A TRANSISTORIZED SONIC GENERATOR AND DETECTOR FOR FINDING YOUNG'S MODULUS OF WOODEN BEAMS

by

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A = cross sectional area

C = capacitance

E = Young's modulus, modulus of elasticity

F = force

I = moment of inertia

K = stiffness constant

L = inductance

M = mass

Q = charge

R = resistance

R_m = mechanical resistance

S = complex frequency variable

T = transistor

V = voltage

Z = impedance

a = acceleration

b = width normal to direction of flexure

e = voltage

f = frequency

g = acceleration due to gravity

h = depth in the direction of flexure

k = dimensionless constant

l = length

LIST OF SYMBOLS (Continued)

m = bending moment

t = time

u = velocity

x = distance along the length of a beam

y = displacement

β = beta, feedback factor

γ = minimum voltage gain required for oscillation

ρ = density

ω = frequency, radians per second

INTRODUCTION

Young's modulus, often called the modulus of elasticity, gives a measure of the stiffness of a material to an imposed load.

The modulus of a wooden beam is most often obtained by destructive tests which destroy the specimen. If a practical method can be found to measure Young's modulus non-destructively, several advantages can be realized: First, any number of specimens can be thoroughly tested and accepted or rejected according to the results of the measurement. Second, a single beam can be tested repeatedly. Finally, a wooden beam already in use can be measured.

A background on the measurement of Young's modulus of wooden beams is presented. The standard destructive test is described as are several non-destructive techniques employing acoustics. Examples of non-destructive tests at sonic and ultrasonic frequencies are given.

From this background a non-destructive method of testing which makes use of the reactions of a wooden beam when excited at its natural resonant frequency is selected for further study. The mathematical background necessary to interpret the results and to relate them to Young's modulus is developed. Test equipment is set up to determine the practicality of this method.

Since this non-destructive method seems feasible, a sonic generator and detector is designed and constructed as a single unit. It is built with the qualifications that it be rugged, compact, easy to operate, and relatively inexpensive. The design calls for a variable frequency oscillator, a ten watt amplifier, excitation and detection transducers, a detection amplifier, and a display meter. The design of the equipment is discussed in detail, and the reliability and accuracy of the apparatus over an extended period of time are predicted.

Methods of operation of the sonic generator and detector are discussed, and the results of a short series of measurements made with the equipment are presented.

A TRANSISTORIZED SONIC GENERATOR AND DETECTOR FOR FINDING YOUNG'S MODULUS OF WOODEN BEAMS

BACKGROUND ON TESTING

This chapter presents a background of the various methods of measurement of Young's modulus. The standard destructive test is described and is compared to non-destructive methods. Examples of non-destructive tests employing acoustics are given. In the examples, measurements at both sonic and ultrasonic frequences are explained.

1. Destructive Testing

The American Society for Testing Materials has set up procedures which are to be followed in the destructive testing of wooden beams (1, p. 12). The size of the standard test specimen is two by two by 30 inches. The beam is supported one inch from each end so that it has a center span of 28 inches. A vertical force is applied downward on the center of the beam. Static bending equipment used to destructively test standard 30 inch beams is represented in Figure 1 on the following page (2,p.5).

At any time during the test before the proportional limit of the beam has been reached, the force applied and the corresponding vertical deflection of the center of the beam are used to compute Young's modulus. Equation (1) is used for this computation.

$$E = \frac{Fl^3}{48yI}$$

F = force applied to the beam, pounds

l = beam lenth, inches

y = beam deflection at the center of the beam, inches

I = moment of inertia of the cross section of the beam, $inches^4$

E = Young's modulus, pounds per $inch^2$

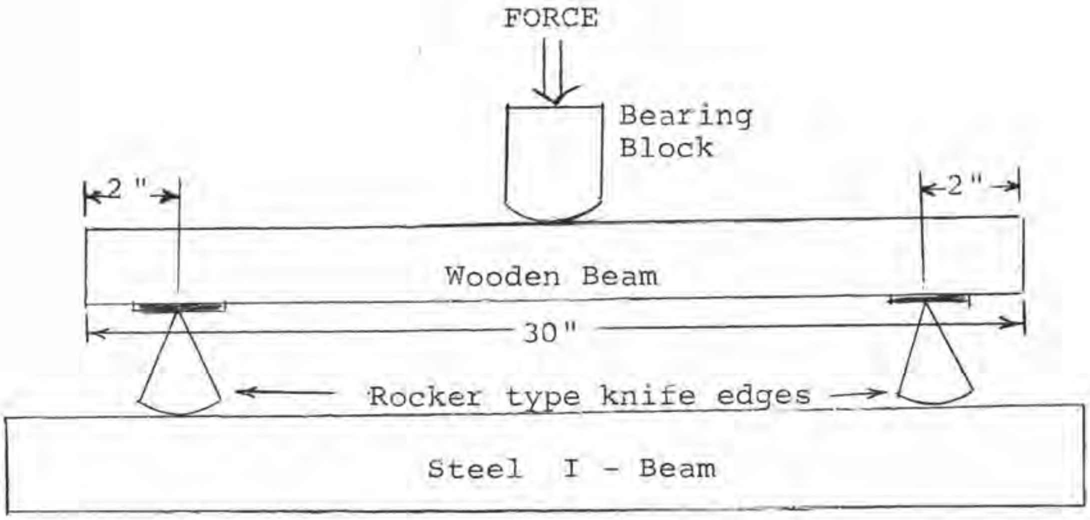

Figure 1: Static bending equipment used to destructively test a 30 inch wooden beam.

2. <u>Non-destructive Testing</u>

In its widest sense the term "non-destructive testing" may be applied to any method of examination which does not alter the properties of the material during the course of the test (3, p. 1). Wood may be tested non-destructively by optical, radiographic, magnetic, electrical, thermal, mechanical, and acoustical methods. This paper is confined to acoustic techniques.

Non-destructive testing of wooden beams has the following advantages over destructive testing:

(1) Any number of specimens may be thoroughly tested. Consequently, if a suitable test is found, all the timber intended for a specific purpose can be tested and accepted or rejected according to the results of the test.

(2) A single specimen may be tested repeatedly. Experiments may be carried out on a single beam to determine the effects of moisture, temperature, or decay.

(3) A beam already in use may be tested. For example, a timber which is part of a structure may be inspected. Also, it may be possible to obtain results from standing trees.

Non-destructive tests which fall under the classification of acoustic methods employ pressure waves at sonic or ultrasonic frequencies. The sonic frequencies are generally considered to be those within the audio range, and ultrasonic frequencies to be those above the audio spectrum.

A basic but thorough description of the various means of generating sonic and ultrasonic energy by electrical and mechanical methods is given by Charles O. Morris (11, p. 4-10).

3. Non-destructive Tests at Ultrasonic Frequencies

Among other methods Young's modulus has been measured non-destructively at ultrasonic frequencies by the following techniques:

(1) Determination of pulse velocity.

(2) Measurement of the percentage of ultrasonic energy which is transmitted through the wood.

One method of determining the variations in Young's modulus non-destructively is to measure the velocities at which ultrasonic waves travel in known directions within the beam. The velocities are dependent on Young's modulus, the direction in which the wave front travels with respect to the axes of elastic symmetry, and the density of the wood. Assuming that the latter two are known, it is possible to calculate the elastic constant, Young's modulus, from the velocity of the wave by measuring the time taken for the onset of an ultrasonic pulse of longitudinal waves to travel across the diameter of a disk. Each disk is cut so that its circular face lies in the plane in which variations in the elastic modulus are to be measured.

I.D.G. Lee of the Timber Development Association used two transducers, which converted electric waves to pressure waves, placed on opposite sides of the specimen. Each transducer contained a barium titanate disk. The transmitting transducer was fed with pulses at a repetition rate of 50 per second. Each pulse produced a short train of damped ultrasonic vibrations in the material at a frequency equal to the resonant frequency of the transducer element which was 150 kilocycles. These pulses were detected by the receiving transducer, and the velocity was computed from the transit time (6, p. 1-30).

Lee's results indicated that ultrasonic pulse measurements might give a rapid guide to the conditions of grain orientation, such as spiral and interlocked grain, which might not be visible from the outer faces (7, p. 8).

The Young's modulus of wood is affected by both density and moisture content. The fundamental concept that the speed of propagation of a longitudinal compression wave through an elastic material is determined only by the elastic constants and the density is not applicable to wood. The effects of decreased moisture content are known to increase the Young's modulus of wood by about two percent for a one percent change in moisture.

Using ultrasonic pulse generating equipment with a transmitting transducer and a receiving transducer, the Southern California Edison Company made measurements on 100 Edison standard 3-3/4 by 4-3/4 inch by 8 foot crossarms (5 p. 1-4). Testing was originally conducted early in the summer when the moisture content of the wood varied widely among individual crossarms. Final measurements were made after seasoning and prior to physical testing when the moisture content of the wood had reached near equilibrium with the ambient humidity.

It was noted in the tests conducted at California Edison that a comparison of change in ultrasonic pulse velocity with change in moisture content indicated a similar increase in velocity with decrease in moisture. The results showed that Young's modulus of a crossarm could be measured approximately by ultrasonic pulse techniques, and that this figure for the modulus would usually agree within ten percent with the modulus measured by destructive tests.

Waid and Woodman used an ultrasonic pulse technique to measure the transmission of energy in sound timber and in timber including a known percentage of decay (15 p. 47). Working at frequencies of 1/4 to 1/2 of a megacycle, the attenuation caused by samples containing diseased wood generally exceeded 50 percent, while a sample which was completely rotten reduced the transmission to zero. The work showed promise of proving valuable in tests on standing timber to locate heart and butt rot at an early stage.

4. Non-destructive Tests at Sonic Frequencies

The experimental sonic procedures by which the sound velocity and the sound attenuation coefficient are determined through measurements of time, length and a damping factor include the following classifications (4, p. 324):

(1) Continuous-wave propagation techniques.

(2) Reverberation and decay techniques.

(3) Resonance techniques.

Wave propagation methods have the advantage that a continuous range of frequencies can be covered with a single test sample, but it is not always possible to provide the conditions necessary for propagation. In solids the length of the specimen must be much greater than the dimensions of the cross section. This is achieved only in long, lossy rods, strips, or filaments. Thus, it would seem that the wave propagation method of testing would not be applicable to the determination of Young's modulus of wooden beams.

The New South Wales Forestry Commission used the sonic reverberation technique of striking standing timber and of noting the characteristics of the resulting vibrations to find the percentage of wood defective in the tree (8, p. 1-5). It was felt that the method was unreliable in its present form, but the fact that it succeeded in some cases indicated that at least some types of defects had a definite influence on the sound emitted when the timber was struck.

The sounds generated by the timber were of short duration, about 30 millseconds, but were well within the time capabilities of electronic analyzing equipment. Examination of sounding patterns indicated that a relation existed between the percentage defect and the rate of decay of the sound.

A tape recorder was used to record the sounds in the field, and they were reproduced in the laboratory on an oscilloscope. The oscilloscope traces were photographed and the photographs were projected onto a ruled screen from which measurements were taken and analyzed.

A SONIC METHOD OF FINDING YOUNG'S MODULUS EMPLOYING NATURAL RESONANCE

Using the background of the first chapter, a method of measuring Young's modulus by finding the natural resonant frequency of the wooden beam is selected for further study. Also, the mathematical background necessary to make use of this technique and to interpret the results is developed.

1. The Selection of a Sonic Method Employing Natural Resonance

What type of acoustic, non-destructive testing would be most applicable for use with inexpensive yet reliable equipment? The equipment should give the experimenter and, possibly at a later date, industry useful results concerning values of Young's modulus of wooden beams.

The most practical method of measuring Young's modulus of wooden beams using ultrasonic frequencies seems to be the noting of variations in the speed of propagation through the wood, but the determination of this velocity with an accuracy of even 10 percent would require expensive display apparatus. Also, ultrasonic techniques require costly transducers which are difficult to fabricate.

For these reasons a sonic method was chosen. The transducers and display equipment could be kept simple, and yet could still be expected to do an accurate job. Furthermore, the design of rugged equipment employing diodes and transistors would involve fewer problems in the audio range than at ultrasonic frequencies.

The sonic technique selected makes use of the natural resonant frequency of the wooden beam. It provides the operator with a constant output indication instead of the decaying waveform of the reverberation method. It does not require the signal power of the wave propagation method, nor does it so severely limit the shape of the beams which can be tested as does the propagation technique.

2. Mathematical Dependence of the Natural Resonant Frequency of a Wooden Beam on Young's Modulus

Young's modulus and the natural resonant frequency of a wooden beam are directly related mathematically. In the following pages the mathematical background and the formulas necessary to make this correlation are developed. First, an electrical analogy is used to help explain the reactions of a beam when excited at its natural resonant frequency and how these reactions might make the resonant frequency detectable. Second, equations are derived to relate this detected resonant frequency to Young's modulus.

By making the assumption, which is far from the actual situation, that all of the characteristics of a wooden beam are uniform throughout, an electrical analogy for the mechanical behavior of wood can be employed (4 p. 12-20).

$$V = Ld^2Q/dt^2 + RdQ/dt + Q/C, \qquad (2)$$

or

$$V = Ldi/dt + Ri = 1/C \int idt. \qquad (3)$$

V = voltage

L = inductance

Q = charge

t = time

R = resistance

C = capacitance

i = current

The velocity of the mass can be said to be analogous to electric current. Then the displacement of the mass is comparable to charge. Also, the mechanical resistance and electrical resistance are directly analogous as are the inductance and the mass. The stiffness constant of the mass is inversely related to the capacitance of the series circuit. The force applied to the mechanical system is analogous to the voltage of the electrical system.

Because of the manner in which the analogy has been arbitrarily chosen, all of the elements of the mechanical system acting on the mass are in parallel as shown in Figure 2.

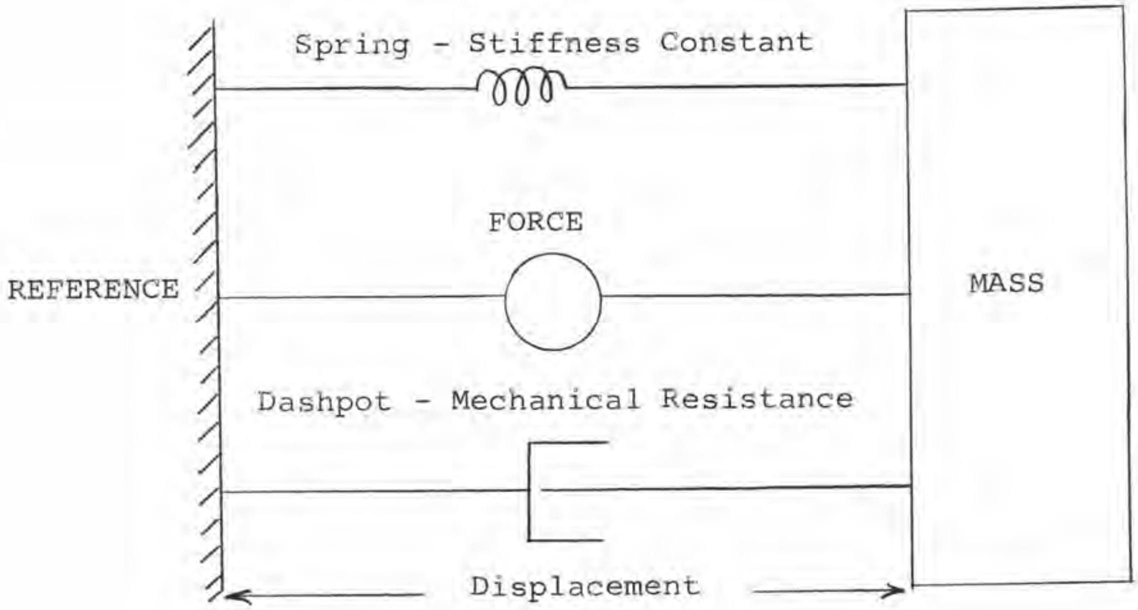

Figure 2: Simplified representation of a mechanical system.

The simplified equations for the mechanical system may be written in the same form as their counterparts in the electrical circuit:

$$F = Md^2y/dt^2 + R_m dy/dt + Ky, \qquad (4)$$

and

$$F = Mdy/dt + R_m u + K\int udt. \qquad (5)$$

M = mass

y = vertical displacement of beam

t = time

R_m = mechanical resistance

K = stiffness constant

F = applied force

If the representation of the mechanical system is further simplified to ignore the mechanical resistance and the stiffness, Equation (4) reduces to

$$F = Md^2y/dt^2. \qquad (6)$$

The equations of motion of a mechanical system may also be derived considering only mechanical characteristics. For simple harmonic motion the displacement of a point on a beam is

$$y = y_o \sin \omega t. \qquad (7)$$

y = displacement of a point on a beam

y_o = maximum displacement of that point

ω = frequency of the motion or vibration

t = time

By taking the derivative of the displacement with respect to time, an expression for the velocity of the mass in simple harmonic motion is obtained.

$$u = y_o \omega \cos \omega t. \qquad (8)$$

u = velocity of the mass

Repeating the operation, the acceleration of the mass is written

$$a = -y_o \omega^2 \sin \omega t. \qquad (9)$$

a = acceleration of the mass

Since the force required must equal the product of the mass and the acceleration, the force necessary for simple harmonic motion is

$$F = My_o\omega^2\sin\omega t. \qquad (10)$$

F = applied force

M = mass

or,

$$F = Md^2y/dt^2. \qquad (11)$$

Equations (6) and (11) are identically equal showing that the simplified mechanical system, ignoring the wood's stiffness and mechanical resistance, corresponds to simple harmonic motion.

If it is assumed that the amplitude of the exciting force is constant at all frequencies regardless of the reaction of the vibrating beam on the force generator, curves of mass displacement, velocity, and acceleration may be drawn as shown in Figure 3 on page 15.

At low frequencies the oscillations are stiffness controlled. That is, the effect of the stiffness constant predominates over the inertia of the mass and the resistive force. In the middle frequency range the stiffness and the inertial force counteract each other. At the resonant frequency the velocity of the mass reaches a maximum value and is controlled by the resistance. Only the velocity has its

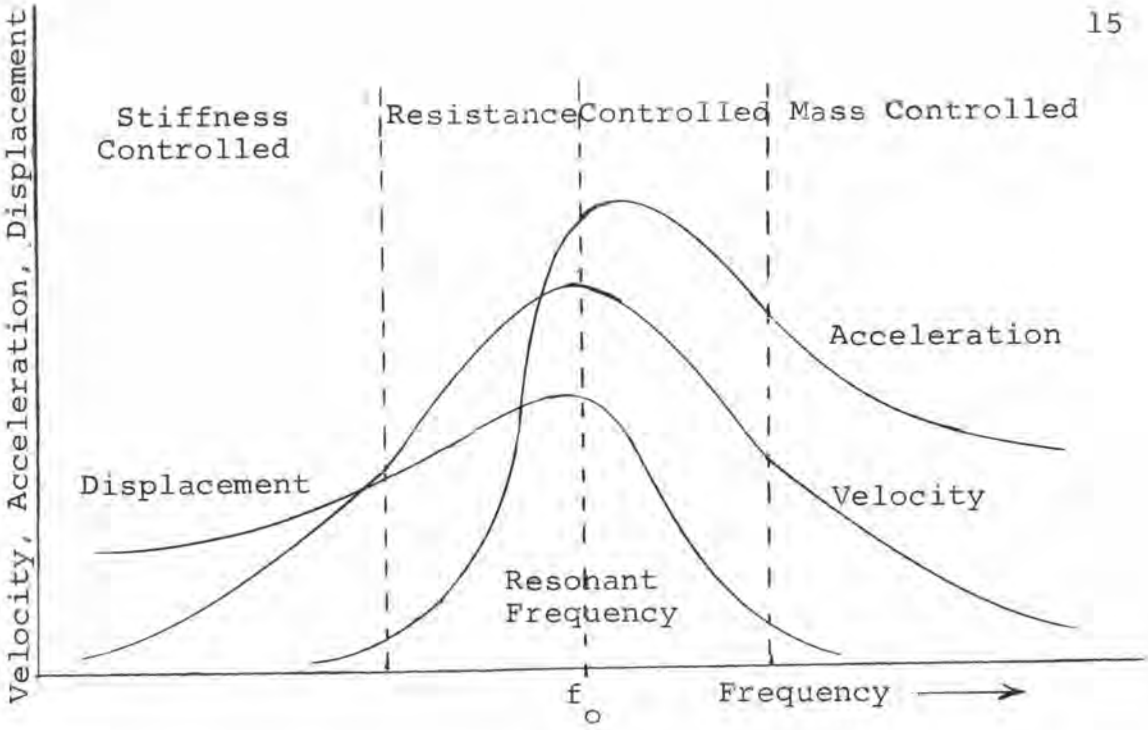

Figure 3: Response of a simplified mechanical system to a constant driving force.

maximum value at the resonant frequency. The maximum for the acceleration occurs at a slightly higher frequency, while the displacement maximum is at a frequency lower than that of resonance. These differences are slight, and all three parameters are generally considered to peak at resonance. It is this maximum displacement at resonant frequency that is detected. The resonant frequency is used in the determination of Young's modulus.

If it is still assumed that the beam is uniform, and that the cross sectional dimensions are small in comparison to the length of the beam, the differential equation for the deflection curve is of the form

$$EId^2y/dx^2 = -m. \tag{12}$$

E = Young's modulus

I = moment of inertia of cross section

y = vertical displacement

x = distance along the length of the beam

m = bending moment

A solution of Equation (12) which will later give the frequency of the beam vibrations may be found (14, p.220-232). If both ends of the beam are free, the solution has the form

$$(-\cos kl + \cosh kl)^2 - (\sinh^2 kl - \sin^2 kl) = 0. \tag{13}$$

l = length of the beam

k = dimensionless constant

By using trigonometric identities, Equation (13) may be simplified to

$$\cos kl \cosh kl = 1. \tag{14}$$

The first three consecutive roots of this equation are

$$k_1 l = 0, \tag{15}$$

$$k_2 l = 4.73, \tag{16}$$

$$k_3 l = 7.85. \tag{17}$$

By further manipulation of Equation (12) these roots may be used to write an expression for the frequency of vibration in terms of beam parameters (14, p. 220-232).

$$f = \frac{k^2}{2\pi}\sqrt{\frac{EIg}{A\rho}}. \tag{18}$$

f = frequency in cycles per second

g = acceleration due to gravity

A = cross sectional area of beam

ρ = density of beam

The frequencies of vibration of the beam corresponding to the roots of Equation (13) may now be computed. The formulas for the three basic modes of oscillation as well as the shape of the vibrating beam for each mode are seen in Figure 4 on the following page.

The $k_2 l$ mode will be referred to as the fundamental mode of vibration and is the mode which will be used in computing Young's modulus.

After differentiation and substitution, Equation (12) on page 16 has the form

$$\partial^2 y/\partial t^2 + \frac{EIg}{A} \partial^4 y/\partial x^4 = 0. \tag{19}$$

The solution of Equation (19) states that the displacement is equal to zero at two locations along the beam for the

$$k_1 l = 0, \quad f_1 = 0$$

$$k_2 l = 4.73, \quad f_2 = \frac{(4.73)^2}{2\pi l^2}\sqrt{\frac{EIg}{A\rho}}$$

$$k_3 l = 7.85, \quad f_3 = \frac{(7.85)^2}{2\pi l^2}\sqrt{\frac{EIg}{A\rho}}$$

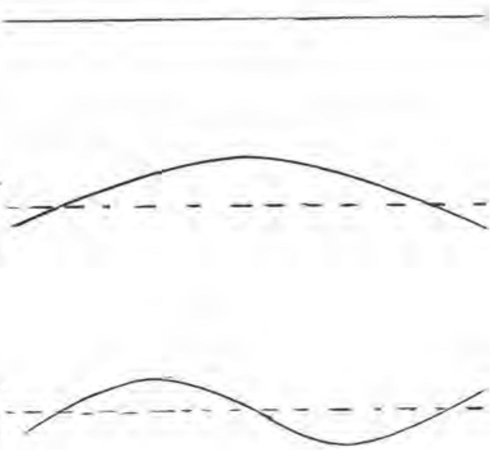

Figure 4: Equations and diagrams for the three lowest modes of lateral vibration of beams.

fundamental mode of vibration. One mode is found 0.22 of the total beam length from each end of the beam (14, p. 222-224).

The equation of Figure 4 for the fundamental or $k_2 l$ mode of vibration may be simplified for beams with rectangular cross sections. The moment of inertia of a rectangle is

$$I = bh^3/12. \tag{20}$$

b = width normal to the direction of flexure

h = depth in the direction of flexure

The cross sectional area of the beam may be written as the product of b and h. Collecting constants, Equation (18) giving the fundamental frequency of vibration of a beam with a rectangular cross section is rewritten (9. p. 51).

$$f = \frac{20.3h}{l^2}\sqrt{\frac{E}{\rho}}. \qquad (21)$$

To find the Young's modulus, Equation (21) is rearranged.

$$E = \frac{0.00242f^2l^4\rho}{h^2}. \qquad (22)$$

E = Young's modulus

f = frequency

l = length of the beam

h = depth in the direction of flexure

ρ = density of the beam

For further clarification of the physical meaning of Equation (18) on page 17, a dimensional analysis is worked out by substituting units for the terms of the equation.

$$f = \frac{k^2}{2\pi}\sqrt{\frac{EIg}{A\rho}} \qquad (18)$$

k = dimensionless constant

E = pounds per inch^2

I = inches^4

A = inches^2

ρ = pounds per inch^3

g = inches per second^2

f = - per second

$$f = \frac{1}{in^2}\sqrt{in^4\,\frac{\cancel{lb}}{\cancel{in}^2}\,\frac{\cancel{in}}{sec^2}\,\frac{1}{\cancel{in}^2}\,\frac{\cancel{in}^3}{\cancel{lb}}}$$

f = 1/sec.

3. Initial Test Equipment

Test equipment was set up using the mathematical results for the frequency dependence of Young's modulus and for the location of the nodes for the fundamental mode of vibration. An actual wooden beam could not be expected to have the uniformity assumed in the mathematical development, so it was questionable just how practical the theory would be.

Using beam supports with a large mass provided a stable base for the vibration measurements. The base used was the beam-supporting apparatus from a static bending stand used in the destructive testing of wooden beams. It consisted of a horizontal bar and two upright supports which could be moved horizontally along the bar to vary the distance between them. The total weight of the bar and supports was well over 100 pounds. The vertical supports were adjusted until each was 0.22 of the total beam length from an end. These distances were predicted previously to be node locations.

A Hewlett-Packard Model 200CD Wide Range Oscillator provided the signal source, and a RCA type R025-174 amplifier with a maximum output of 25 watts provided the audio power necessary to operate the exciting transducer which was the driver unit from a 25 watt speaker. The exciting transducer was placed just beneath the beam at the point midway along the beam's length. (From Figure 4 on page 18 it is noted that this should be the point of maximum vertical displacement when the beam is vibrating in its fundamental mode.) A 0.2 inch air gap was left between the transducer and the beam so that the transducer would not physically interfere with the vibrations.

The detection transducer was placed at the end of the beam. It was a crystal phonographic pickup cartridge with a rated peak output of 0.7 of a volt. The transducer was mounted on its side so that vertical vibrations of the beam would cause a motion of the needle similar to the movement encountered in the needle's normal use in a phonograph.

The detection transducer was wired directly to the vertical input terminals of a Tektronix Model 545A oscilloscope. The voltage output of the cartridge was more than sufficient to give a readable trace on the oscilloscope when the beam was vibrating at a resonant frequency.

The test equipment is shown in Figure 5 on page 23. The variable frequency signal source and the amplifier appear on the left. The beam supports are seen in the center of the photograph with a specimen in test position. The exciting transducer is beneath the center of the beam, and the detection transducer is mounted on its bracket and is touching the right end of the beam. The detection transducer's output is fed into the oscilloscope which appears on the right.

When the Young's modulus of a beam was measured, the oscilloscope was adjusted to maximum sensitivity. Then, starting at the lowest frequency of the variable frequency oscillator, the frequency of the exciting signal was increased until a sinusoidal trace appeared on the oscilloscope. This was the frequency used in the determination of Young's modulus.

One very important fact concerning this type of test was noticed almost immediately. No matter what the harmonic content of the waveform emitted from the exciting transducer was, only the fundamental frequency was passed on to the detection transducer when the beam was vibrating in its fundamental mode. The detected wave as it appeared on the oscilloscope is found in Figure 6 on page 23.

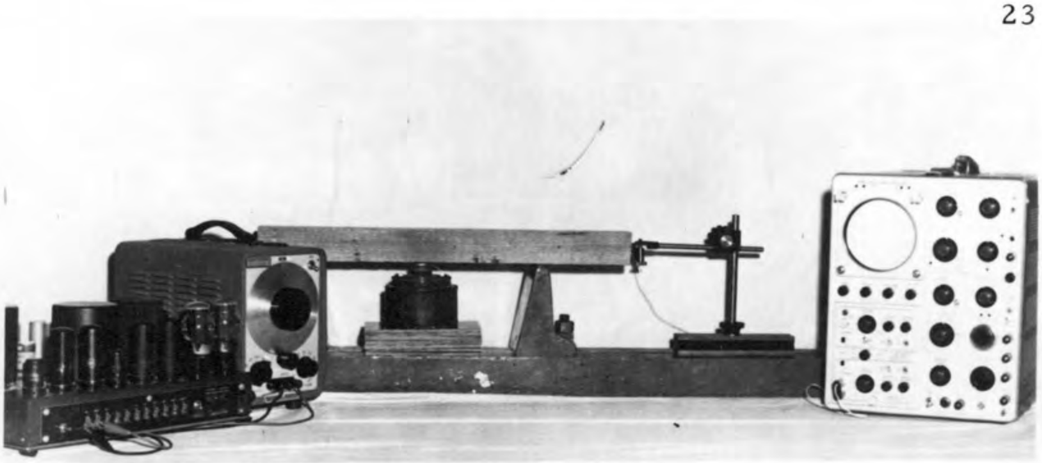

Figure 5: Original test equipment used to measure Young's modulus of wooden beams.

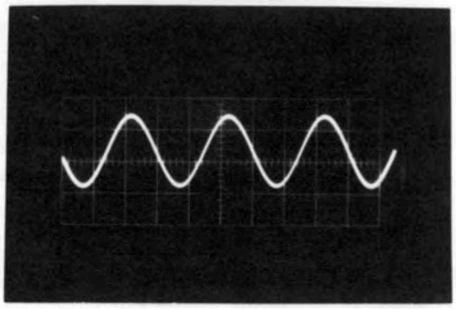

Figure 6: Detected waveform for all types of exciting waveforms when a beam is vibrating in its fundamental mode.

EQUIPMENT DESIGN

The natural resonance method of measuring the frequency of the fundamental mode of vibration of a wooden beam seemed practical, and it was felt that it merited further study. This investigation would have to be carried out by the School of Forestry, but it would be valuable to them to have equipment which would be compact, reliable, and easy to operate. Obviously, the test equipment, consisting of a separate oscillator, amplifier, and oscilloscope, did not fulfill any of these requirements. It was heavy, bulky, expensive, and required a good deal of practice to operate properly.

For these reasons a sonic generator and detector using semiconductors was designed and constructed as one unit which would be reliable, rugged, compact, easy to operate, and as inexpensive as possible. (The exact costs are found in the appendix.)

Included in the sonic generator and detector are a variable frequency oscillator, a 10 watt amplifier whose output is fed to the excitation transducer, a detection amplifier which obtains its input from the detection transducer, and a display meter powered by the output of the detection amplifier.

1. Design Considerations

The equipment was designed with cost and reliability governing the majority of the circuit decisions. The two were tied closely together since the cost was minimized by keeping the circuits as simple as possible, and the simplicity of design increased the reliability.

Although the power requirement for standard test specimens was at most one or two watts depending upon the particular beam, the equipment was designed with an output of 10 watts. This was done to make the sonic generator and detector more adaptable to other test situations involving larger specimens.

The frequency range of the oscillator in the sonic generator extends from 130 to 10,000 cycles per second. This coverage allows the Young's modulus of a one by one beam up to 40 inches in length to be tested, or a 10 by 10 inch beam as long as 124 inches to be measured. Reducing the lower limit of the oscillator's frequency range would complicate the circuitry, so provision is made to test very slender beams with low resonant frequencies by plugging the output of an external oscillator into the back of the sonic generator. This added feature makes the equipment useful for nearly any shape of wooden beam.

All components used in the sonic generator and detector are standard and are readily available when replacement of circuit elements is required. Also, with the exception of the driver and power amplifier stages, all transistors are the same type.

The generator and detector are physically constructed in a manner which provides easy access when repairs are required. But access is complicated by the fact that the oscillator circuitry has to be shielded from the remainder of the equipment to reduce a.c. pickup. To alleviate this problem, the oscillator unit is constructed so that it may be completely removed from the main chassis.

2. Oscillator

The design of the variable-frequency signal source for the sonic generator may be broken down into the following steps:

(1) A Wien-bridge oscillator is selected as the most suitable type of variable-frequency signal source for this apparatus.

(2) The operation of the oscillator is described using feedback theory.

(3) Modifications are made to the basic oscillator circuit to make it more applicable to the sonic generator and detector and to correct design problems

inherent to the original circuit.

(4) Tests are conducted on the completed oscillator to determine its accuracy and reliability over an extended period of time.

It was necessary to decide what type of variable frequency oscillator should be used as the signal source. Because of the low frequency requirement, an LC oscillator would not be practical. The physical size of the inductor would be too large. An RC phase-shift oscillator would overcome the inductance problem, but varying the frequency over a range would require the simultaneous adjustment of three circuit elements. Varying resistance of the phase-shift network would change the driving point impedance and might load the active element sufficiently to stop oscillations. If the capacitance were varied, it would be necessary to track three isolated air capacitors. The RC phase-shift oscillator would be more applicable to fixed frequency oscillators.

By elimination, the RC bridge oscillator is the logical choice. One type of bridge oscillator which uses the circuit of Figure 7 is know as a Wien-bridge oscillator (10, p. 480).

The principles of operation of the Wien-bridge oscillator may be explained from feedback theory. A portion

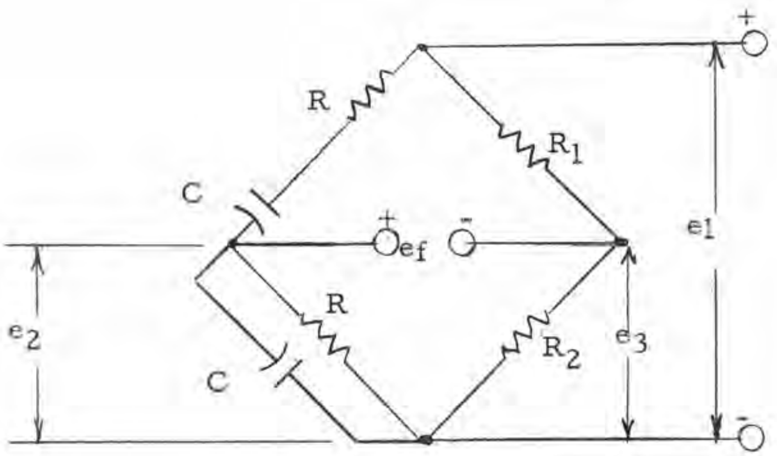

Figure 7: Circuit diagram of the Wien-bridge frequency selective network.

of either the output voltage or output current from an amplifier may be fed back to the input of the amplifier. Consider the case of voltage feedback. The fraction of the output voltage which is fed back is known as beta. If the feedback network is adjusted so that the phase and magnitude of the voltage fed back are identical to the voltage applied to the amplifier, the amplifier will theoretically oscillate. In practice it is necessary to increase the magnitude of the feedback voltage slightly. Because beta represents the fraction of the output which is returned to the input, it may be considered as the transfer ratio of the feedback network. Figure 7 above represents the feedback network of the Wien-bridge oscillator.

The beta of the bridge circuit of Figure 7 may be developed mathematically. First, consider only the series RC and parallel RC branches of the bridge. A transfer function for these two branches only may be written as

$$e_2/e_1 = \frac{\frac{R}{RCS+1}}{\frac{R}{RCS+1} + \frac{RCS+1}{CS}} . \qquad (23)$$

e_2 = voltage across the parallel branch

e_1 = voltage across both the parallel branch and the series branch

R = the resistance in the parallel RC branch and in the series RC branch

C = the capacitance in the parallel RC branch and in the series RC branch

S = the complex frequency variable

Equation (23) reduces to

$$e_2/e_1 = \frac{1}{3 + j(\omega RC - 1/\omega RC)}. \qquad (24)$$

$j\omega = S$

It is seen in Equation (24) that the imaginary term in the denominator disappears when

$$\omega = 1/RC, \qquad (25)$$

which will be referred to as the resonant frequency. Also, when the imaginary term of Equation (24) is zero, the transfer function has a value of 1/3.

Looking at the entire bridge circuit of Figure 7 on page 28, the output voltage can be written

$$e_f = e_2 - e_3. \tag{26}$$

e_f = output voltage

e_3 = voltage across R_2

The ratio of the voltage across R_2 to the voltage across both the series and the parallel RC branches, which is the input voltage to the bridge, is

$$e_3/e_1 = R_2/(R_1 + R_2). \tag{27}$$

e_1 = input voltage to the bridge

e_3 = voltage across R_2

The beta, or overall transfer ratio of the bridge, may then be expressed as

$$\beta = e_2/e_1 - e_3/e_1 = e_f/e_1. \tag{28}$$

β = beta

e_2 = voltage across the parallel RC branch

e_f = output voltage of the bridge

At resonant frequency beta is

$$\beta = 1/3 - R_2/(R_1 + R_2). \tag{29}$$

If the ratio of resistances in Equation (29) is given the value

$$R_2/(R_1 + R_2) = 1/3 - 1/\delta \ , \qquad (30)$$

then

$$\beta = 1/3 - 1/3 + 1/\delta \ ,$$

$$\beta = 1/\delta \ . \qquad (31)$$

Under these conditions the theoretical threshold voltage gain is δ. The term $1/\delta$ may also be considered as the degree of bridge unbalance (12, p. 438). If the loop gain were infinite, the bridge could be perfectly balanced at the resonant frequency, and the circuit would still oscillate. As δ decreases to three, the resistances R_1 and R_2 go to infinity, and the bridge circuit degenerates into just a series and a parallel RC network. Conversely, as the loop gain, δ, increases, the bridge can be operated nearer to the balanced condition. By placing the bridge closer to balance, it is made more selective, and the harmonic content of the waveform amplified is reduced.

A circuit may be designed employing the Wien-bridge principles just outlined. Since the phase shift in the feedback network is zero at resonance, the circuitry, excluding the feedback network, must have a 360 degree phase shift. A circuit diagram for the Wien-bridge oscillator is seen below in Figure 8. A 180 degree shift is obtained from the combination of T_1 and T_2, and an equal shift is realized from T_3.

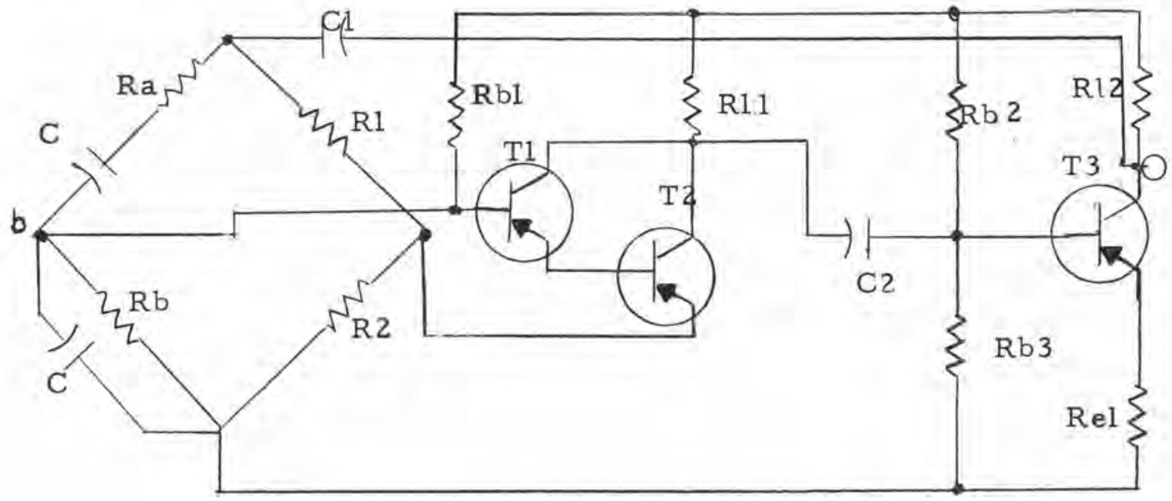

Figure 8: Circuit diagram of the Wien-bridge oscillator circuit.

The circuit of Figure 8 above does not meet the requirements of the sonic generator. Numerous modifications must be made:

(1) In addition to being equal, the capacitive elements of the bridge must be variable so that the frequency can be varied within a given range.

(2) A network to switch in different values R_a and R_b must be provided so that the oscillator can cover more than one frequency range.

(3) If special provisions are not made, varying the frequency range of the circuit changes the bias conditions of the first transistor. This difficulty is alleviated by placing a capacitor between the base of T_1 and point b on the bridge.

(4) A non-linear element must be included to provide a constant output amplitude with changing frequencies.

(5) Several variable resistors and capacitors must be provided so that adjustments can be made on the oscillator. A potentiometer, R_2, is placed in series with the non-linear element to control the element's effect on the circuit. Trim potentiometers, R_t, are provided for each range to control the magnitude of the output voltage. Padding capacitors in parallel with the bridge's air capacitor vary the frequency.

The oscillator's non-linear element merits further discussion. Thermistors of various types have been tried as non-linear elements, but a higher voltage than is available in a transistor circuit is required before the types tested exhibit the necessary non-linear qualities. On the other hand, tungsten has non-linear characteristics at the few volts available in the circuit. A three-watt 120 volt tungsten light globe, when placed in series with a potentiometer to form R_2 of the bridge circuit, controls the amplitude of the output satisfactorily.

The operation of the non-linear element is explained as follows: As the output voltage decreases because of a decrease in the amplification, the resistance of the non-linear element, R_2, drops. Consequently, beta increases as explained in Equations (27) and (28). In other words, as the amplification changes, the extent to which the Wien-bridge is unbalanced adjusts in a manner to keep the product of the amplification and beta nearly constant. Because of the thermal time lag of the tungsten filament, the lamp appears as a linear resistor with a fixed value during the course of a single cycle.

In addition to the modifications listed above which must be made to the circuit of Figure 8 on page 32, several design considerations are worth noting:

(1) In order to avoid saturating T_2 of Figure 8, the value of R_{b1} must be large. This keeps the base current of T_2 within tolerable limits.

(2) Precision components should be used as the frequency-determining elements of the bridge. One percent precision resistors are used for R_a and R_b. The remainder of the RC frequency network is a two-gang variable air capacitor whose value does not change with time for a given setting unless it is physically damaged.

(3) The output amplitude, as well as the frequency of the oscillator, must remain constant for a given setting over an extended period of time. Stability of the output voltage is increased by not placing a capacitor in parallel with R_{e1} and also by using a value for R_{11} which is small in comparison to the input impedance of the second stage, T_3. Amplification is sacrificed, but there is still ample gain for proper operation of the oscillator.

The modified Wien-bridge oscillator is seen in Figure 9. It incorporates all of the modifications and design considerations which have been discussed. This circuit is the variable-frequency signal source of the sonic generator.

The reliability of a given frequency reading of the final oscillator circuit was determined. This was done to gain information as to the accuracy over an extended period of time of the frequency read on the oscillator dial. Each factor which might have an effect on frequency was changed by a known amount, and the resulting variation in frequency was noted.

(1) Adjusting the amplitude of the output voltage of the oscillator from minimum to the point where the waveform was noticeably limited increased the frequency by one percent. This adjustment was made with

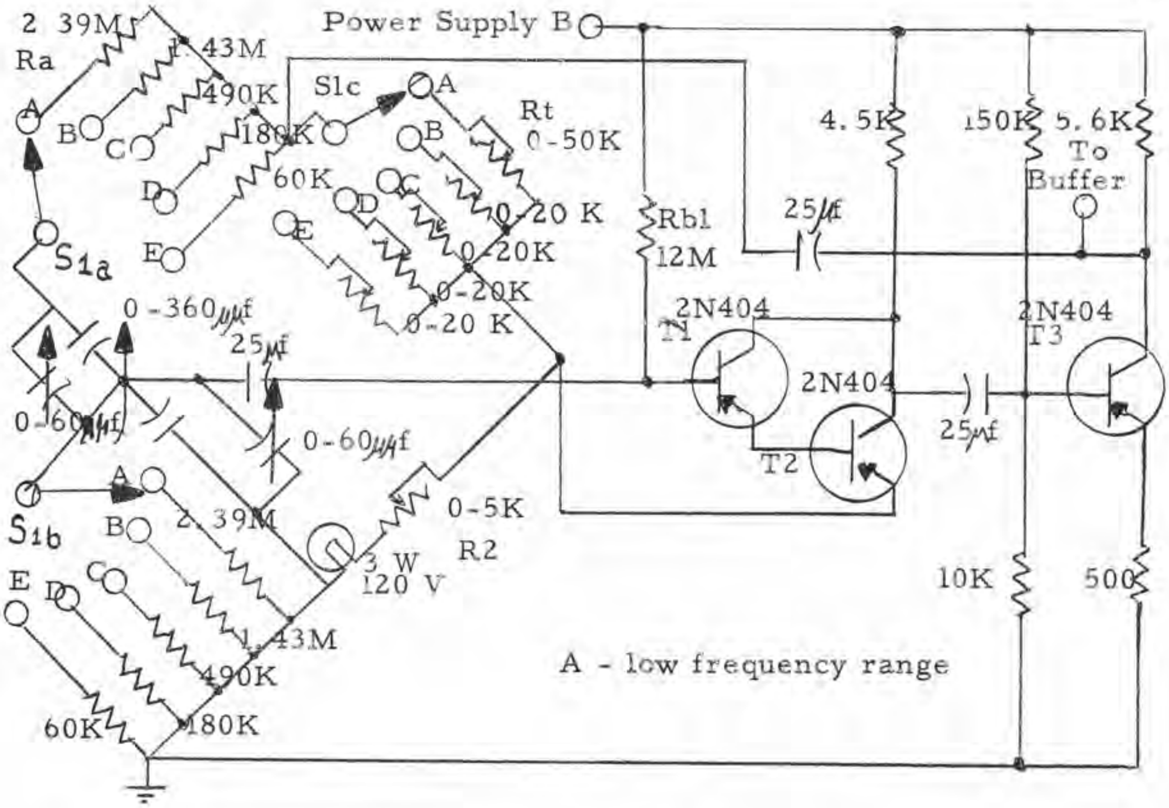

Figure 9: Circuit diagram of the Wien-bridge oscillator used in the sonic generator.

the trim potentiometers, R_t.

(2) When the oscillator supply voltage was changed 25 percent, a two percent variation in frequency resulted.

(3) The oscillator's load impedance was changed from a no-load condition to a 5,000 ohm load with a resultant frequency rise of 1.5 percent.

(4) When the potentiometer in series with the non-linear element in the bridge was moved from its maximum value

to its minimum setting, the frequency decreased by one percent. At the same time that the potentiometer was reset, the trim potentiometer for the particular range was also adjusted to keep the output amplitude constant.

(5) When R_a and R_b, the resistors in the RC frequency network, were both lowered in value by four percent, the frequency was increased by four percent. When one of the resistors was decreased in value by four percent, and the other was not disturbed, the output frequency increased by only one percent. The effect was approximately the same with either resistor changed. There was also a loss in magnitude of the output when R_a and R_b no longer had the same value, but this was corrected with the trim potentiometers, R_t.

(6) Lowering the value of the first stage's bias resistor, R_{b1}, by 25 percent raised the frequency less than 0.5 percent.

(7) Individually replacing the three transistors with a transistor which had an amplification of only half that of the original transistors changed the frequency less than one percent.

Using the above data and the fact that the one percent precision resistors will not usually change their value more than three percent after they are in the circuit, the frequency reliability of the oscillator can be stated: Considering the worst case, the frequency is unlikely to change more than plus or minus 10 percent over an extended period of time.

3. Signal Amplifier

The signal amplifier is comprised of three stages: First, a buffer provides isolation between the oscillator and the remainder of the sonic generator. Second, a driver stage raises the signal to the level required by the final amplifier. Third, the power amplifier, the final stage, amplifies the signal to provide an output of 10 watts. This output is fed to the exciting transducer.

To further insure that the magnitude of the output signal from the sonic generator will remain constant, the oscillator is isolated from the amplifying stages by a buffer stage. This circuit has a 3,300 ohm resistor in series with the emitter which raises the buffer's input impedance to over 100,000 ohms. Since this high impedance is in parallel with the 5,600 ohm load resistor, R_{12}, of the oscillator's second stage, only a small fraction of the output of the oscillator is used by the buffer. This prevents changing conditions in the amplifier from having any significant effect on the oscillator.

The amplitude of the sonic generator's output signal is controlled by a potentiometer which is located in the collector circuit of the buffer. This control, as well as the buffer and the driver stages, is seen in Figure 10 on page 40.

The driver stage, which uses a Honeywell H7 medium-power transistor, amplifies the signal from the volume control to a level sufficent to drive the final amplifier. This transistor is operated far below its maximum power capabilities, but the 200 milliwatt input power requirement of the final stage would exceed the 120 milliwatt maximum dissipation rating of the 2N404's used in previous stages.

The driver is transformer-coupled to the push-pull power amplifier with a 24 volt filament transformer. The frequency spectrum covered by the sonic generator is almost entirely below 10 kilocycles. The output voltage of the transformer is only down five decibels from its low-frequency value at 10 kilocycles. This frequency response allows the filament transformer to be used without serious attenuation even in the high frequency ranges of the sonic generator.

A pair of 2N301 power transistors in a common emitter, push-pull circuit form the output stage. The 2N301's are

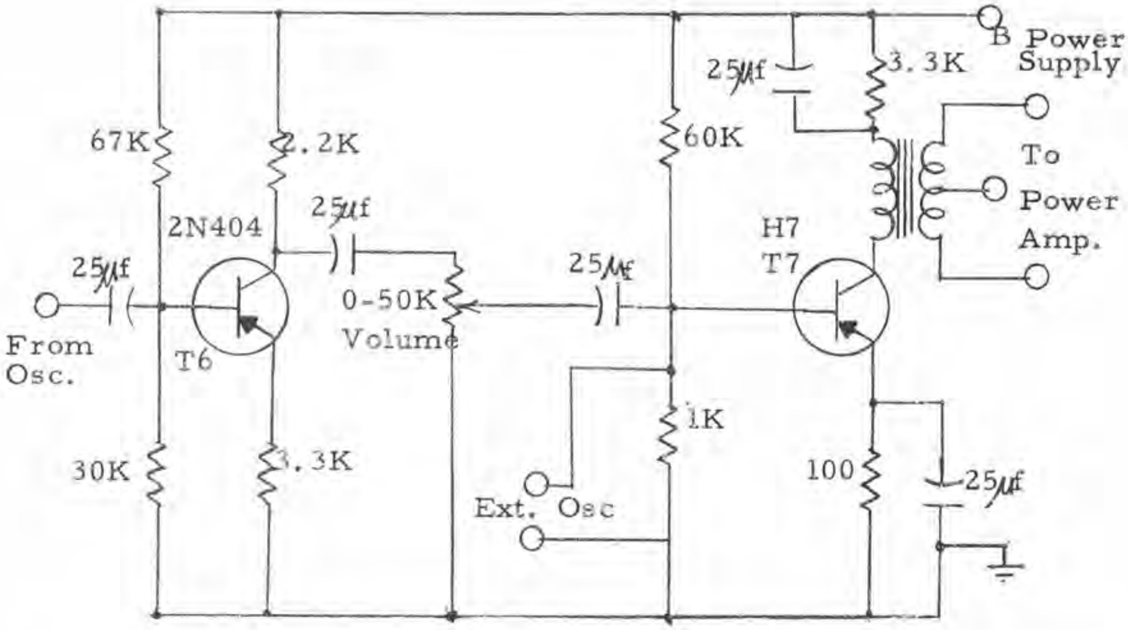

Figure 10: Circuit diagram of the buffer and driver stages of the sonic generator.

inexpensive and have the required output power capabilities. Each transistor is capable of dissipating 11 watts at an ambient temperature of 25 degrees centigrade. In this circuit each transistor is required to put out five watts of signal power. To provide for adequate heat dissipation, the 2N301's are mounted in a 3/16 inch aluminum plate which covers the entire back of the chassis. Since the transistors are operated in the common emitter configuration, their cases are electrically isolated from the aluminum plate with mica washers.

The power amplifier is operated as close to Class B as possible without generating crossover distortion. The quiescent points of the 2N301's are such that 700 microamperes of base current are flowing in each transistor when there is no signal from the driver stage.

The output is connected to the exciting transducer through an output transformer which matches the collector impedance to the transducer. The power amplifier and transducer are found in Figure 11.

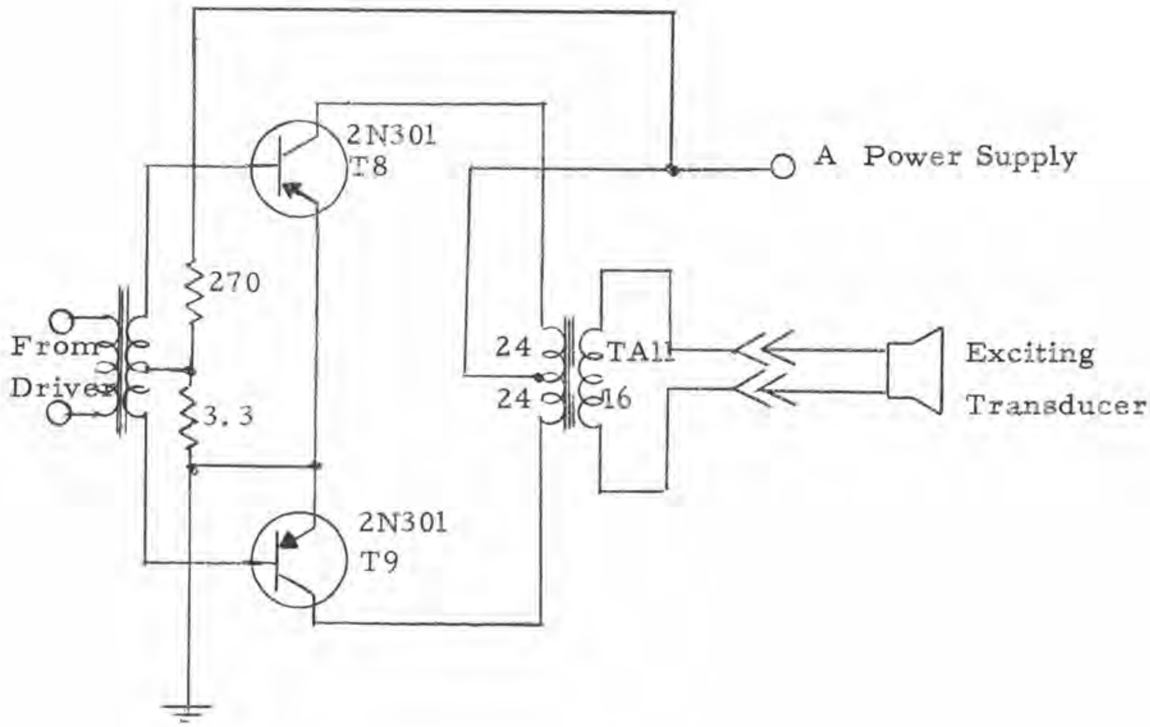

Figure 11: Circuit diagram of the power amplifier and the exciting transducer.

4. Exciting Transducer

The exciting transducer is a Stromberg Carlson driver unit from a loudspeaker. It is classed as a moving-coil driver, and its maximum power rating, although not marked, is probably between 15 and 20 watts.

The driver unit alone without the horn has an input impedance of approximately 20 ohms (13, p. 62). This impedance varies rather widely with frequency when no horn is attached. The variation is reduced by "loading" the driver with the beam which is placed close to the driver aperture during the measurement of the resonant frequency of the beam. Still, it is difficult to predict the transducer's impedance at any given frequency.

5. Detection Transducer and Amplifier

A phonographic cartridge and needle are used as the detection transducer. The cartridge is an Asiatic type 57TM with a rated peak output voltage of 0.7 of a volt and a frequency response of 30 to 15,000 cycles. A sapphire needle is used with the cartridge.

The output of the cartridge is more than sufficient to drive the detection amplifier. Two 2N404's in a compound configuration form this amplifier circuit which is shown in Figure 12 on the following page.

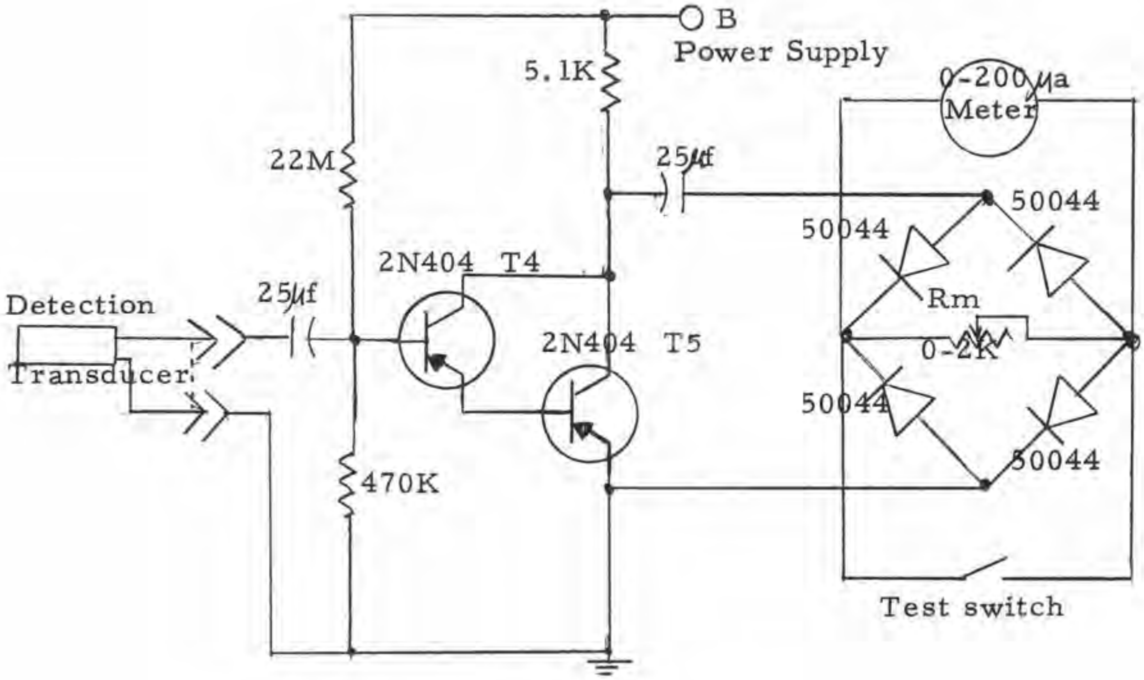

Figure 12: Circuit diagram of the detection transducer and amplifier.

A diode network in the collector of the second transistor converts the amplified a.c. signal from the detection transducer into a full-wave rectified d.c. signal. This d.c. signal actuates the zero to 200 micro-ammeter. The deflection of the meter is proportional to the magnitude of the signal picked up by the detection transducer.

A trim potentiometer across the meter varies the meter sensitivity by shunting out a portion of the current which would flow through the meter. There is also a shorting switch across the meter which is left closed until measurements are to be made to prevent damage to the movement by the charging and discharging of the capacitor in the collector circuit through the meter when the equipment is turned on and off or when the detection transducer is being positioned.

6. Power Supply

A 24 volt transformer and four diodes in a full-wave bridge provide the d.c. power to operate the transistor circuits of the sonic generator and detector.

Over ninety percent of the power required is drawn by the final amplifier. Since this stage operated push-pull, its supply requires much less filtering than do the other stages. For these reasons the filtering circuit for the power amplifier and the filtering network for the remainder of the equipment are separate as is seen in Figure 13 on the following page.

Three ohms of resistance and a 2000 microfarad capacitor comprise the filter for the power amplifier's supply. Because only a few ohms are required in the filter resistor, there is only a four volt change in the power amplifier's d.c. collector voltage from the no-signal condition to full output. This variation could be reduced

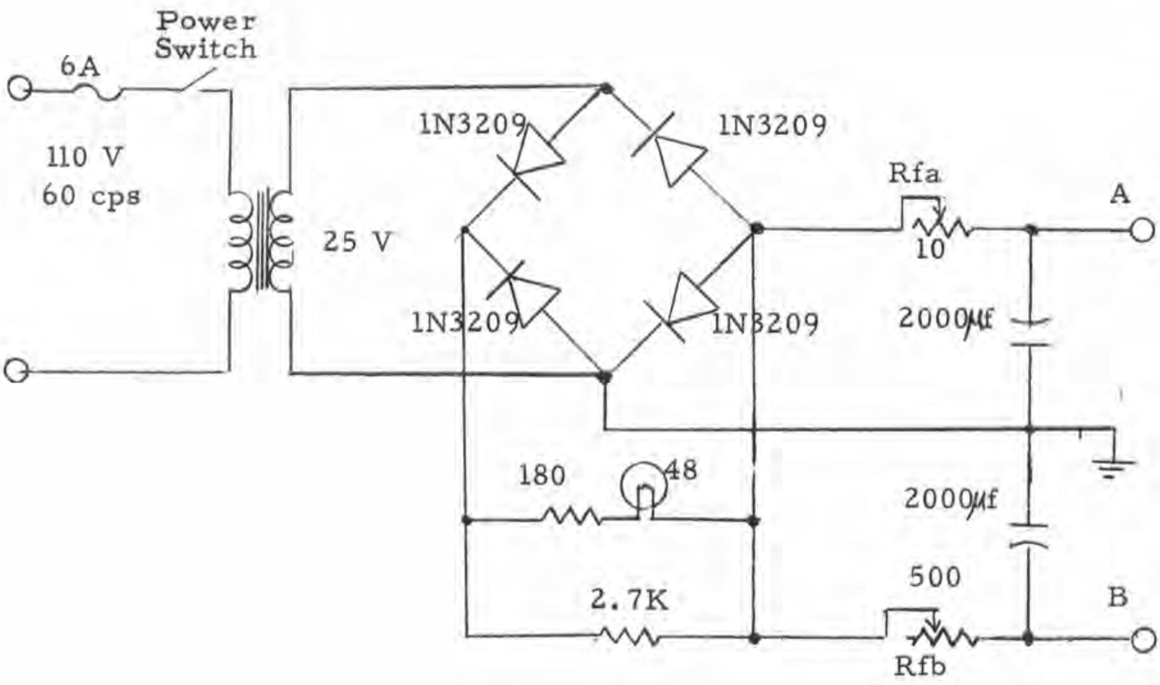

Figure 13: Circuit diagram of the power supply.

with a regulation network, but this would further complicate the circuit. The distortion caused by the four volt change is not large enough to be noticeable on the oscilloscope. This distortion does not affect measurements since the wooden beam being tested passes only the fundamental frequency on to the detection transducer.

Three hundred ohms of resistance and 2000 microfarads of capacitance provide the filter network of the supply for the remainder of the transistors. The filtering components reduce ripple to 0.1 percent. No regulation is required in this second filter network for two reasons:

First, all transistors which are drawing current from it are operated Class A. Thus, there are no variations in the current required with changing signal conditions. Second, even if the supply voltage should change, the most critical element, the oscillator, drifts in frequency one percent with a 25 percent change in supply voltage.

OPERATION OF THE SONIC GENERATOR AND DETECTOR

1. Mounting the Beam

The specimen is placed on two supports, each support being located 0.22 of the total beam length from one end. The exciting transducer is placed beneath the center of the beam with the mouth of the transducer 0.2 of an inch below the beam. The detection transducer is mounted on a bracket and placed with the needle just touching the end of the beam. The cartridge of the exciting transducer is mounted on its side so that a vertical vibration of the specimen causes the needle to move from side to side. The sonic generator and detector with a specimen in place on the supports is shown in Figure 14 on page 50.

2. Measuring the Resonant Frequency

To determine the resonant frequency of the beam, the equipment is operated as follows:

(1) Set the "volume" control at the middle of its range.

(2) Place the "test" switch in off position.

(3) Turn the "range"switch to the lowest frequency range.

(4) Tune the variable frequency knob to the lowest frequency on that range.

(5) Turn the "power" switch to the on position and allow

two minutes for the equipment to warm up.

(6) Turn the "test" switch to on position.

(7) Starting with the lowest frequency, sweep each frequency range in succession until several major deflections are noted on the meter.

(8) If the meter goes above 200 on any of these peaks, reduce the audio volume.

(9) If no peaks are noted on the meter, increase the audio volume, and repeat step (7).

(10) After the meter has been set so that major peaks cause nearly a full scale deflection, find the frequency of the lowest-frequency major meter peak. This is the frequency to be used in the computation of Young's modulus.

(11) Turn the "test" switch to off position.

(12) If more tests are to be run, the "power" switch may be left in the on position.

(13) If the tests are completed turn the "power" switch to the off position AFTER turning the "test" switch to the off position.

WARNING: Do not turn the "power" switch on or off unless the "test" switch is in the off position.

3. Computing Young's Modulus

Once the frequency of the fundamental mode of vibration is determined, the previously derived equations are applied to compute Young's modulus. For clarity the final equation is repeated below.

$$E = 0.00242 f^2 l^4 \rho / h^2 \qquad (19)$$

E = Young's modulus, pounds per inch^2

f = frequency measured on sonic generator and detector, cycles per second

l = length of the beam, inches

ρ = density of the beam, pound per inch^3

h = depth in the direction of flexure, inches

This equation is derived on pages 14 through 17 of this paper. A sample computation of Young's modulus appears in the appendix.

NOTE: Range A is not reliable and should not be used.

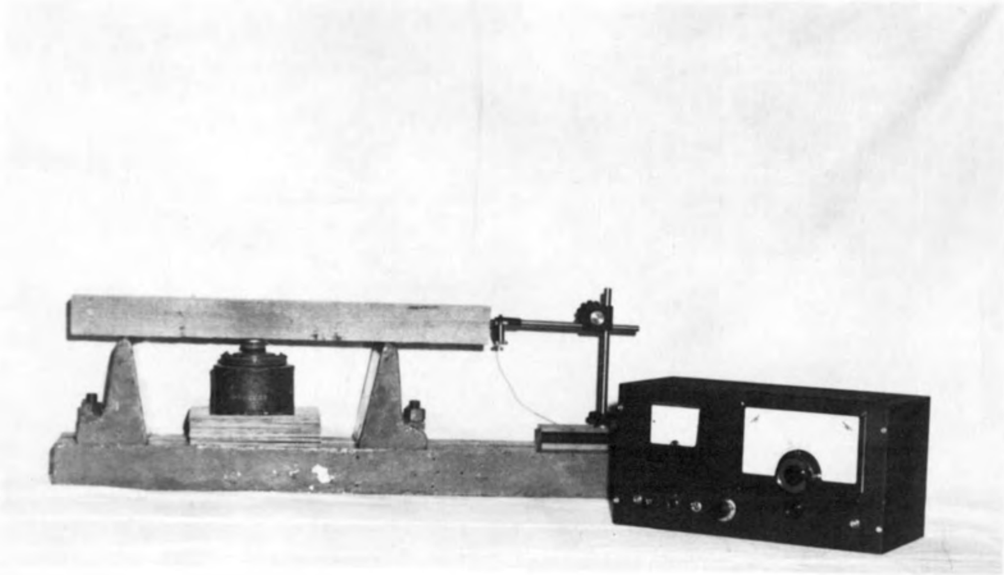

Figure 14: Sonic generator and detector with a beam in test position.

MEASUREMENTS MADE WITH THE SONIC GENERATOR AND DETECTOR

Extensive tests will have to be conducted before any conclusions can be drawn about Young's modulus as measured with the sonic generator and detector. A study of this type is not within the scope of this paper.

In order to briefly check the method and the equipment, Young's modulus of ten two by two by 30 inch beams was measured with the sonic generator and detector. Five of these beams had knots in them, and five had clear wood. A forest products class of the School of Forestry at Oregon State University then tested the beams destructively. Each beam was broken by a different member of the class. None of the men were experienced in the use of the destructive testing equipment.

A comparison of Young's modulus of these ten beams as measured with the sonic generator and detector and as found destructively is made in Table I on page 52. Although no conclusions can be reached because of the small sample size, some correlation between the results obtained by the two methods is noted.

There are several possible reasons why there is not complete correlation:

(1) The static Young's modulus measured by destructive

TABLE I

COMPARISON OF YOUNG'S MODULUS MEASURED USING THE SONIC GENERATOR AND DETECTOR AND MEASURED DESTRUCTIVELY

BEAM NUMBER	KNOTS OR CLEAR WOOD	YOUNG'S MODULUS DESTRUCTIVE	SONIC	PERCENT DIFFERENCE
		Pounds per square inch	Pounds per square inch	Percent
1	knots	1.38×10^6	1.55×10^6	11.6
2	knots	1.09×10^6	1.33×10^6	19.6
3	knots	1.24×10^6	1.46×10^6	16.3
4	knots	1.32×10^6	1.48×10^6	11.4
5	knots	1.15×10^6	1.56×10^6	30.2
6	clear	1.52×10^6	1.75×10^6	14.1
7	clear	1.40×10^6	1.72×10^6	20.5
8	clear	1.66×10^6	1.99×10^6	18.1
9	clear	1.57×10^6	2.02×10^6	25.0
10	clear	1.25×10^6	1.67×10^6	28.7

testing and the dynamic Young's modulus found with the sonic generator might not have the same value.

(2) The calibration of the destructive testing stand used might not be exact.

(3) The variation in the percent difference between the values obtained by the two methods might be caused by the fact that each beam was destructively tested by a different man.

(4) The non-destructive method of finding Young's modulus by determining the natural resonant frequency of the beam might not be accurate.

The above statements can only be considered as possibilities and not as conclusions.

FUTURE APPLICATIONS

Although thus far the sonic generator and detector has been used with small beams, it has been designed to test much larger specimens. It is difficult to estimate the size beam which the equipment could test, but the two by two by 30 inch specimens have only required a small fraction of the generator's 10 watt output power.

The sonic generator and detector might also prove to be valuable in determining the elastic constants of laminated beams.

More sophisticated equipment would have many possibilities if the method proves to be accurate. For example, lumber might be graded according to its Young's modulus. The decision as to what cuts should be made on a log might be based on sonic measurements made when the log entered the sawmill.

BIBLIOGRAPHY

1. ASTM Committee D-7 on Wood. ASTM standards on wood, wood preservatives, and related materials. Philadelphia, American Society for Testing Materials, 1954. 358 p.

2. Doolittle, Fred B. and Robert F. Townsend. Characteristics of 100 western hemlock crossarms. Los Angeles, Southern California Edison Company, 1956. 25 p.

3. Hearmon, R.F.S. Non-destructive tests to evaluate the physical and mechanical properties of wood and wood products. Address to the Fifth World Forestry Congress, Seattle, Washington, 1960.

4. Hueter, Theodo F. and Richard H. Bolt. Sonics. New York, John Wiley and Sons, 1955. 456 p.

5. Langner, L. L. Soniscope testing of western hemlock crossarms. Los Angeles, Southern California Edison Company, 1956. 11 p.

6. Lee I.D.G. A non-destructive method for measuring the elastic anisotropy of wood using an ultrasonic pulse technique. London, The Timber Development Association Ltd., 1958. 15 p.

7. _______________ Non-destructive testing of wood by vibration methods. London, The Timber Development Association Ltd., 1958. 13 p.

8. McHugh, B.J.J. Determination of the soundness of trees and logs by sonic methods. Sydney, Australia, New South Wales Forestry Commission, n.d. 5 p.

9. McMaster, Robert C. (ed.) Non-destructive testing handbook. New York, The Ronald Press Company, 1959. 2 vols.

10. Millman, Jacob. Vacuum-tube and semiconductor electronics. New York, McGraw-Hill, 1958. 644 p.

11. Morris, Charles O. Ultrasonics for wood industries. Corvallis, Oregon, Oregon Forest Research Center, 1960. 40 p.

12. Strauss, Leonard. Wave generation and shaping. New York, McGraw-Hill, 1960. 520 p.

13. Thurman, Harry L. Dynamic impedance characteristics of a moving-coil loudspeaker motor element. Master's thesis. Corvallis, Oregon State University, 1949. 67 numb. leaves.

14. Timoshenko, S. Vibration problems in engineering. New York, D. Van Nostrand, 1928. 351 p.

15. Waid, J. S. and M. J. Woodman. A non-destructive method of detecting diseases in wood. Nature 180:47. July 6, 1957.

APPENDIX

SAMPLE COMPUTATION OF YOUNG'S MODULUS
FROM THE NATURAL RESONANT FREQUENCY OF A
BEAM

Beam dimensions; two by two by 30 inches

Beam weight; 2.1 pounds

Measured natural resonant frequency; 450 cycles per second

From Equation (22) on page 19

$$E = 0.00242 \frac{f^2 l^4 \rho}{h^2} .$$

E = modulus of elasticity - unknown

l = beam length = 30 inches

h = beam depth in direction of flexure = 2 inches

ρ = beam density = weight/volume

$$= \frac{2.1 \text{ pounds}}{(2)(2)(30) \text{ inches}^3}$$

$$= 0.0175 \text{ pounds/inch}^3$$

f = resonant frequency = 450 cycles per second

$$E = \frac{(0.00242)(450)^2(30)^4(0.0175)}{(2)^2} \text{ pounds/inch}^2$$

$$E = 1.73 \times 10^6 \text{ pounds/inch}^2$$

COST LIST FOR SONIC GENERATOR AND DETECTOR

Chassis and cabinet	$ 11.45
Transistors and diodes	18.96
Transformers	16.85
Switches	4.06
Precision resistors	6.00
Variable air capacitor	1.89
Capacitors	10.16
Resistors	4.50
Potentiometers	7.30
Exciting tranducer - 15 watt loudspeaker driver unit	14.00
Detection transducer - phonograph cartridge	6.00
Dial assemble	7.80
Transistor sockets	3.00
Microammeter	13.05
Jacks and plugs	4.50
Miscellaneous	6.75
TOTAL	$ 136.27

The source of the prices was Allied Electronics' 1962 catalog.

ALIGNMENT

The sonic generator and detector should be operating for 15 minutes before any adjustments are made. Also, the audio emitted from the exciting transducer may be greatly reduced during alignment by screwing on the cap which is provided with the transducer.

(1) Sensitivity of the Detection Amplifier

The sensitivity of the detection amplifier may be varied by changing the setting of the potentiometer, R_m, which is across the terminals of the display meter. Decreasing the sensitivity reduces the effect of vibrations external to the testing equipment and increases the power which must be supplied to the exciting transducer to produce a given deflection of the display meter.

(2) Waveshape of the Output Signal from the Oscillator

If oscillations do not occur on one or more frequency ranges, or if the signal put out by the oscillator is limited, the trim potentiometers, R_t, in the oscillator's bridge circuit must be adjusted.

(3) Frequency Correction

The coverage of all five frequency ranges may be adjusted simultaneously by changing the settings on the padding capacitors in the oscillator's bridge circuit. Both padders must be changed by the same amount if the amplitude of the oscillator's output signal is to remain constant as the oscillator frequency is varied. If it is necessary to correct the frequency of one range individually, there are two more calibration cards under the one presently used to denote oscillator frequencies. The corrected frequency readings may be printed on one of these extra cards.

(4) D.C. Supply Voltage

The d.c. supply voltages may be adjusted by changing the settings of the variable resistors, R_{fa} and R_{fb}, in the power supply filter networks.

(5) Non-linear Element

The effect of the non-linear element located in the oscillator's bridge circuit may be varied by adjusting potentiometer R_2.

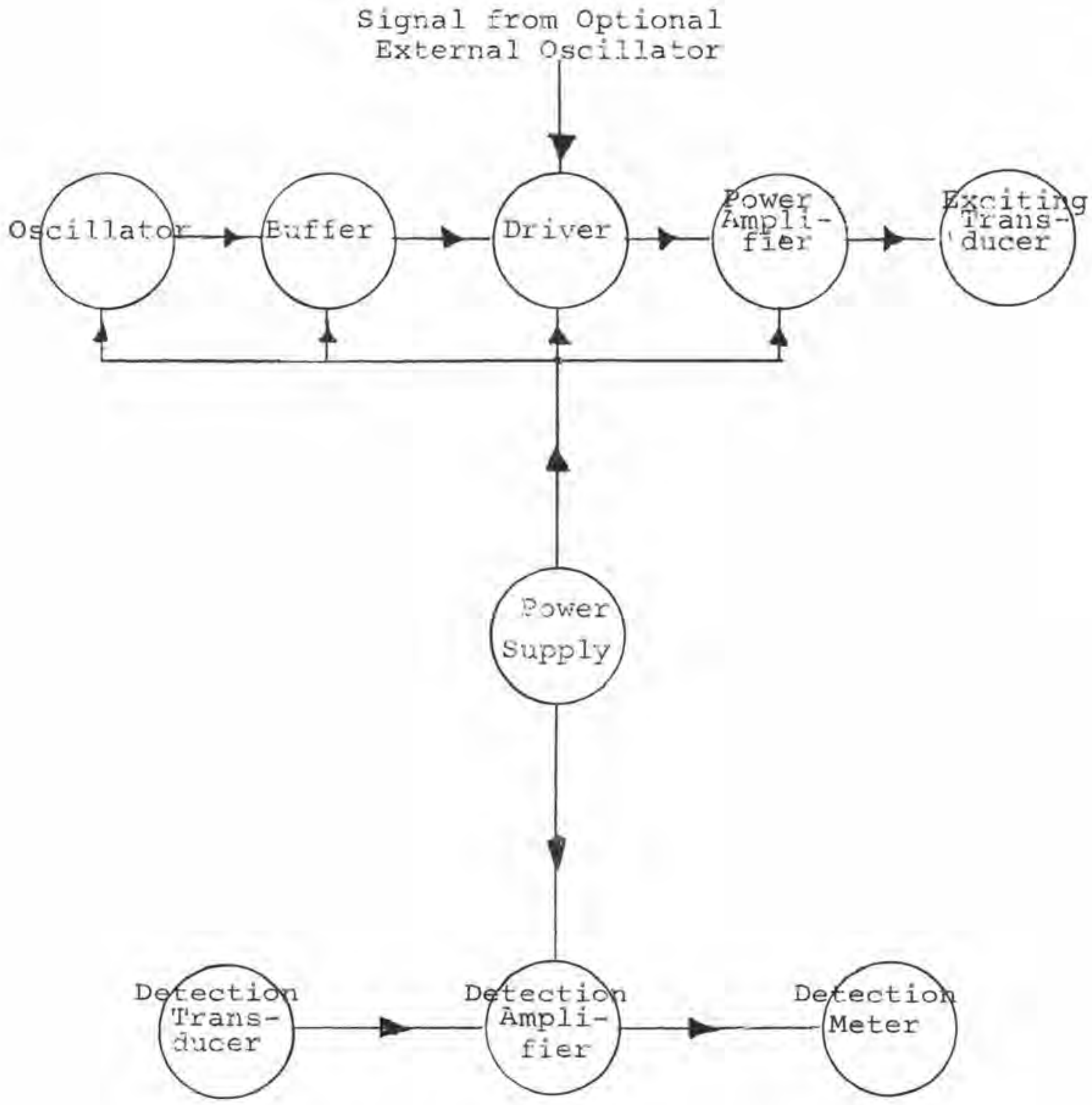

Figure A1: Block diagram of the sonic generator and detector.

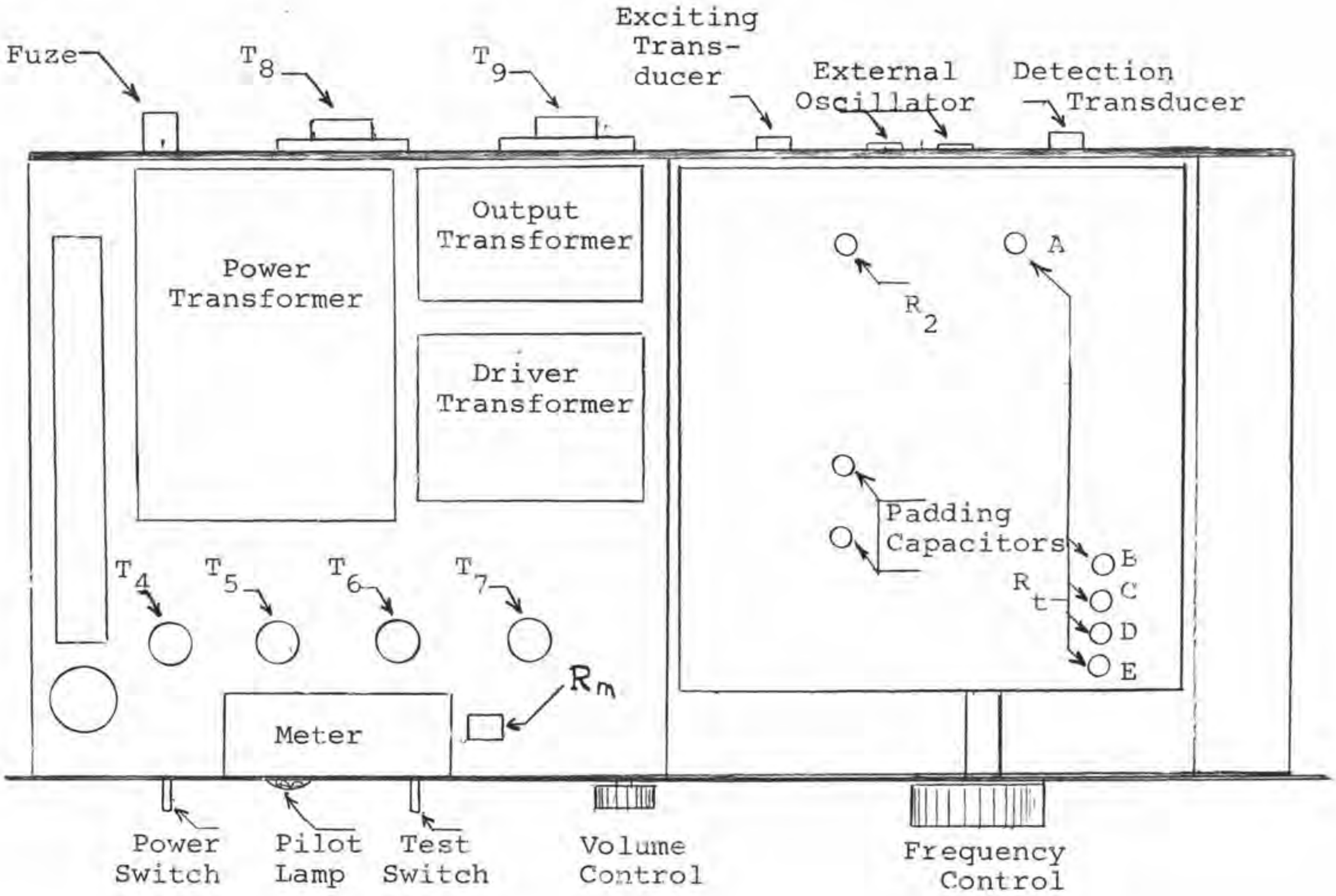

Figure A2: Top view of sonic generator and detector with the case removed.

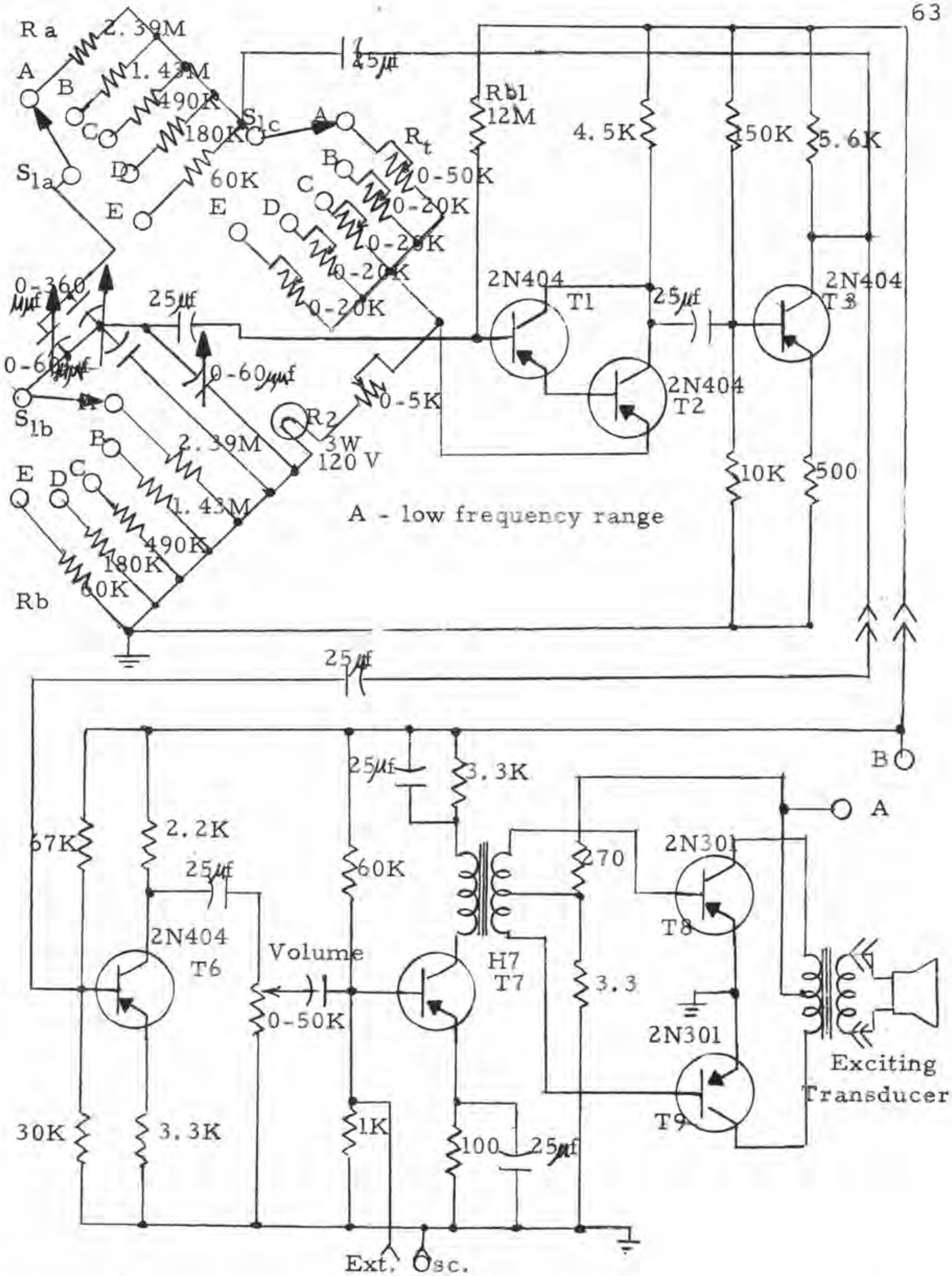

Figure A3: Circuit diagram of the oscillator and signal amplifier.

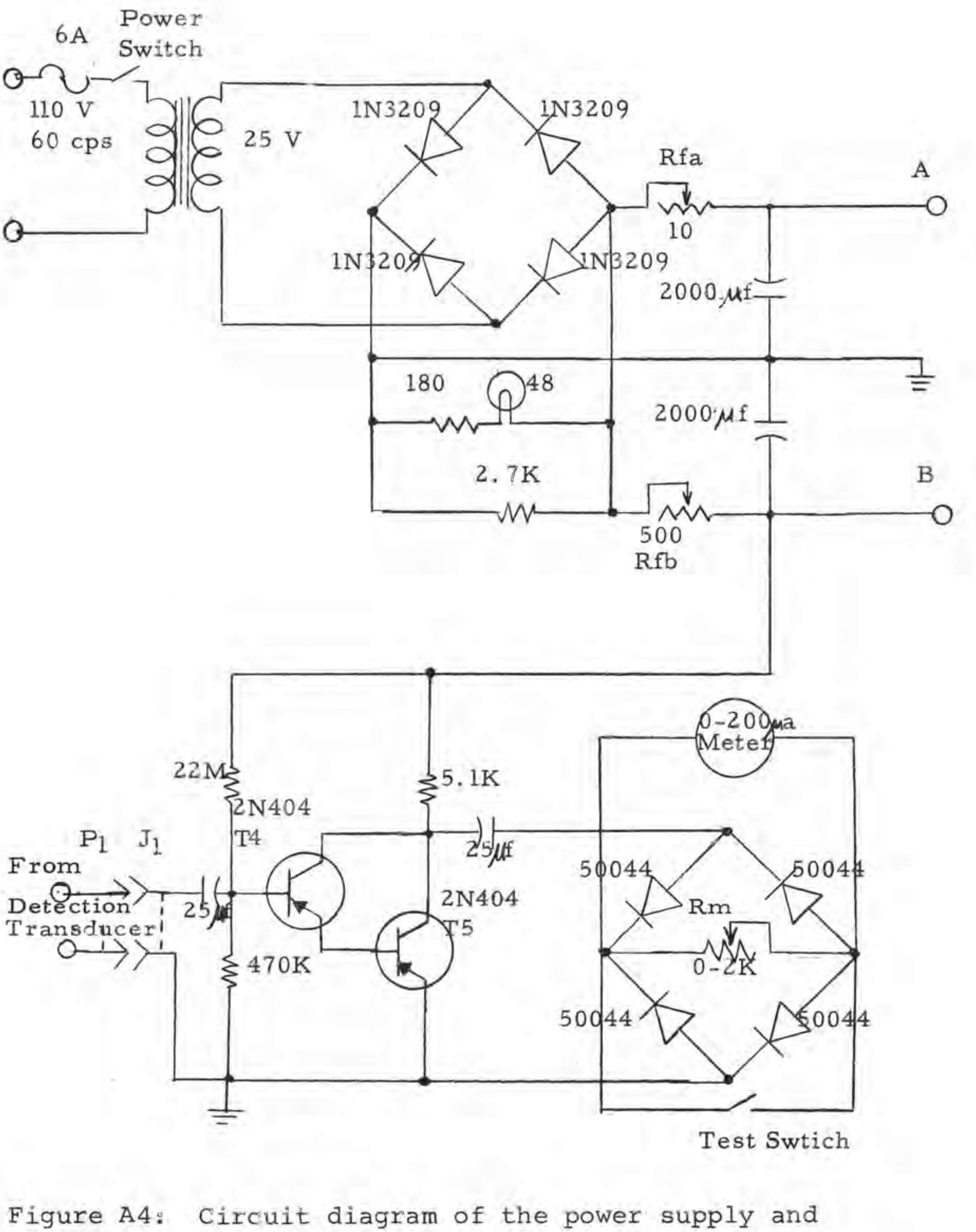

Figure A4: Circuit diagram of the power supply and detector.