Ultrasonic Power Sources

Ultrasonics is a term applied to a field of engineering in which high-frequency acoustical energy is used to effect an ultimate improvement in a product or process. The improvement may take place in cleaning, soldering, welding, drilling, defoaming, and degassing, or in control, measurement, detection, and medical diagnostics.

The frequency range used in ultrasonics is typically between 15 kHz and 10 Mhz. A few applications employ lower frequencies to achieve maximum particle displacement; at these lower frequencies, however, the power level must be kept low to avoid painful discomfort to those working in the vicinity. In testing applications, higher frequencies are required because the smaller the wavelength, the smaller the flaw that can be detected.

The power level used in ultrasonic engineering depends upon the application. Large-scale industrial-cleaning operations may require many kilowatts, while measuring and testing applications may require only a few microwatts. Table XXVIII lists some of the general industrial applications of ultrasonics, together with a brief description of the various applications and the typical power level and frequency required for each.

CHARACTERISTICS OF ULTRASONIC TRANSDUCERS

Many devices can be used to produce ultrasonic energy; these devices are called transducers. All transducers can be classified in one of three groups: mechanical, magnetostrictive, or electrostrictive. Mechanical transducers are applied for the most part to the production of acoustic and ultrasonic oscillations in air or other gaseous media. Mechanical transducers used as sources of ultrasonic waves in air include whistles, gas-jet generators, and sirens. The power sources used in these devices usually incorporate a type of pressurized gas or fluid. The gas and liquid transducers convert a steady mechanical force into a vibratory mechanical force.

In solids, however, the same effect is not possible. In this case a source of electrical energy at the required operating frequency is converted into a vibrating mechanical force. This conversion is accomplished through the use of special materials which have magnetostrictive or electrostrictive properties.

Magnetostriction is the name applied to the change in length of a magnetic material under the influence of an external magnetic field. Whether a magnetic material (such as iron, nickel, cobalt, or a magnetic alloy) lengthens or shortens depends on a property of the material and is not dependent on the direction of the magnetic field. Fig. 337 shows the strain (change in length per unit length) as a function of magnetic field strength for several magnetostrictive materials. The figure shows that nickel gets shorter as the magnetic field is increased, while Permendum gets longer. Fig. 338 shows how a bar of material that has a positive strain coefficient (lengthens with increased magnetic field) would react to an alternating magnetic field with no static biasing

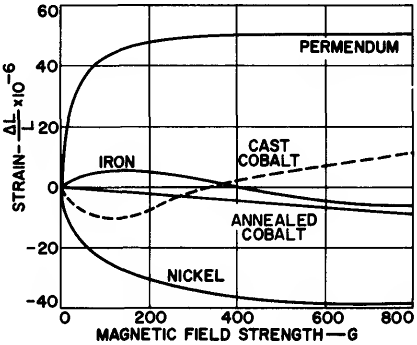

Fig. 337 - Strain as a function of magnetic field strength for several magnetostrictive materials.

Table XXVIII - Ultrasonic Applications

Application	Description	Power Range (Watts)	Frequency Range (kHz)
Ultrasonic cleaning and degreasing	Cavitated cleaning solution scrubs parts immersed in solution.	50 to 25,000 (Typically 100 watts per gallon of solution).	20 to 40
Drilling, cutting, and polishing of hard and brittle materials.	Abrasive slurry between vibrating tool and work piece cuts into material.	50 to 2,000	16 to 30
Soldering and brazing.	Ultrasonically vibrating solder removes oxide film eliminating the need for flux.	0.5 to 250	16 to 30
Welding metals and plastics.	Vibrating tool generates high temperature at interface of the two materials.	10 to 1,000	16 to 30
Emulsification, dispersion, and homogenization.	Mixing and homogenizing of liquids, slurries and creams.	100 to 2,000	16 to 1,000
Control and measurement, alarm systems, counting.	Interruption or deflection of beam, damping of transducer.	0.1 to 50	16 to 45
Flaw detection.	Determination of size and location of flaws in solids by the pulse echo technique.	0.5 to 20	1,000 to 10,000
Medical: surgery and diagnostics.	Ultrasonic surgical knife cuts through tissue. Locating tumors and other flaws using the pulse-echo technique.	1 to 1,000	100 to 10,000

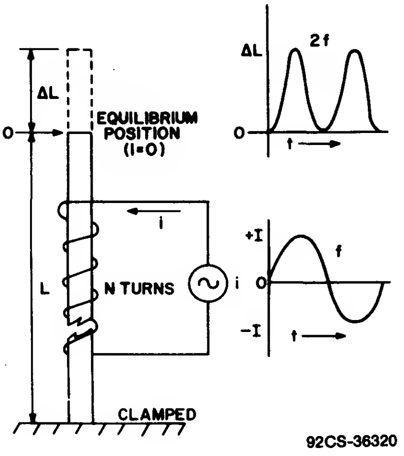

Fig. 338 - Reaction of a bar of material that has a positive strain coefficient to an alternating magnetic field when no static biasing field is used. Waveforms show change in length of bar (top) and alternating current (bottom) used to produce the magnetic field.

field. The figure shows that the bar vibrates at twice the generator frequency and that the amplitude is ΔL peak to peak.

Fig. 339 shows the effect of adding a static biasing magnetic field. This bias could also be supplied by a permanent magnet. The dc bias field yields an initial displacement ΔL. Under these conditions, the bar oscillates about its equilibrium position at the frequency of the generator with a peak-to-peak amplitude of 2ΔL.

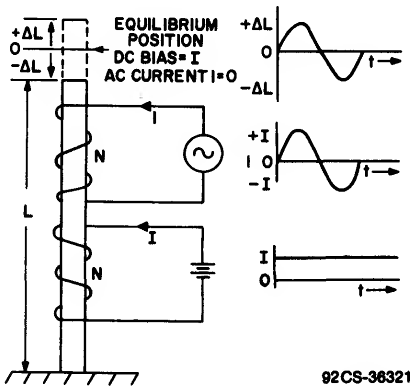

Fig. 339 - Reaction of bar of material that has a positive strain coefficient to an alternating magnetic field when static biasing is employed. Waveforms show change in length of bar (top), alternating current used to produce alternating field (center), and direct current (bottom) used to produce the bias field.

The **piezoelectric effect** is a phenomenon that occurs in certain crystals; the crystals are deformed when subjected to an electric field. The converse is also true; i.e., if the crystal (quartz, Rochelle salt, barium titanate) is strained, an electric charge appears at its edges.

The piezoelectric effect in the first mode is used in the generation of high-frequency sound waves. This effect is accomplished by application of an alternating voltage of the desired frequency to the crystal. Fig. 340 shows an example of this method.

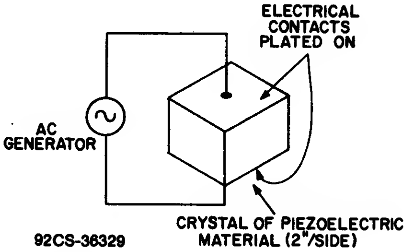

Fig. 340 - Application of an alternating voltage to a piezoelectric crystal to produce high-frequency sound waves.

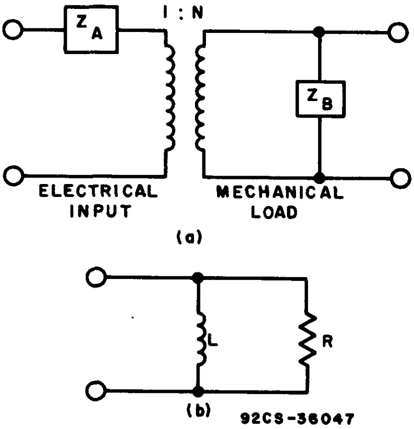

Fig. 341 - (a) Actual equivalent circuit and (b) simplified approximation of a magnetostrictive transducer.

In the design of equipment that uses electromechanical transducers, a useful equivalent circuit for the transducer must be available. Fig. 341(a) shows the equivalent of a magnetostrictive transducer in which Z_A, Z_B, and N depend upon the magnetic and physical properties of the core material. Fig. 341(b) is an approximate equivalent circuit for the transducer. The reactive component of the input impedance is attributed primarily to the inductance of the winding. This inductance is a function of the number of turns and the transducer core material. The resistance R represents the mechanical load. To obtain mechanical energy, it is necessary to provide electrical power to this resistance. Because magnetostrictive transducers usually operate with a static bias field, a dc component of current must be supplied to the transducer. Fig. 342 shows a typical circuit.

In the circuit, the choke is used to prevent the high-frequency signal from shorting through the low-impedance dc supply. The capacitor C is required to prevent dc from flowing through the generator. In addition, the value of C can be chosen so that the inductive reactance of the transducer is

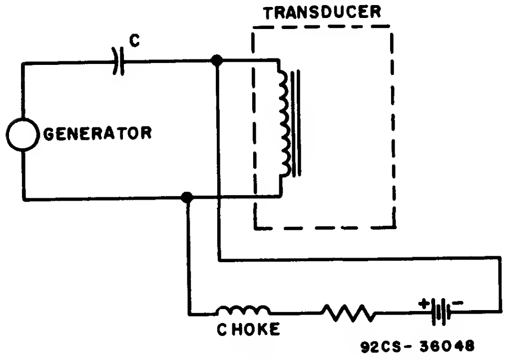

Fig. 342 - Circuit showing application of electrical power to a magnetostrictive transducer.

cancelled (series resonance).

Fig. 343(a) is the equivalent circuit for a piezoelectric crystal; Z_A, Z_B, and N are functions of the electrical and physical properties of the crystal. Fig. 343(b) shows the approximate equivalent circuit used to represent a piezoelectric transducer for the purpose of making calculations. The capacitance is usually tuned out by use of either a parallel or series inductor in the matching circuit between the generator and transducer.

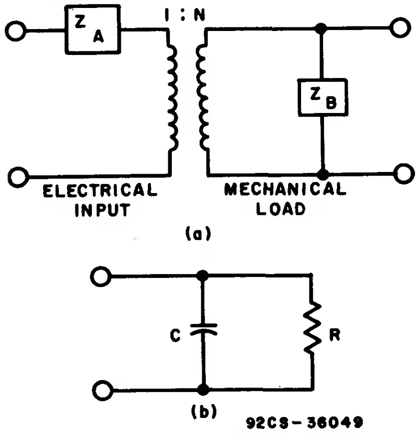

Fig. 343 - (a) Actual equivalent circuit and (b) simplified approximation of a piezoelectric crystal.

ULTRASONIC GENERATORS

The majority of ultrasonic applications employ a continuously oscillating power source. In fact the only application listed in Table XXVIII that does not make use of a continuous wave is flaw detection by the pulse-echo technique. For this reason, the following discussion of ultrasonic power sources is limited to the continuous-wave type. Table XXVIII shows that most of the frequencies and power levels required are such that transistors can be used in the power generators. Therefore, the power sources discussed below are of the solid-state type.

The waveform delivered to the transducer can be of the square or sinusoidal type. As a result, there are four basic methods of power generation:

1. A low-power square-wave inverter followed by a class B push-pull power amplifier,
2. A square-wave power inverter that drives the load directly,
3. A low-power sine-wave oscillator followed by a class B push-pull amplifier,
4. A self-oscillating power amplifier that drives the load directly.

The detailed explanation of circuit operation and design procedures for each of these circuits is given in other parts of this Handbook.

If the transducer used can operate with a square-wave power source, then an inverter should be used because it affords very high efficiency. However, if the electromechanical transducer is required to deliver sinusoidal power to its load (cleaning solution, abrasive slurry, and the like), sinusoidal electrical power must be delivered to the resistor representing the load in the equivalent circuit of the transducer.

Inverter Circuits

Fig. 344 shows one method of obtaining a voltage sine wave across R_L. In this circuit, the

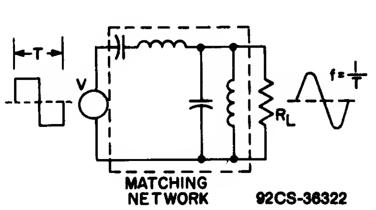

Fig. 344 - Use of a transducer and resonant matching network to convert a square-wave input to a sinusoidal output. Reactive component of transducer is used as the shunt inductor or capacitor of the matching network depending upon whether a magnetostrictive or electrostrictive type of transducer is used.

generator supplies a square-wave voltage; the matching network filters out the harmonics so that only the fundamental component remains. The matching network includes the reactive component of the transducer as a shunt inductor or capacitor, depending upon whether the transducer is of the magnetostrictive or electrostrictive type. In other words, the reactive component of the transducer is used as part of the filter. With this type of network, a transistorized inverter can be used to drive the transducer. The Q of the series tuned matching circuit should be at least 5.

The simplicity of this type of system is shown in Fig. 345. In the push-pull inverter with a series tuned load, each transistor provides current half of the time. The current flows only during the time that the transistor collector-to-emitter voltage is near zero [$V_{CE}(sat)$]. During the half-cycle when the voltage across the transistor is equal to $2V_{CC}$, there is no current flow. During both half-cycles, the dissipation in the device is very low. Theoretically, then, the efficiency could be very high. A thorough analysis and detailed design procedure for inverters is given in the section on **Power Conversion**.

Class C Oscillators

One disadvantage of the inverter approach is that the fundamental frequency is determined by the feedback network. Any time there is a change in the reactance of the load, its resonant frequency changes and the operating frequency of the inverter must be adjusted to the new resonant frequency. If the frequency is not adjusted, the power delivered to the load decreases and the power dissipated in the transistor increases. With most practical transducers, the reactive component is continually changing.

One method used to overcome this problem is to let the load determine the frequency by use of a tuned-load class C oscillator, such as that shown in Fig. 346. With this arrangement, the operating frequency is always the resonant frequency of the load.

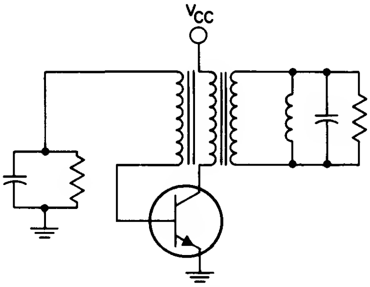

Fig. 346 - Class C oscillator that operates into a tuned load circuit.

Fig. 347 shows that the class C oscillator provides a pulse of current to the load. The load is parallel tuned; the voltage across the load, therefore, is sinusoidal. The period (T)

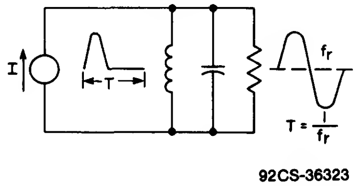

Fig. 347 - Simplified equivalent circuit for the class C oscillator shown in Fig. 346.

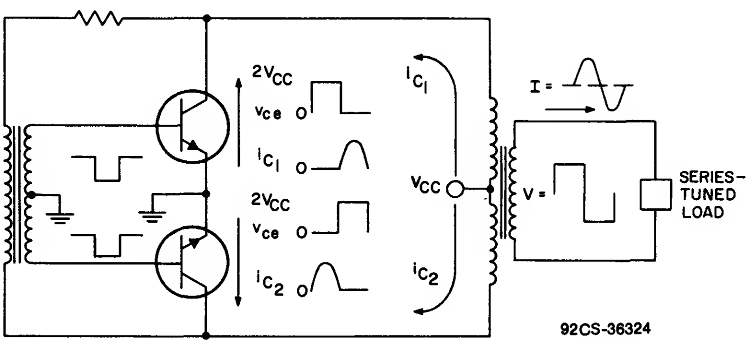

Fig. 345 - Use of a push-pull switching inverter to drive a transducer that forms part of a series-tuned load circuit.

of the current pulse is equal to the reciprocal of the resonant frequency f_r of the load. Therefore, if f_r changes, there is a corresponding change in T. Fig. 348 shows the collector voltage and collector current for the class C oscillator.

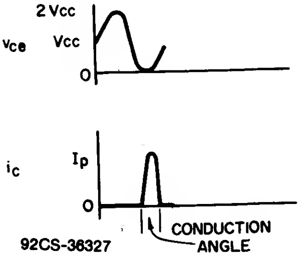

Fig. 348 - Collector voltage and current waveforms for the class C oscillator shown in Fig. 346.

The magnitude of the collector-current pulse is determined by the load power. The current peak occurs at V_{CE}(sat), which is approximately zero. As the conduction time of i_C is made smaller, the efficiency increases; however, i_C must also increase to maintain the same power output. In the limit, an infinite pulse of zero width would yield 100-per-cent efficiency. However, this limit would require an infinite circuit Q. It can easily be shown that, for a fixed V_{CC} the power output is proportional to the area under the current pulse shown in Fig. 348, where the area is determined by the magnitude and conduction angle of the current pulse. The maximum value if i_C is limited by the maximum current rating of the transistor used. The maximum power output [for a given V_{CC} and I_C(max)], therefore, is proportional to the conduction angle. However, because the efficiency is inversely proportional to the conduction angle, it is obvious that some sort of compromise must be made. The following examples should help to determine the best compromise:

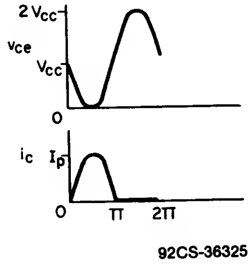

Fig. 349 - Collector voltage and current waveforms for an oscillator circuit that has a conduction angle of 180 degrees.

Example No. 1—In class C oscillators, the maximum collector voltage rises to a value equal to twice the supply voltage [i.e., $V_{CE}(max) = 2V_{CC}$], as indicated in Fig. 349. This condition occurs when the transistor is reverse-biased. The V_{CEV}(sus) rating of the transistor used, therefore, should be equal to, or greater than, $2V_{CC}$. The relationship between dc input power P_s, power delivered to the load P_L, transistor dissipation P_d, and circuit efficiency η can be calculated for a typical transistor operated in a circuit of this type. The parameters assumed for the transistor are as follows:

V_{CEV}(sus) = 100 volts
I_C(max) = 20 amperes
T_d(max) = 200° C
TR_{J-C} (includes heat sink) = 3° C/W
T_A = 80° C (ambient)

For these parameters, P_d should not exceed (200 - 80)/3, or 40 watts. For $V_{CC}=100/2=50$ volts, $I_p=I_C(max)=20$ amperes, and the conduction angle $\theta=\pi$ (maximum power output), the quantities P_s, P_L, P_d, and η are calculated as follows:

$$P_s = \frac{1}{2\pi}\int_0^{2\pi} V_{CC}\, i_C\, d\theta$$

$$= \frac{V_{CC}}{2\pi}\int_0^{\pi} I_p \sin\theta\, d\theta$$

$$= \left[\frac{V_{CC} I_p}{2\pi}(-\cos\theta)\right]_0^{\pi}$$

$$= \frac{V_{CC} I_p}{2\pi}(1+1)$$

$$= \frac{V_{CC} I_p}{\pi} = 0.317\, V_{CC} I_p = 320 \text{ watts}$$

$$P_L = \frac{1}{2\pi}\int_0^{\pi} V_{CC}\sin\theta\, I_p \sin\theta\, d\theta$$

$$= \frac{V_{CC} I_p}{2\pi}\int_0^{\pi}\sin^2\theta\, d\theta = \frac{V_{CC} I_p}{4}$$

$$= 0.25\, V_{CC} I_p = 250 \text{ watts}$$

$$P_d = P_s - P_L = 0.067\, V_{CC} I_p = 70 \text{ watts}$$

$$\eta = P_L/P_s = 78\%$$

The calculated value for the transistor dissipation (P_d=70 watts) exceeds the maximum allowable value (40 watts). This condition indicates the value calculated for the maximum power output (P_L=250 watts) cannot be obtained because of thermal limitations.

Example No. 2—If the conditions V_{CC}=50 volts and $\theta=\pi$ are maintained, then the efficiency η is still 78 per cent. The peak current I_p, therefore, must be reduced so that the transistor dissipation P_d does not exceed 40 watts. (The same heat sink and thermal temperature used in example No. 1 are assumed.) The new value of I_p is calculated as follows:

P_d=0.067 V_{CC} I_p=40 watts

I_p=40/(0.067 x 50)=11.9 amperes

The power delivered to the load P_L then becomes

P_L=(0.25)(50)(11.5)=149 watts

Although the transistor current is only slightly more than one-half the maximum current rating, the dissipation is equal to the maximum allowable value under the given conditions. In other words, the junction temperature is at its maximum rating.

Example No. 3—If the conditions angle is decreased to 1/3 of the cycle (i.e., $\theta=2\pi/3=$ 120°), the transistor dissipation is substantially reduced. Fig. 350 shows the collector current and voltage waveforms for this condition. If all other conditions are assumed to be the same as for example No. 1, the dc input power, load power, transistor dissipation, and efficiency are calculated as follows:

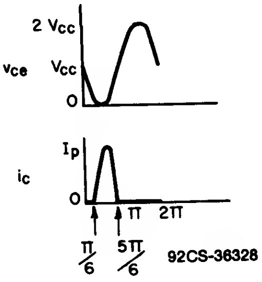

Fig. 350 - Collector voltage and current waveforms for an oscillator circuit that has a conduction angle of 120 degrees.

$$P_S = \frac{1}{2\pi}\int_{\pi/6}^{5\pi/6} V_{CC}\, I_p \sin\frac{3}{2}\,\theta\, d\theta$$

$$= \left[\frac{V_{CC}\, I_p}{2\pi}\left(-\frac{2}{3}\cos\frac{3}{2}\,\theta\right)\right]_{\pi/6}^{5\pi/6}$$

$$= \frac{-V_{CC}\, I_p}{3\pi}\left[\cos\frac{3}{2}\left(\frac{5\pi}{6}\right) - \cos\frac{3}{2}\left(\frac{\pi}{6}\right)\right]$$

$$= \frac{V_{CC}\, I_p}{3\pi}\,(2)\left(-\frac{1}{\sqrt{2}}\right)$$

$$= 0.15\, V_{CC}\, I_p = 150 \text{ watts}$$

$$P_L = \frac{1}{2\pi}\int_{\pi/6}^{5\pi/6} V_{CC} \sin\theta\, I_p \sin\frac{3}{2}\,\theta\, d\theta$$

$$= \frac{V_{CC}\, I_p}{2\pi}\int_{\pi/6}^{5\pi/6} \sin\theta \sin\frac{3}{2}\,\theta\, d\theta$$

$$= \frac{V_{CC}\, I_p}{2\pi}\left[\frac{\sin\left(\frac{3}{2}-1\right)}{2\left(\frac{3}{2}-1\right)} - \frac{\sin\left(\frac{3}{2}+1\right)}{2\left(\frac{3}{2}+1\right)}\right]_{\pi/6}^{5\pi/6} = \frac{V_{CC}\, I_p}{2\pi}$$

$$\left[\sin\frac{1}{2}\,\theta - \frac{\sin\frac{5}{2}\,\theta}{5}\right]_{\pi/6}^{5\pi/6}$$

$$= \frac{V_{CC}\, I_p}{2\pi}\,(0.966-0.05-0.26+0.193)$$

$$= \frac{0.85}{2\pi}\, V_{CC}\, I_p = 0.135\, V_{CC}\, I_p$$

$$= 35 \text{ watts}$$

$$P_d = P_s - P_L = 0.015\, V_{CC}\, I_p$$

$$= 15 \text{ watts}$$

$$\eta = P_L/P_s = 90 \text{ per cent}$$

For a conduction angle of one-third of a cycle, therefore, the transistor is not limited by power dissipation under the conditions stated. The transistor can operate at full voltage and current ratings. If the heat sink used in examples Nos. 1 and 2 is employed, the junction temperature is maintained well below the rated level.

Example No. 4—The design of a practical class C oscillator which has a conduction angle θ of 120° and an over-all circuit efficiency η of about 80 per cent is illustrated by the following example:

The design conditions are as follows:

V_{CC}=50 volts; P_L=125 watts
R_L=1000 ohms in parallel with a 0.005-microfarad capacitor
f=25 kHz
TR_{HS}=2° C/W
T_A=80° C
θ=2π/3

For these conditions, the following values are calculated:

P_L=(0.135) (V_{CC}) (I_p)
125=(0.135) (50) (I_p)
I_p=18.5 amperes
P_d=(0.015) (50) (18.5)=14 watts

The Q of the load circuits, which is equivalent $R_L/2\pi fL$ for a parallel tuned network, is 2.5. The value of the load-circuit inductance L, therefore, may be calculated as follows:

$L=1000/(2\pi)(25)(10^3)(2.5)$
$=2.5$ millihenries

The load-circuit capacitance then is determined as follows:

$2\pi f=1/(LC)^{1/2}$
C=0.01 microfarad

Because the load resistance R_L is shunted by a capacitance of 0.005 microfarad, the actual value of the capacitor used in the output tuned circuit is 0.015 — 0.005, or 0.01 microfarad.

The transistor requirements are as follows:

$V_{CEV}(sus) \geq 2\ V_{CC}=100$ volts
$I_C(max) \geq 18.5$ amperes
$P_d(max) \geq 14$ watts at T_C=108° C
[80° C ambient + (14) (2° C/W)]

Therefore, the thermal resistance from junction to case $\theta_{J\text{-}C} \leq 7$° C/watt.

Information on the selection of core size and material is given in the section on **Power Conversion**. For this design, a toroid of linear material (Arnold Engineering No. A438381-2 or equivalent) is used. Use of 100 turns of No. 24 wire for the secondary winding provides 2.7 millihenries of open-circuit inductance. This secondary provides the inductance of the matching network.

The power output P_L is equal to 125 watts, and the load resistance R_L is equal to 1000 ohms. The peak voltage across the load, therefore, is 500 volts. The transformer turns ratio then becomes

N=500/50=10:1

Ten turns of No. 22 wire, therefore, are required for the primary. Fig. 351 shows the schematic diagram of the completed circuit, and Fig. 352 shows the circuit waveforms.

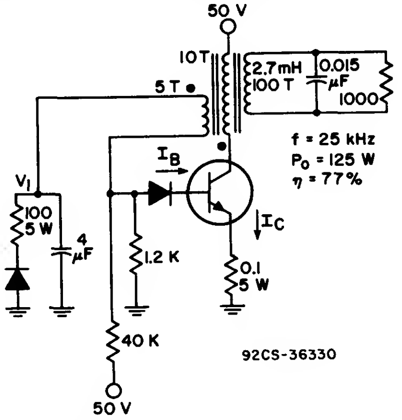

Fig. 351 - 125-watt, 25-kHz, class C oscillator.

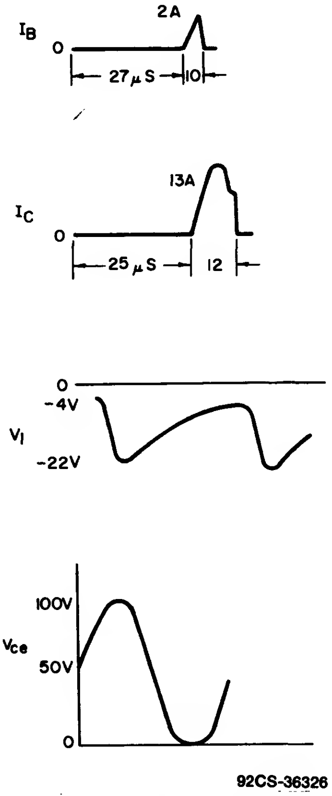

Fig. 352 - Current and voltage waveforms for the class C oscillator shown in Fig. 351.

ULTRASONIC POWER AMPLIFIERS

In general, the power amplifiers used to drive ultrasonic transducers are the same as those used to drive the loudspeakers in audio-amplifier applications. The basic design considerations and circuit configurations described in the section on **Audio Power Amplifiers** are applicable, therefore, to the design of power amplifiers for ultrasonic applications. The frequency range of the basic amplifier configurations can be readily extended into the range of 10 kHz to 100 kHz normally used in ultrasonic systems by selection of higher-frequency power transistors, use of smaller inductive and capacitive coupling components, and a proper choice of values for feedback elements.