particle size and geometry, and to the moisture content of the particles. Before trying to design a production process based on electrical alignment, we needed to know, in a systematic and quantitative way, the effects of several variables on the aligning force acting on individual particles in an electric field. As no published information was available, the

present phase of the work was begun to satisfy this need.

OBJECTIVES

The specific objectives of this research were to measure the alignment torque on individual particles in an electric field and to relate this torque to each of several variables either by empirically derived relationships or by relationships derivable from established physical laws. The variables studied were:

1. Angle between particle axis and field direction.
2. Field strength: 0 to about 10^5 volts per meter.
3. Particle size and geometry
Rods: Length, diameter, length/diameter ratio
Flakes: Length, width, length/width ratio from 1 to 10, circular flakes
4. Material of particles: Wood (Douglas-fir, *Pseudotsuga menziesii*), metal, carbon, fused quartz
5. Frequency: DC, and AC from 30 to 10^4 Hz.
6. Moisture content of wood particles

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over a range as controlled by various relative humidities with which they were allowed to equilibrate. (Moisture content of wood in turn controls electrical conductivity and dielectric constant of wood at a given temperature.)

7. Temperature: This phase of the work was limited to room temperature to simplify the required apparatus, although temperature is known to affect conductivity and dielectric constant of wood. [Davidson 1958]

EXPERIMENTAL APPARATUS AND PROCEDURE

The apparatus (Fig. 1) consisted of a closed chamber of clear acrylic plastic made in three separable sections. The lower section was an open-topped rectangular box with the end plates extended down to form a stand, with an offset lip around the top to receive and align the middle section. The middle section, or "field box," was open at top and bottom and had the two opposite sides lined with aluminum foil to form the field electrodes, which were connected by lead wires to appropriate voltage sources. The electrodes were about 0.2×0.4 meter with a spacing of 0.2175 meter. The upper section was a lid to cover the field box and had an elevated central part on which was mounted an angular indexing head carrying a pin-vise projecting downward.

The torque-measuring element was a drawn fused-quartz fiber mounted in the pin-vise and having at the bottom end an integral welded quartz sample hanger, which suspended the sample particle horizontally at the center of the field box. A reading telescope with a protractor eyepiece was mounted to view the suspended sample from below through an optical right-angle prism mounted in the bottom of the lower section of the enclosure. This allowed measuring the angle between the particle axis and the field direction.

The torque balance was calibrated by computing its torsional spring constant, in newton meters per radian, from the measured period of oscillation when a copper

wire sample of known weight and length was suspended on the balance and set in motion as a torsional pendulum. Torque exerted on a sample could then be measured by determining the angular difference in setting of the upper indexing head required to position the sample at a fixed angular position relative to the field direction (usually 45°) with and without application of the field voltage. This angular difference measures the torsional displacement within the quartz fiber, and, when multiplied by the torsional spring constant of the fiber, gives the torque exerted on the sample by the field. The ratio of maximum measurable torque to that just detectable was about 10^4 . Relative precision of torque measurement was about $\pm 0.5\%$ at higher torque values but at low values was limited by the $\pm \frac{1}{2}^\circ$ precision of the torque-angle measurement afforded by the optical goniometer.

Plastic trays of saturated aqueous salt solutions in the bottom of the enclosure controlled the relative humidity at desired levels. A small axial-flow fan with its motor mounted outside the box circulated the air to equalize temperature and humidity throughout the box. A dial thermometer sealed through the side of the lower section measured the temperature in a box.

It was not possible to measure the electrical conductivity of the wood particle samples directly at the time of the torque measurements. Therefore, a wafer of the same wood having end-grain surfaces coated with silver conductive paint was mounted in the box. Shielded lead wires connected the wafer to a sensitive electrometer capable of measuring resistances to 10^{12} ohms. The measured resistance and known dimensions of the wafer allowed computation of its specific resistivity for each relative humidity level, and this same resistivity was assumed to apply to the wood particle sample suspended on the torque balance and equilibrated in the same atmosphere. Moisture equilibration of this wafer was slower than that of the smaller particle samples and was thus the determining factor in the time required for equilibration after chang-

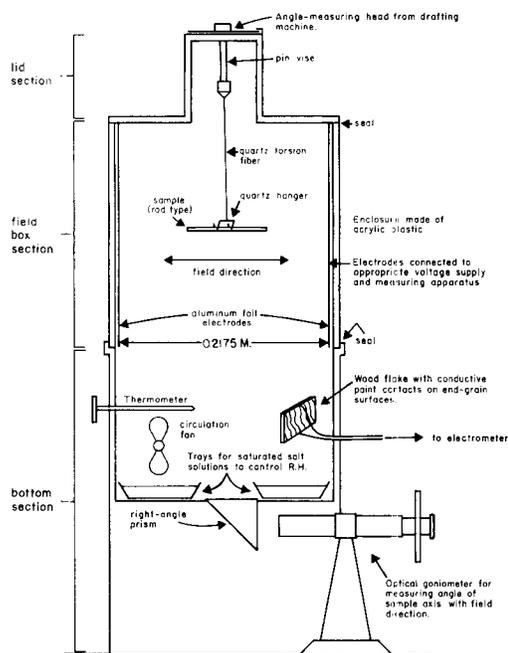


FIG. 1. Arrangement of apparatus to measure the torque exerted on a particle by a uniform electric field in an atmosphere of controlled humidity.

ing salt solutions. Eight hours' equilibration gave steady resistance readings. Overnight equilibration time was used for convenience. Care was taken to approach equilibrium always from the dry side to avoid discrepancies caused by hysteresis in the moisture content-humidity relation.

The DC resistance measurement of the wood wafer was compromised in that the circuit of the electrometer did not allow resistance measurement at a single fixed voltage over the whole resistance range, although the DC resistance of wood is known to change with applied voltage. The applied voltage was recorded for each resistance measurement. These resistance measurements were used primarily to determine when moisture equilibrium had been attained.

The available field voltage range was 0–22 kV in the DC mode and 0–22 kV peak to peak (0–15.5 kV rms) in the 60-Hz AC mode. In the variable frequency mode, 2

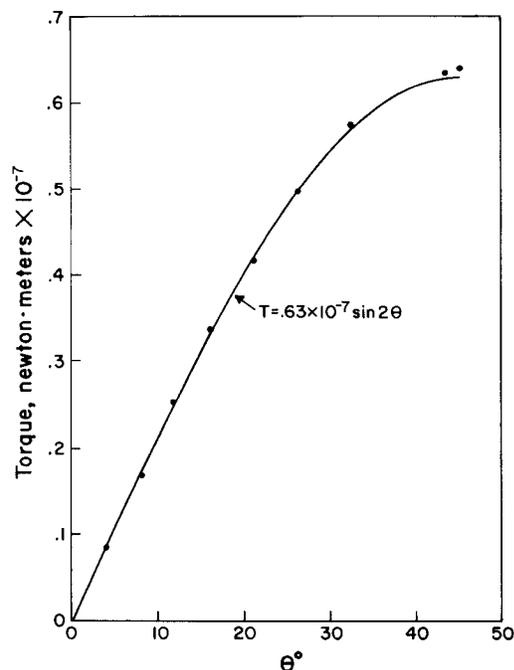


FIG. 2. Torque is proportional to twice the sine of the angle, θ , between the particle axis and the field direction. Copper cylinder of length 7.43 cm and radius of 0.238 mm. $E = 1.655 \times 10^4$ volts per meter, AC, 60 Hz.

kV was the highest voltage that could be supplied through the 30–10,000-Hz frequency range without distortion of the wave form.

Torque measurements were made on samples of wood, copper, quartz, and carbon. All the wood particle samples and the wood wafer for resistance measurements were prepared from a single small piece of kiln-dried coast Douglas-fir heartwood having about 40 annual rings per inch. The wood samples were either thin cylinders or thin flakes. The cylinders had diameters of $\frac{1}{4}$ to $\frac{1}{2}$ mm and lengths to about 7 cm, with the wood grain in the cylinder axis direction. These were prepared by a centerless abrasion process developed for this purpose. This method resulted in the thinnest cylinders, with diameters less than one annual ring, having more latewood than average for the parent block.

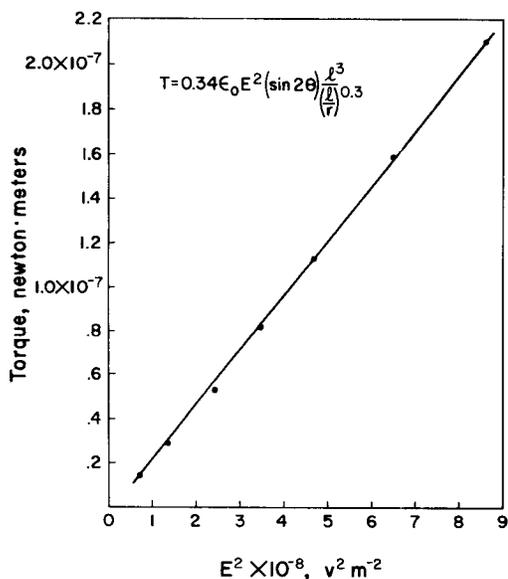


FIG. 3. Torque is proportional to the square of field intensity. Copper cylinder of length 7.43 cm and radius 0.238 mm. $\theta = 45^\circ$, AC, 60 Hz.

One series of wood flakes, about $\frac{1}{2}$ mm thick, 3 cm long, and from 0.25 to 3 cm wide, was cut with faces in the radial-longitudinal plane of the wood (RL) and the long dimension of the flake in the grain direction. A second series consisted of 3-cm-diameter circular flakes but with the faces parallel to the RL, RT, and TL wood planes. All flakes had fused quartz hangers cemented to the faces. The cemented hangers were separately tested and found to contribute no measurable torque.

Copper samples were cut from annealed copper wire that had been straightened by stretching. Quartz samples were cut from drawn fused quartz fibers. "Carbon" samples were leads for mechanical pencils, thus consisting of graphite and kaolin.

EXPERIMENTAL RESULTS

The nature of the relation of torque to each of the experimental variables listed under "Objectives" was first explored by holding all factors constant but one and by measuring aligning torque at fixed values of the factor under consideration.

The first factor was the angle, θ , between

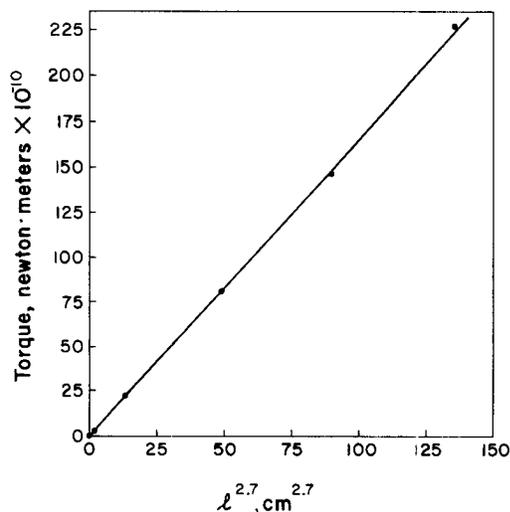


FIG. 4. For cylinders of fixed radius, torque is proportional to the 2.7 power of length. Copper cylinders of radius 0.280 mm; $\theta = 45^\circ$; $E = 1.84 \times 10^4$ volts per meter, AC, 60 Hz.

sample axis and field direction. This was measured for copper and wood cylindrical rods and for rectangular wood flakes. As expected, torque was zero when the long axis of the sample was either parallel or perpendicular to the field direction. Maximum torque occurred at 45° . When torque was plotted as a function of θ , it followed the relationship $T = K \sin 2\theta$ within experimental error (Fig. 2). The same relationship held for copper and for moist wood cylinders, moist wood flakes (at fiber saturation), and carbon cylinders in both DC and AC 60-Hz modes. No measurable torque was exerted on quartz cylinders in either DC or AC fields. Therefore, θ was fixed at 45° for all further torque measurements.

The second factor was field strength, E , volts/meter. Measured torque values plotted as a function of E^2 gave a straight line (Fig. 3). These values were for a copper cylinder in DC mode, and were plotted on double log paper for compactness. On linear coordinate paper, the plot was also a straight line, within experimental error. That torque is proportional to E^2 was also demonstrated for copper samples in a 60-Hz mode, for moist wood cylinders and flakes in both

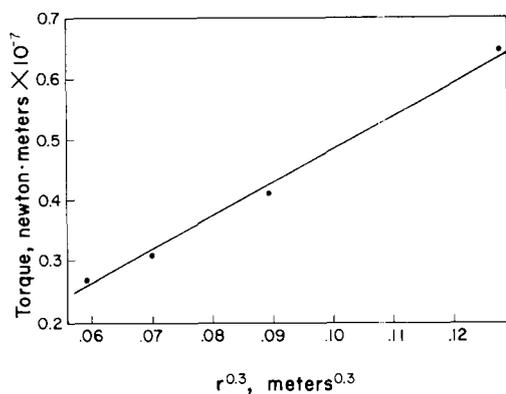


FIG. 5. For cylinders of fixed length, torque is proportional to the 0.3 power of the radius. Copper cylinders 3 cm long; $E = 4.6 \times 10^4$ volts per meter; $\theta = 45^\circ$, AC, 60 Hz.

modes, and for carbon cylinders in both modes.

The third factor—or more properly set of factors—was particle size and geometry. Cylindrical elements of various lengths, l , and various radii, r , were first considered. Measured torque values plotted as a function of $l^{2.7}$ were linear for copper cylinders of the same radius (Fig. 4). The 2.7 value of the exponent of l was the only value that gives a linear plot for this relationship. This was shown to hold for copper and moist wood cylinders in both AC 60-Hz and DC modes. Torque plotted as a function of $r^{0.3}$ was linear for cylinders of the same length (Fig. 5). The 0.3 value of the exponent was the only value that gave a linear plot over this more than 10 to 1 range of r . This relationship also was found to apply to moist wood cylinders in DC and 60-Hz AC modes.

Square and circular moist wood flakes of all grain orientations gave zero torque values within the precision of their squareness or circularity (the dimensions change with humidity). For rectangular flakes, the more complex relation of torque to size and geometry will be presented later under "Discussion."

The relationship of aligning torque to the 5th and 6th variables, i.e., field frequency and wood moisture content, is an expression

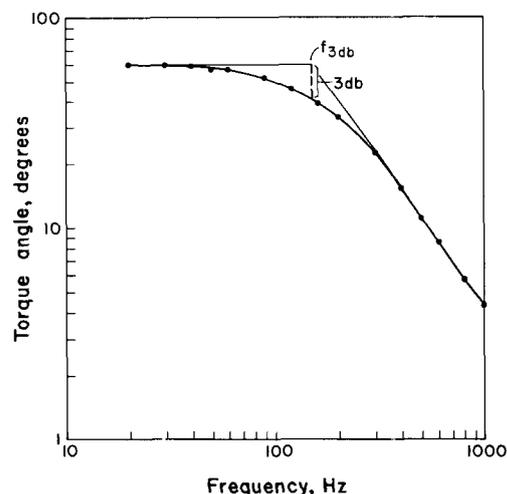


FIG. 6. Frequency response of torque on a wood particle at constant humidity. The cut-off frequency, f_{3db} , is determined by the intersection of the two asymptotes of the response curve. Relative humidity 88%, $l/r = 194$; $\theta = 45^\circ$.

of the phenomenon of charge-relaxation time. Our preliminary hypothesis supposed that charge-relaxation time was a material property controlled by the electrical properties of the material of the particles and thus uninfluenced by particle geometry. Experimental proof to the contrary forced extension of the experimental plan to include measurement of the effect of particle geometry on charge-relaxation time.

It would have been desirable to measure directly the time-dependence of the relationship of torque to moisture content of wood particles and thus to afford a direct measure of the charge-relaxation time, or conversely, the time for the charge separation in the particle to build up to a value in equilibrium with a suddenly applied field. As the apparatus was not appropriate for this, we measured instead the relationship of torque as a function of field frequency. At low frequencies the torque was constant. As frequency increased, torque began to fall off, slowly at first and finally at a constant rate of about one order of magnitude per decade of frequency increase.

On double-log coordinate paper, this constant fall-off plotted out as a straight line,

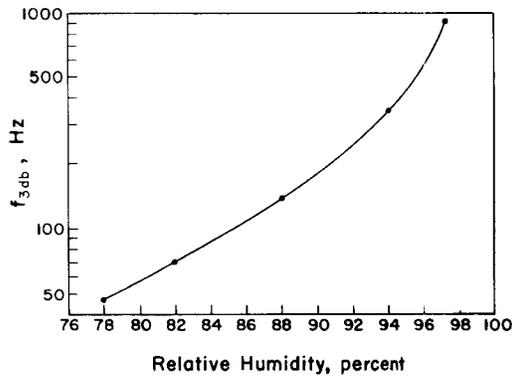


FIG. 7. Cut-off frequency, f_{3db} , as a function of relative humidity for a wood particle of $l/r = 194$.

which can be extrapolated back to intersect the low-frequency torque level at a frequency where the torque is, in electronics terminology, "3 db down"—that is 0.707 of the low-frequency level (Fig. 6). The "cut-off frequency" so determined, f_{db} , characterizes the time dependence of the torque for a given combination of those variables capable of affecting the charge relaxation time of the particle.

The cut-off frequency was first determined for a given wood particle as a function of relative humidity with all other factors held constant (Fig. 7). For this cylindrical particle, with $l = 0.0616$ meter and $r = 0.00032$ meter, the cut-off frequency ranged from 47 Hz at 78% RH to 920 Hz at 97.2% RH.

Copper and carbon cylindrical particles had uniform torque out to 10,000 Hz, the limit of the equipment.

Next, the cut-off frequency was measured at a constant humidity for a series of 10 wood cylinders having different lengths and radii. Cut-off frequency was found to be a function of the dimensionless slenderness ratio, l/r . More particularly, it appeared to be inversely proportional to $(l/r)^{1.5}$ (Fig. 8).

Finally, the effect of field intensity of the cut-off frequency was explored indirectly by measuring torque on a wood cylinder as a function of voltage at a frequency a little above the cut-off frequency previously determined for the same sample and humidity

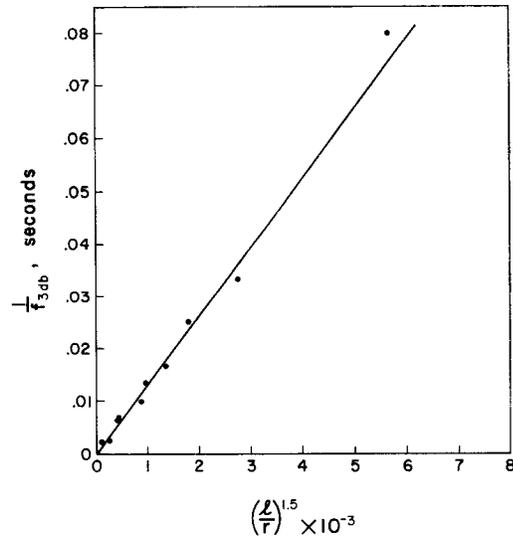


FIG. 8. Cut-off frequency as a function of slenderness ratio, l/r , for fixed humidity (88%). f_{3db} is proportional to $(l/r)^{1.5}$.

level. The torque thus measured was proportional to the voltage squared, as in dc mode—which would not be the case if the cut-off frequency were being affected by voltage.

The effect on cut-off frequency of temperature and of the angle, θ , between the particle axis and the field direction was not measured. The measurements were all made at $\theta = 45^\circ$, and at room temperatures ranging from 20 to 25 C.

DISCUSSION

The experimental results can best be summarized by dividing the variables into two groups. The first group comprises those variables that determine the aligning torque on *any* conductor in a DC field: angle θ ; field strength E ; particle size and geometry. The second group comprises those variables that affect the charge relaxation time of the particle and thus the frequency dependence of the torque. This is not entirely a clean separation as the relaxation time is influenced by particle geometry as well as by particle material, and in addition, the moisture content if the material is wood.

Considering the first group, the relation-

ship of the torque, T , to the experimental results presented above can be expressed as:

$$T = K_1 E^2 (\sin 2\theta) \ell^{2.7} r^{0.3}$$

for slender cylindrical particles of conductive material. This equation can also be written as:

$$T = K_1 E^2 (\sin 2\theta) \frac{\ell^3}{(\ell/r)^{0.3}} \quad (1)$$

showing that the torque is proportional to ℓ^3 for constant l/r ratio. Equation (1) can be solved for the constant K_1 , yielding:

$$K_1 = \frac{T}{E^2 (\sin 2\theta) \frac{\ell^3}{(\ell/r)^{0.3}}} \quad (2)$$

Expressing all parameters in the MKS unit system where fundamental units are mass (M) in kilograms, length (L) in meters, time (T) in seconds, and charge (Q) in coulombs, the dimensions of K_1 suggest that Eq. (1) should contain a permittivity term, ϵ_0 . If such a term is inserted in Eq. (1), there results:

$$T = K \epsilon_0 E^2 (\sin 2\theta) \frac{\ell^3}{(\ell/r)^{0.3}}$$

where K is a new dimensionless proportionality constant. Substitution of ϵ_0 (permittivity of free space) and the experimental values for the other variables in Eq. (2) yields a numerical value, $K = 0.34$. Thus Eq. (2) can now be expressed as:

$$T = 0.34 \epsilon_0 E^2 (\sin 2\theta) \frac{\ell^3}{(\ell/r)^{0.3}} \quad (3)$$

Equation (3) is an empirical equation containing no particle parameters other than size (ℓ^3) and geometry (l/r), and thus predicts that the torque on a particle will not be affected by such factors as density, material of the particle, or electrical properties of the particle—other than that the particle be “conductive.”

Equation (3) was shown to predict torque values, accurate within experimental error, for slender ($l/r = 10$ to 400) cylindrical particles of copper, moist wood, and

carbon in both DC and AC 60-Hz fields. The particle-geometry parameter l/r does not adequately describe the geometry of non-cylindrical particles such as splinters and flakes. Remembering that charge distribution in a conductor is a surface phenomenon, we can propose, and test, a more general geometry parameter based on surface area. Because the perimeter, p , of a cylinder is $2\pi r$, we can modify Eq. (3) thus:

$$T = \frac{0.34}{(2\pi)^{0.3}} \epsilon_0 E^2 (\sin 2\theta) \left(\frac{\ell^3}{p}\right)^{0.3} \quad (4)$$

Equation (4) still predicts the same torque values for cylinders as Eq. (3), and further, it accurately predicts the torque for narrow thin flakes with length/width ratios (l/w) above 7.5. The agreement between actual and predicted torque gets rapidly worse as the l/w ratio approaches 1, as for square flakes, which actually have zero torque.

Therefore a further generalizing modification of (4) can be obtained by replacing p by its equivalent (in flakes) $2(t+w)$ and by then making the equation symmetrical in l and w :

$$T = 0.196 \epsilon_0 E^2 (\sin 2\theta) \left[\frac{\ell^3}{2(t+w)} - \frac{w^3}{2(t+w)} \right]^{0.3} \quad (5)$$

where the negative term is intended to account for the reverse tendency of the flake to orient in the other direction as w increases in proportion to l .

How well this intuitively modified hypothesis fits the measured torque for moist flakes can be shown by plotting experimental torque values against $p^{0.3}$ (where $p = 2(t+w)$), for flakes of different aspect ratios (l/w) (Fig. 9). The sloping straight line of Fig. 9 is a plot of Eq. (4), which is appropriate for slender cylindrical or prismatic elements (including narrow flakes). The curved line is a plot of Eq. (5). The circles are plotted data points for moist flakes having length/width ratios as noted by each. The agreement with Eq. (5) is very good at all l/w ratios. Values for l/w ratios above 7.5 agree well also with Eq. (4).

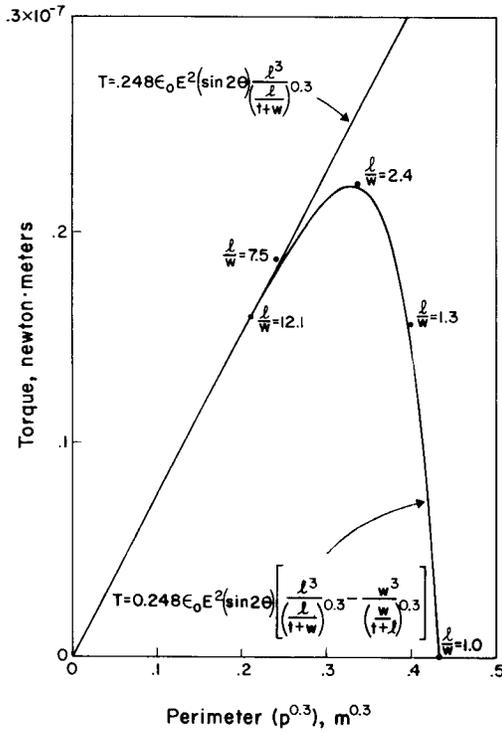


FIG. 9. Aligning torque for thin wood flakes. A comparison of two torque predicting equations with measured torque values for flakes with length/width ratios as noted by the plotted values.

The torque on a cylindrical wood particle of length, l , and radius, r , can be calculated by assuming that the wood particle behaves as if it were conductive. This, of course, is analogous to the case of a metallic filament introduced into a uniform electric field E_0 (Fig. 10).

The electric field can be separated into two components; a transverse component $E_t = E_0 \sin \theta$ and an axial component $E_a = E_0 \cos \theta$. The transverse component will cause a surface charge to appear on the cylindrical surface such that the surface remains an equipotential surface. A torque component will appear as a result of the effect of the axial field component on this surface charge. It can be shown [Elliot 1966] that the equation for this component of the torque is:

$$T_1 = 4\epsilon_0 E_0^2 (\sin 2\theta) r^2 \ell$$

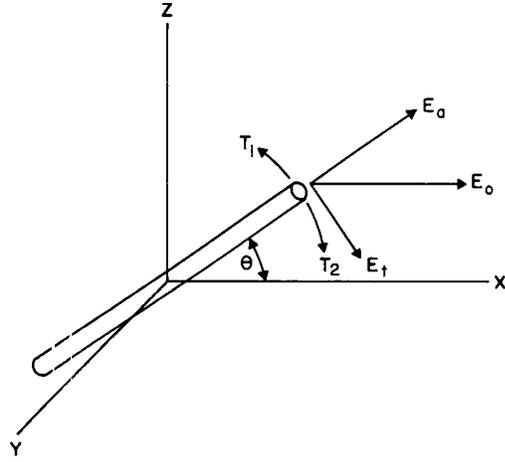


FIG. 10. Resolution of the electric field into two components, an axial component E_a and a transverse component E_t . On an elongated particle the main torque component is that produced by E_t acting on the charge distribution induced by E_a .

In addition to the above torque, there is a torque component produced by the effect of E_t on the surface charge induced on the cylindrical conductor surface by E_a . The calculation of the surface charge is not straightforward, but a good approximation can be obtained by representing the cylindrical element by an elongated ellipsoid. [Moon and Spencer 1961]. The resultant expression for the torque can be simplified, by certain approximations to the form:

$$T_2 \approx \frac{\pi}{12} \epsilon_0 E^2 (\sin 2\theta) \left[\frac{\ell^3}{\ln \frac{\ell}{r} - 1} \right] \quad \ell^2 / r^2 \gg 1.$$

The total torque on the conductive fiber is:

$$T = T_2 - T_1 = \epsilon_0 E^2 (\sin 2\theta) \left[\frac{\pi}{12} \frac{\ell^3}{\ln \frac{\ell}{r} - 1} - 4r^2 \ell \right]$$

For elongated wood particles, where $\ell^2 \gg r^2$, the first torque component, T_1 , is negligible and we can thus use for the total torque:

$$T = \frac{\pi}{12} \epsilon_0 E^2 (\sin 2\theta) \left[\frac{\ell^3}{\ln \frac{\ell}{r} - 1} \right] \quad (6)$$

appropriate to slender cylindrical particles. How well this approximation agrees with

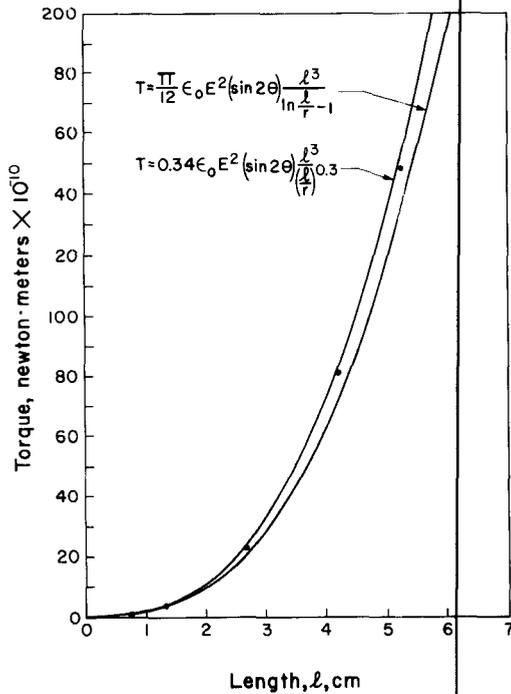


FIG. 11. Comparison of the torque predictions of the empirical equation (3) and the theoretical equation (7) with the plotted values of measured torque for different length cylindrical particles all of the same radius.

the experimental results and with Eq. (3) can best be shown by plotting experimental values of torque against length and superposing on this plot the graphs of Eq. (3) and Eq. (7) (Fig. 11).

Thus we see that Eqs. (3) or (6) and Eq. (5) can be used to predict rather accurately the aligning torque on slender cylinders and on flakes in DC fields and in AC fields at frequencies well below the cut-off frequency.

Turning now to the relation of torque to moisture content and frequency, can we find equally good predictors? Our preliminary hypothesis was that the cut-off frequency would be governed by the charge-relaxation time of the material of the particle. For a conductive material, the charge relaxation time, τ , is usually expressed as:

$$\tau = \rho \epsilon$$

where ρ is the specific resistivity and ϵ the total permittivity of the material. Or, more conveniently, as;

$$\tau = \rho \epsilon_0 \epsilon_r \quad (7)$$

where ϵ_0 is the permittivity of free space and ϵ_r the relative dielectric constant. In this formulation τ is the time required for a point charge placed within a conductor to be dissipated to a value of $1/e$ of the original charge. By analogy to the frequency response of an RC electronic circuit, we expected the charge-relaxation time to determine a corresponding cut-off frequency:

$$f_{3db} = \frac{1}{2\pi \rho \epsilon_0 \epsilon_r} \quad (8)$$

at which the torque would be 0.707 of the low-frequency or DC value. The appropriateness of the analogy was also suggested by the form of the frequency response of torque (Fig. 6).

However, the measured values of f_{3db} were two or three orders of magnitude lower than those predicted by Eq. (8) (Table 1). Only a small part of this discrepancy could be accounted for by uncertainty in the values of ρ and ϵ_r , which could not be measured directly for the particle under test.

If Eq. (8) is modified to include the measured dependence of cut-off frequency on particle geometry shown in Fig. 8, i.e., that at constant moisture content the cut-off frequency varies inversely as $(l/r)^{1.5}$, then we have:

$$f_{3db} = \frac{1}{2\pi \epsilon_0 \epsilon_r (l/r)^{1.5}} \quad (9)$$

The factor $(l/r)^{1.5}$ is dimensionless and thus the dimensions of Eq. (9) remain, correctly, time^{-1} . This empirically modified equation (9) is a much better predictor of cut-off frequency than is Eq. (8) both under conditions of varying humidity (Table 1) and varying slenderness ratio (Table 2).

It should be noted here that the specimens used to obtain the experimental results, presented in Tables 1 and 2, were

TABLE 1. Relationship of predicted and measured cut-off frequency, f_{3db} , to several levels of relative humidity, for a single particle ($l/r = 194$) and at constant voltage (9.20 kV/m). Douglas-fir at 0.5 sp gr.

RH, %		78	82	88	94	97.2	
MC, μ , % ⁽¹⁾		15.3	16.7	19.5	23.1	25.1	
Resistivity, ρ , ohm·m ⁽²⁾		16×10^4	6.3×10^4	1.1×10^4	0.4×10^4	0.25×10^4	
Dielectric const ϵ_r ⁽³⁾		4.55	4.95	5.85	7.13	1.0	
f_{3db} , Hz	Predicted	$\frac{1}{2\pi\rho\epsilon_0\epsilon_r}$	24,600	57,500	278,000	625,000	925,000
	Measured	$\frac{1}{2\pi\rho\epsilon_0\epsilon_r(l/r)^{1.5}}$	9.1	21.3	103	232	342
			47	70	140	350	920

⁽¹⁾ Moisture content corresponding to relative humidity. [Wood Handbook 1955]

⁽²⁾ Resistivity corresponding to moisture content. [Lam 1965]

⁽³⁾ ϵ_r = sp gr ($3.93 \times 10^{0.0212\mu}$). [Brown et al. 1963]

somewhat different in that one of them was accidentally dipped in a somewhat conductive solution. Thus a comparison between the measured f_{3db} values of Tables 1 and 2 at 88% relative humidity and about 194 slenderness ratio will immediately reveal a discrepancy. It is therefore the authors' intention to present the results in the above form in order to bring out the general behavior of f_{3db} as a function of relative humidity and slenderness ratio. Since the values of resistivity and dielectric constant used were extrapolated from handbooks and referenced papers, it is expected that the results will at best represent bulk estimates of the quantities involved rather than accurate quantitative comparisons.

A theoretical justification for Eq. (9) has not been determined. Nevertheless Eq. (9) implies that the relaxation time for the mechanism of polarization of a wood par-

ticle in an electric field must be controlled not only by the material properties of the particle but also by the shape of the particle.

CONCLUSIONS

On the basis of the above results and discussion, one can arrive at the following conclusions:

For particles of a given shape, aligning torque increases as the cube of the particle length. However, as rotational inertia increases as the fourth power of length, the smaller the particle the more quickly it will align. The quicker aerodynamic damping of the oscillation of smaller particles will enhance this effect.

Aligning torque increases as the square of the field intensity. This means that maximum safe voltages should be used with relatively short electrode spacing.

TABLE 2. Relationship of predicted and measured cut-off frequency, f_{3db} , for a fixed 88% relative humidity and variable slenderness ratio, l/r , at constant voltage gradient (13.8 kV/m).

		Predicted value from $f_{3db} = \frac{1}{2\pi\rho\epsilon_0\epsilon_r}$ was 64,000 Hz for all slenderness ratios.									
Slenderness, l/r		21.2	37.6	57	61	92	98	121	148	195	317
$f_{3db} = \frac{1}{2\pi\rho\epsilon_0\epsilon_r(l/r)^{1.5}}$		650	246	149	133	73	66	48	37	23	11
f_{3db} , measured		420	390	150	143	100	78	60	40	30	12.5

Note: Resistivity, ρ , measured from reference wafer, ϵ_r = sp gr ($3.93 \times 10^{0.0212\mu}$). [Brown et al. 1963]

For particles of a given length, aligning torque increases only as the 0.3 power of the length/perimeter ratio while rotational inertia increases more steeply. This means quicker alignment of more slender particles. This is fortunate because particle slenderness also improves board properties.

Low-frequency fields will allow the use of drier particles and lower humidity in the processing equipment. Sixty Hz is an obvious choice. This would require about 16% moisture or more in the particles unless the conductivity could be increased by addition of electrolytes or increasing the working temperature, etc.

Slender particles require high moisture content for a given frequency.

Charge-relaxation time in wood particles is a function of both particle shape and material properties.

Electrical orientation can be accomplished with elongated particles of any material that is even slightly conductive or that

can be made transiently conductive during orientation.

Equilibrium aligning torque in a DC field is independent of the material of the particle.

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