6.1 Ultrasonic power transducers 6.1.1 General

Most high intensity ultrasound applications, such as ultrasonic cleaning, require half wavelength transducers with resonant frequencies between 18 kHz and 45 kHz. The length in the main excursion direction of, say, a PZT4 transducer would therefore range from 9 cm to 3.5 cm since the sound velocity in this ceramic is approximately 3200 m/s. What's more, to reach the required output power level, the device would need a large surface area. The resulting single-piece ceramic block can present enormous manufacturing problems. And such blocks might be relatively inefficient anyway, since the whole transducer body would dissipate vibrational energy at a rate inversely proportional to the mechanical quality factor, Q_m, which is generally much lower in ceramics than it is in metals.

In a half-wavelength transducer, the stress amplitude reaches a maximum in the centre, the two end portions acting mainly as inert masses. These end portions can therefore be replaced by metal parts, which are cheaper and have a higher mechanical quality factor.

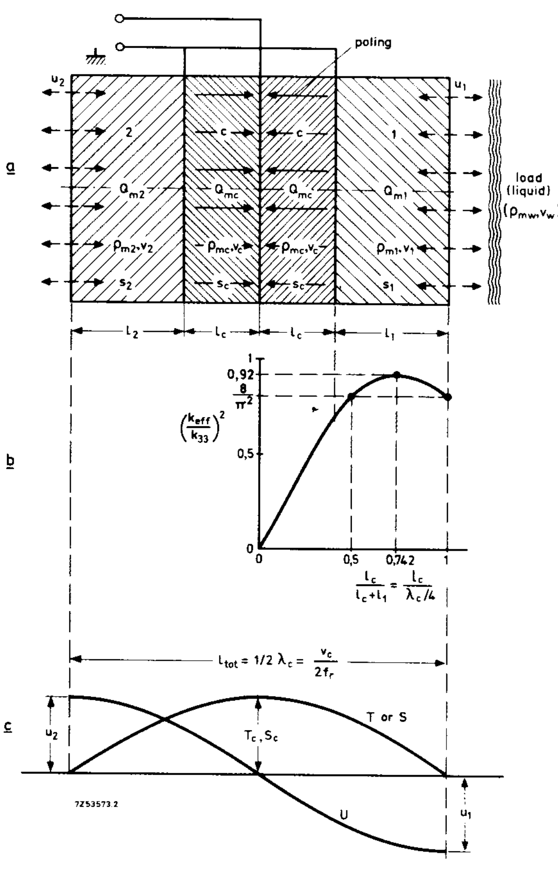

Fig.6.1 Composite ultrasonic transducer

With high intensity transducers the overall electro-acoustic efficiency is of particular importance:

$$\eta \approx 1 - \frac{1}{1 + k_{\text{eff}}^2 Q_E Q_L} - \frac{1}{1 + \dfrac{Q_{m0}}{Q_L}} \tag{6.1}$$

(dielectric losses) (mechanical losses)

where:

Q_{m0} = unloaded mechanical quality factor
Q_E = electrical quality factor
Q_L = quality factor due to the acoustic load alone.

The efficiency reaches a maximum when:

$$Q_L = \frac{1}{k_{eff}} \sqrt{\frac{Q_{m0}}{Q_e}} = Q_{Lopt} \tag{6.2}$$

then:

$$\eta_{\max} = 1 - \frac{2}{k_{\text{eff}}\sqrt{Q_E Q_{m0}}} \quad (k_{\text{eff}}\sqrt{Q_E Q_{m0}} \ll 1) \tag{6.3}$$

It should be noted that at high drive levels Q_E and Q_{mo} can no longer be treated as constants - they are then often much lower than the low drive-level values.

6.1.2 Advantage of composite transducers

The mechanical quality factor Q_{m0} (no-load condition) of composite transducers is higher than that of single-piece transducers. In addition, owing to the better heat conductivity of the metal end pieces, the operating temperature of the ceramic components will be lower. So according to Eq.6.3, the overall electro-acoustic efficiency can be higher.

Another reason for the high efficiency of composite transducers is the fact that their piezoelectric coupling coefficient k_{eff} is not necessarily much lower than that of single-piece transducers. This is illustrated in Fig.6.1 in which the end portions 1 and 2 have the same acoustic properties and cross-sectional area as the central ceramic parts. In such cases, the excursion amplitudes u of the end faces 1 and 2 are equal ($u_1 = u_2$) as are their velocity amplitudes w, Consequently, the maximum attainable velocity amplitudes $(\omega_s u)_{\max}$ at the end faces are related to the permissible stress amplitude in the central nodal plane $T_{c\max}$ by:

$$(\omega_s u_1)_{\max} = (\omega_s u_2)_{\max} = \frac{T_{c\,\max}}{\rho_{mc} v_c} \tag{6.4}$$

where ρ_{mc} is the density of the ceramic material and vc is the sound velocity in the material.

If end face 1 is loaded with a liquid (density ρw in which the sound velocity is v_w) into which it launches perfectly planar waves, Eq.6.4 is also valid for the particle velocity amplitude inside the liquid near face 1. The maximum attainable ultrasound intensity in the liquid $I_{w\,max}$ may be evaluated by inserting Eq.6.4 into the basic equation:

$$I_{w\ \max} = \frac{1}{2}\,(\omega_s u_1)^2_{\max}\,\rho_{mw} v_w \ (\mathrm{W/m^2}). \tag{6.5}$$

If the end portions 1 and 2 have equal lengths and the same acoustic characteristics, the fractional bandwidths (B_F) of such a simple composite transducer are:

coil tuned:

$$B_{FLm} \approx \frac{k_{\mathrm{eff}}}{\sqrt{1 - k^2_{\mathrm{eff}}}} \tag{6.6}$$

single load:

$$B_{Fm} \approx \frac{1}{Q_{m0}} + \frac{2\rho_{mw} v_w}{\pi\,\rho_{mc} v_c} \tag{6.7}$$

double load:

$$B_{Fm} \approx \frac{1}{Q_{m0}} + \frac{2}{\pi}\cdot\frac{(\rho_{mw} v_w)_1 + (\rho_{mw} v_w)_2}{\rho_{mc} v_c} \tag{6.8}$$

In many cases the industrial application or the laboratory experiment requires much higher values of I_{wmax} and B_{Fm} than those offered by the simple composite half wavelength transducer discussed so far. In the next section we shall discuss methods to improve these parameters.

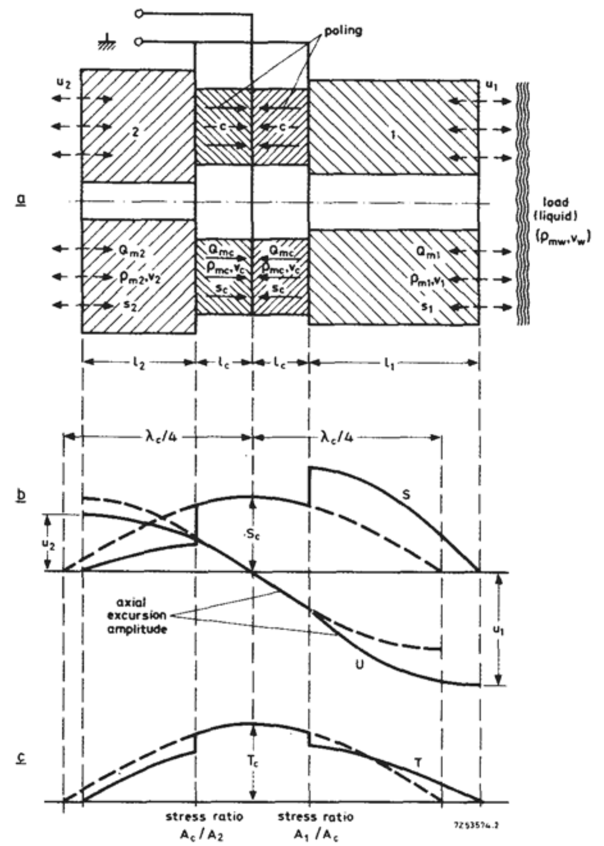

Fig.6.2 (a) A composite half-wavelength transducer consisting of four portions. The cross-sectional areas A of the two ceramic middle portions are equal, but differ from the areas of either end portion. The same applies to the acoustic properties. The curves (b) and (c) are valid only if ($\rho_{m2}V_2$ > $\rho_{mc}vc$ > $\rho m_1 v_1$; $s_2 < s_c < s_1$ and $A_2 > A_c > A_1$ (when using the materials steel-PZT4-magnesium, for instance)

6.1.3 *Improving radiation intensity and bandwidth by means of different end sections*

With an arbitrary material used for each end portion and the bond plane between the ceramic central portions maintained as the nodal plane (in which the stress amplitude T_c reaches a maximum of $T_{c\ \max}$), the simple amplitude and frequency relations of Section 6,1.2. and Fig.6.1 are no longer valid. The new equations can be conveniently expressed in terms of two numerical parameters q_i and G_i (i is either end portion 1 or 2):

$$q_i = \frac{\rho_{mc} v_c A_c}{\rho_{mi} v_i A_i} \tag{6.9}$$

where q_i *is* the ratio of the characteristic acoustic impedances (ρv multiplied by cross-sectional area) of the central and end portions, with cross-sectional areas A_c and A_i respectively. In practice, $A_i > A_c$ (Fig.6.2), and

$$G_i = q_i^2 - (q_i^2 - 1)\,\sin^2\frac{\omega_s l_c}{v_c} \tag{6.10}$$

where G_i is the coefficient of gain, i.e. the ratio of gain in ultrasound intensity at the end faces to the gain in a homogeneous transducer (Fig.6.1) for constant T_c.

Both q_i and G_i are unity for the simple composite transducer discussed so far, but they are greater (less) than unity for up (down) transforming end portions. Obviously G_i ranges between q_i^2 and unity, and increases as the specific acoustic impedance $\rho_{mi} v_i$ decreases.

Using the above variables and assuming a load on both end faces we can write (see Eqs. 6.1, 6.2 and 6.5):

$$I_{wi\ \max} = \frac{1}{2}\,G_i\left(\frac{T_{c\ \max}}{\rho_{mc} v_c}\right)^2 (\rho_{mw} v_w)_i \quad (\mathrm{W/m^2}) \tag{6.11}$$

$$B_{F\ m} \approx \frac{1}{Q_{m0}} + \frac{2}{\pi}\cdot\frac{G_1\,(\rho_{mw} v_w)_1 + G_2(\rho_{mw} v_w)_2}{\rho_{mc} V_c}. \tag{6.12}$$

The following resonant condition should be satisfied:

$$\tan\left(\frac{\omega_s l_i}{v_i}\right)\cdot\tan\left(\frac{\omega_s l_c}{v_c}\right) = q_i. \tag{6.13}$$

Here both angles *ωl/v* range between 0 and *n/2* radians and can be conveniently represented in a diagram using q_i as a parameter. An even clearer picture is obtained if the angles are multiplied by 2/π, so that fractional lengths act as an ordinate and an abscissa:

$$\frac{2}{\pi}\cdot\frac{\omega_s l_i}{v_i} = \frac{l_i}{\lambda_i/4}, \quad \text{and} \quad \frac{2}{\pi}\cdot\frac{\omega_s l_c}{v_c} = \frac{l_c}{\lambda_c/4} \qquad (6.14)$$

A family of $l_i/(\lambda_i/4)$ versus $l_c/(\lambda_c/4)$ curves for *qi* values in the useful range of 0.4 to 4.0 is shown in Fig.6.3(a). All the corresponding G_i versus $l_c/(\lambda_c/4)$ curves are drawn in Fig.6.3(b).

These curves are very useful to the engineer for working out the first concept of a high intensity transducer as they provide a short-cut through the detailed calculations required for final design. It should be borne in mind that such detailed calculations require an appropriate choice of the material constants v_i and v_c (or λ_i, and λ_c). For instance, if diameter D of a mechanical transmission line increases to such an extent that the D-to-λ/4 ratio changes from unity to two, the effective phase velocity of extensional waves of the first mode already falls considerably below:

$$v_{bar} = \frac{1}{s\rho_m} \qquad (6.15)$$

commonly called the *thin wire value.*

The correction needed on the value of v_{bar} depends on the value of Poisson's ratio of lateral contraction σ. Figure 6.4 gives the phase velocity of extensional waves in cylindrical bars in terms of v_{bar} for materials with $\sigma = 0.29$.

Table 6.1 contains numerical data on v_{bar} and other important properties of some materials that are of prime importance for high intensity transducers, either for high intensity end 1 ($G_1 > 1$) or for end 2 whose intensity is usually reduced ($G_2 < 1$) to have it radiate much less power when submerged together with active end 1. The table also gives the fatigue strength T_f and the maximum strain S_f These are particularly important data if a bolt of one of the indicated metals is used for pre-stressing the transducer.

Combining the numerical data of Table 6.1 and the graphical data of Figs 6.2, 6.3 and 6.4, we arrive at the following conclusions:

- The combination of steel-PZT-magnesium is very favourable; the cheaper combination of steel-PZTaluminium (duralumin) is also favourable but to a lesser extent. Aluminium (and magnesium) end portions can be upgraded by drilling holes or cutting slots in them.

- The sound velocity in PZT is relatively low. So the ratio of diameter-to-quarter-wavelength readily exceeds unity in 40 kHz to 50 kHz applications of the available PZT discs or rings. It's necessary, therefore, to take a correction factor into account when determining the actual sound velocity, see Fig.6.4, for instance.

- When the diameter of a half-wave resonator is comparable to, or greater than, its length, *lateral* or radial mode resonances are possible whose frequency may (depending on the diameter-to-thickness ratio) be close to, or lower than the frequency of the fundamental , thickness mode. It's therefore generally best to have D < λ/2 wherever possible with this type of transducer.

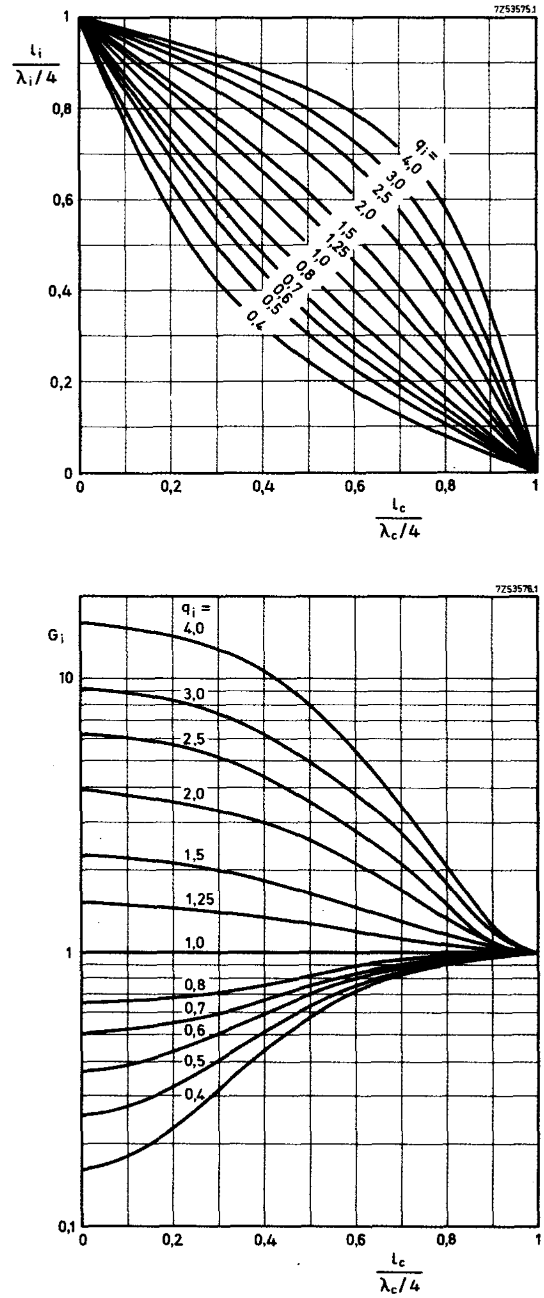

Fig.6.3 (a) Required length l_1 of the end portion of material *i* as a function of the operating frequency ($\omega \approx 1/\lambda_c$) for a pair of central ceramic driving rings (discs) of axial thickness l_c; (b) Ultrasound intensity gain G_i as a function of the operating frequency ($\omega_s \approx 1/\lambda_c$) for a pair of ceramic driving rings (discs) of axial thickness l_c.

TABLE 6.1

Physical properties of materials for high-intensity transducers

		materials for the moderate-intensity end portion 2			ceramic central portion c	materials for the high-intensity end portion 1		
quantity	unit	tool steel	aluminium bronze	brass	PZT4	titanium alloy	dural-umin	magnesium alloy
ρ	10^3 kg/cm^3	7,85	8,50	8,30 . . . 8,45	7,70	4,42	2,79	1,74
$v = 1/\sqrt{\rho\ s}$	m/s	5250	4070	3240 . . . 3400	= 2910	4900	5130	4800
$\rho\ v$	10^7 kg/m^2 s	4,12	3,46	2,74 . . . 2,82	2,24	2,17	1,43	0,835
$\rho_k\ v_k/\rho_{1,2}\ v_{1,2}$	–	0,58	0,69	0,85 . . . 0,88	1,00	1,11	1,68	2,88
s	10^{-12} Pa^{-1}	4,6	7,0	10,5 . . . 11,2	= 15,3	9,4	13,5	23,8
σ		0,29		0,35	≈ 0,30	0,36	0,34	0,28
$\Delta l/l\ \Delta T$	10^{-6}/K	11 . . . 16		18 . . . 20	1 . . . 4	9	23	26
Q_m 2)		≥1400	≥17000	≥3000		≥24000	≥50000	
T_f	10^6 Pa	550	370	150		720	190	
S_f	10^{-3}	2,52	2,59	1,69		6,80	2,57	

1) Composition 90% Ti, 6% Al, and 4% V.

2) Mechanical quality factors at approximately half the fatigue strength; the symbol ≥ is valid for low intensities. See also Section 6.1.4.

According to Fig.63(b), we get the highest intensity gain G_i and the highest G_1/G_2 ratio (which may be of interest in totally immersed transducers) when the wavelength in the ceramic material is greater than 20 or 30 times the thickness of the ceramic disc or ring. In other words, the lowest possible resonant frequency should be chosen. However, there are two factors that count against the use of extremely low operating frequencies for a given pair of PZT discs (axial length l_c = 6.35 mm).

1. The effective piezoelectric coupling factor becomes too low. Although the low-intensity end portion with $q_i < 1$ slightly improves coupling, the high-intensity end portion with $q_i > 1$ reduces coupling by roughly the same amount, so the total coupling doesn't differ much from that of a composite transducer with $q_i = 1$ (see Figs 6.6(a) and 6.1(b)). According to these curves we may write:

   $$k_{eff} < 0.5 k_{33} \text{ for } \lambda c > 25 l_c,$$

   i.e., for $f_s < 20$ kHz (for discs with l_c = 6.35 mm).

2. The ultrasound intensity w in the liquid near radiating surface 1 is no longer given by Eqs 6.5 and 6.11 which only hold for planar waves in the liquid. At low frequencies, the radiated waves are no longer planar. If this effect is to be taken into account, the right-hand terms of Eqs 6.5 and 6.11 must be multiplied by the real part of a radiation coefficient. This coefficient is plotted in Fig.6.6(b) as a function of the diameter-to-wavelength ratio (in water). It's clear that at low frequencies, radiation drops more than linearly with the frequency, which is indeed a severe limitation. A moderate fall in ζ' may be welcomed however, as it is accompanied by less beaming. Therefore allowing a minimum ζ' of approximately 0.75, the minimum diameter of the radiating face would be about half a wavelength in the liquid load.

Since the liquid load adds a substantial effective mass to the transducer, a considerable mismatch results (see curve ζ'' in Fig.6.6(b)). This mismatch can usually be allowed-for in the circuit design. So in the case of a single pair of PZT rings 6.35 mm thick and with D_c = 38.1 mm, and an aluminium or magnesium end portion with a diameter D_I only slightly larger, the minimum operating frequency is 20 kHz. The same minimum frequency is also derived from coupling factor considerations. For frequencies below 20 kHz, the effective coupling factor can be improved by using more than one pair of rings.

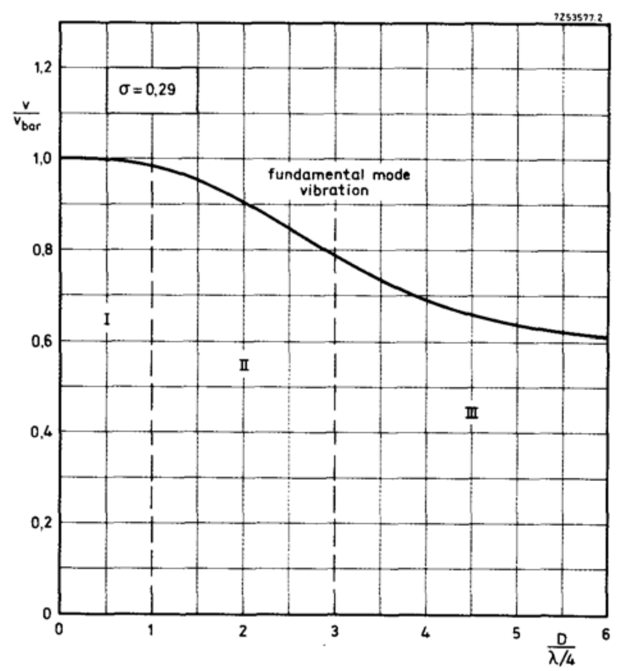

Fig.6.4 Normalized phase velocity of extensional waves in round bars (diameter D) for materials with a Poisson's ratio σ - 0.29. In region I, the excursion of the whole radiating face is almost uniform. In region II the radiating faces show no circle of zero axial amplitude (nodal circle), but in region III there is one such circle

Fig.6.5 Some high-intensity ultrasonic transducers for cleaning applications (see also Figs.6.8, 6.9 and 6.10)

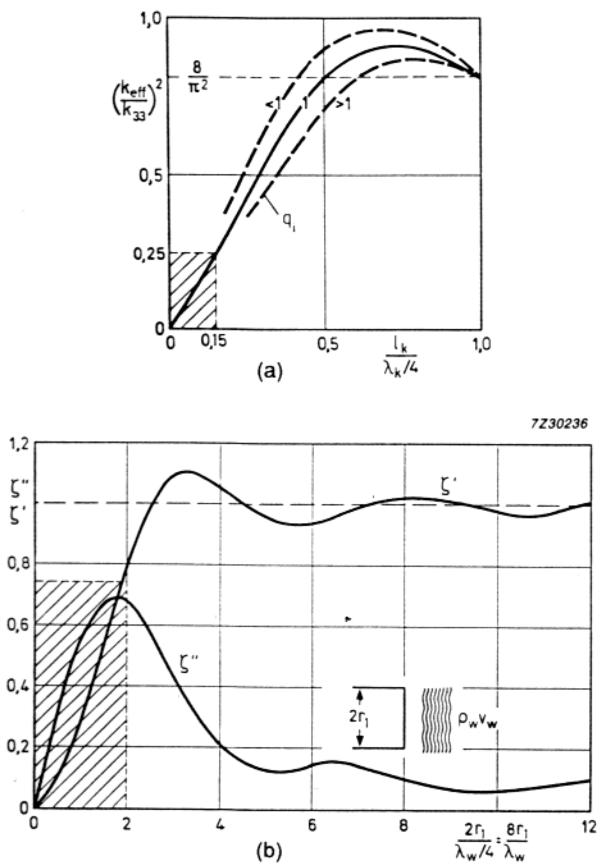

Fig.6.6 (a) Relationship between the effective coupling coefficient and the thickness l_c of the PZT rings or discs (for determining the minimum required length l_c). The shaded area shows the range in which $k_{eff} < 0.5\, k_{33}$, $f_s < 20$ kHz for l_c = 6.35 mm; (b) Relationship between the factors ζ' and ζ '' (ζ = ζ' + j ζ '') and the diameters D_1 and D_2 of the radiating faces *1* and *2*. The shaded area shows the range in which the real part of the radiation coefficient becomes unacceptably low.

6.1.4 Performance of non-pre-stressed composite transducers

In Sections 6.1.2 and 6.1.3 we mentioned that the maximum radiation intensity is proportional to the square of $T_{c\,max}$, the maximum permissible dynamic tensile stress amplitude. $T_{c\,max}$ must always be greater than the fatigue strength T_f of the material present at or near the nodal plane where the stress amplitude reaches a maximum (see Fig.6.7(a)). The fatigue strength of both the piezoelectric ceramic *(T_{fc})* and the bond material *(T_{fb})* should be considered, i.e.:

$$\beta T_{fc} \geq T_{c\,max} \leq \beta T_{fb} \tag{6.15}$$

where β can be considered a safety factor. Table 6.2 gives Approximate data on fatigue strength under conditions of negligibly small thermal stresses

TABLE 6.2
Fatigue strength amplitudes at ultrasonic frequencies

material		fatigue strength T_f × 10 Pa
piezoelectric ceramic PZT4		20 – 30
hot-set epoxy cement	fresh	30 – 50
	aged*	20 – 30
cold-set epoxy cement (Araldite)	fresh	20 – 30
	aged*	10 – 20

* Shelf-aging under normal humid conditions. Aging in dry atmosphere would not reduce the fatigue strength significantly.

Sometimes the critical stress amplitudes, or fatigue strengths tabulated in Table 6.2, are not very reliable as they may be drastically reduced by static thermal stresses caused by the differing thermal expansion coefficients of the cemented parts. When cementing aluminium or magnesium to PZT4 (according to Table 6.2), a differential thermal strain of 20 or more ppm/K is to be expected, so that the curing of epoxy cement at, say, 150 °C, would lead to differential thermal radial stresses of approximately 50 x 10^6 Pa to 150 x 10^6 Pa. In other words, the surface layer of a large ceramic disc would be severely prestressed in the radial direction with the correct sign but in an uncontrolled, inhomogeneous way. Considering such illdefined conditions, which also exist when the transducer is dissipating large amounts of energy at high intensities, and allowing for a safety factor (β = 0.5, the resulting critical stress amplitude in the frequency range 20 kHz to 50 kHz would be no more than:

$T_{c\,max} \approx 4 \times 10^6$ Pa

Substituting this into Eq.6.5, and assuming a water load $p_{mw}v_w$ = 1.485 x 10^6 kg/m^{2}s, we find for the attainable intensity:
$I_{wi\,max} = 2G_i$ (W/cm2)

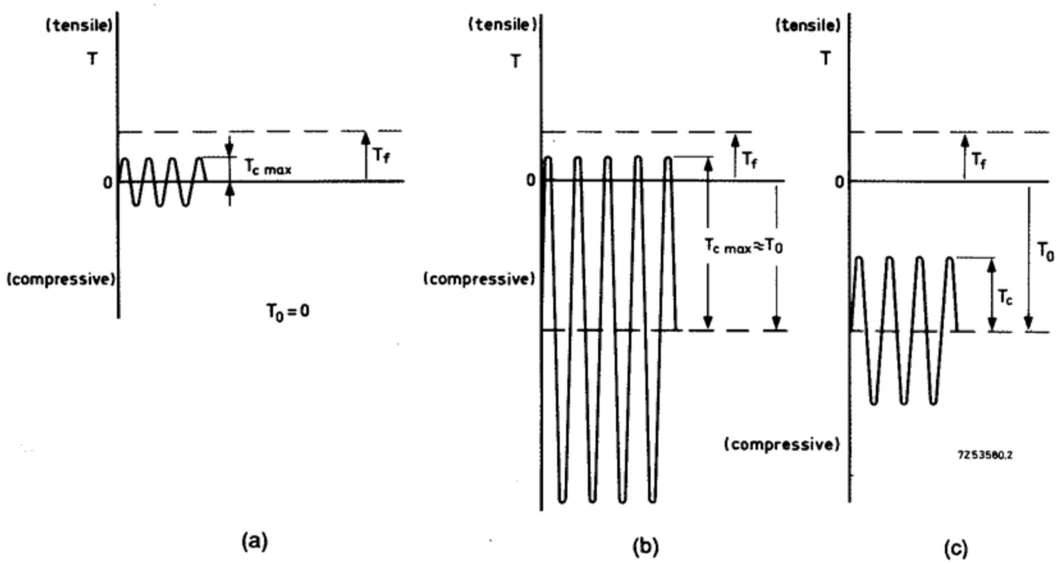

Fig.6.7 Fatigue strength T_f pre-stress T_o and maximum permissible stress amplitude $T_{c\ max}$ in the centre of the transducer; (a) without pre-stress, $T_{c\ max}$ small (T_c limited by fatigue strength of ceramic or bonds); (b) with pre-stress, $T_{c\,max} = T_o$ (T_c limited by fatigue strength of bolts)

The gain factor may be derived from Table 6.2 and Fig.6.3(b), i.e.:

$I_{wi\ max} \approx 10\ W/cm^2$

(magnesium end portion with a gain *G* of approximately 5),

$I_{wi\ max} \approx 4$ W/cm 2

(duralumin end with a gain G of approximately 2).

6.1.5 Pre-stressed composite transducers (with applications)

As already explained, it's often useful to assemble high-power ultrasonic transducers from thin rings or discs of PZT material with metal end pieces to match. For many types of transducer used for ultrasonic cleaning, the power requirements are often so severe that the tensile strength of the ceramic material is inadequate for the high mechanical stress involved. This can be remedied by mechanically pre-stressing such transducers in the axial direction by means of one or more bolts, the useful amount of pre-stress T_0 being about 25 x $I0^6$ Pa. Under these conditions, T_0 replaces $T_{c\ max}$ in the intensity equation (Eq.6.II), as illustrated in Fig.6.7(b).

Figure 6.8 shows the impedance Z (at f_s), which is a good indication of the damping, and the resonant frequency (f_s) as a function of the pre-stress for a specific transducer design. At $T_0 = 25 \times 10^6$ Pa, the resonant frequency has reached a stable value and the damping is acceptable (Ref.7).

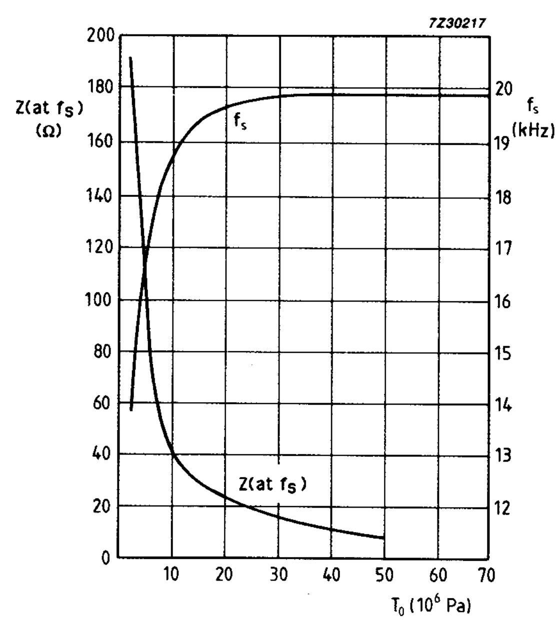

Fig.6.8 The influence of prestress (To) on impedance (Z) and resonant frequency (f_s)

Too high a pre-stress may cause the bolt to break. It could also cause major irreversible changes in the properties of the ceramic material (depolarization). What's more, repeated application and removal of the same mechanical pre-stress could cause the relationship between capacitance and stress, or between coupling factor and stress, to vary in an unreproducible manner. However, provided the prestress is kept below about 30 x I0^{6} Pa, the variations are reasonably reproducible. Too low a pre-stress reduces efficiency because there is an increase in mechanical loss at the various interfaces.

Construction of two high intensity transducers

Figures 6.9(a) and (b) show two designs of high intensity transducer that have been thoroughly tested. Both of them can be built around PZT4 or PZT8. The design shown in Fig.6.9(a) consists of two PZT rings (in the centre) clamped between two end pieces by means of a bolt. The bolt is insulated from the centre electrode by means of a thin PVC sleeve. A transducer constructed in this way has a slightly higher efficiency than one in which the centre bolt is replaced by six or eight bolts around the circumference of the transducer (Fig.6.9(b) because the centre bolt construction allows for a more uniform and radially symmetric application of pre-stress to the PZT. However, the centre bolt assembly with its conical front portion may be more costly to produce, and its greater length may be a disadvantage where space is important.

If the transducer is bonded to the cleaning tank (usually of stainless steel), the temperature needed to harden the glue may be high enough to impair the properties of the PZT rings or discs. It's therefore advisable to first bond the front block of the transducer to the tank wall, and to complete the assembly after the bonding agent has had time to harden and cool. If the torque needed to tighten the bolt is not taken up by a holding tool applied to the coupling portion, there is a risk of the bonded joint to the tank being broken. The main advantage of the transducer of Fig.6.9(b), with bolts around-the circumference, lies in its compactness, and in the possibility of first bonding the front portion to the tank and then assembling the transducer. The bolts can be tightened without overloading the bond because the torque for any one of the bolts is substantially lower than that required for the one large bolt in the transducer of Fig.69(a). A special holding tool is then not needed.

The PZT components used for the transducers shown in Fig.6.9 consist of two rings (outside diameter 38.1 mm, inside diameter 12.7 mm, thickness 6.35 mm) or two discs (38.1 mm diameter and 6.35 mm thick) of PZT4 or PZT88. The electrodes are of copper-beryllium alloy (250 µm gauge), which has a high fatigue strength. The soldering tags must be damped with a pliable substance (e.g. silicone rubber) to prevent breakage due to fatigue, particularly if other materials, such as sheet copper, are used. The steel cylinders (often of free cutting steel) should be protected against corrosion: chemically-protected or cadmium-plated steel or, even better, stainless steel can be used. The front portion radiating ultrasound can be made of duralumin or free cutting alloy (e.g., Al, Cu, Mg, Pb alloy). When assembling the transducer, it's important to apply the right amount of pre-stress (e.g., 25 x I0^{6} Pa). There are various methods of measuring the stress, the most reliable way being to measure the charge generated in the PZT under short-circuit conditions. A capacitor of, say, 10 µF (not an electrolytic one) is connected to the electrical terminals and to a DC voltmeter whose internal resistance should be at least 10 MΩ. This meter measures the charge generated as the bolts are tightened. If the total area of the PZT rings is, for instance, 2 x I0^{-3} m^{2}, and the piezoelectric charge constant d_{33} = 290 x 10^{-12} C/N (PZT4), the charge after pre-stressing is 14.5 µC. Together with a capacitance of 10 µF this results in a voltage of 1.45 V, which can easily be measured. With $R_i \approx$ I0 MΩ,

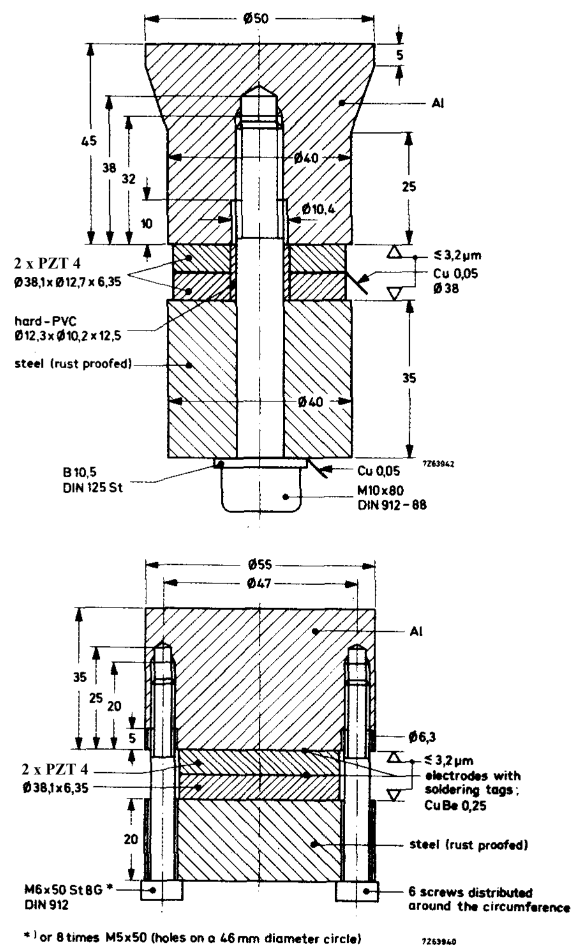

Fig.6.9 Composite mechanically pre-stressed transducer with a low intensity and a high-intensity end. The pre-stress is provided by means of bolts positioned around the circumference

a time constant of about 100 s is obtained and therefore the bolt must be tightened as quickly as possible (within a few seconds). This will not be necessary if $R_i >> 10$ MΩ. A simpler method than charge measurement, though less accurate, is to use a torque wrench. (A torque wrench is always necessary for tightening multi-bolt transducers to ensure that the stress is applied uniformly). Since the torque required for a certain amount of pre-stress depends to a large extent on the finish of the transducer parts, this method is particularly recommended for series production where the components are always the same. The torque wrench must first be calibrated in some way, for instance, by charge measurement. To ensure a uniform pre-stress distribution in multi-bolt transducers, the bolts positioned diagonally across from each other must be tightened in turn, and the torque should be increased progressively by small increments until the required value is reached all round.

The forces taken up by the bolt, or bolts, to obtain a pre-stress of 25×10^6 Pa can be considerable: for PZT rings or discs of 38 mm diameter they amount to about 25 kN to 30 kN. When an AC voltage is applied to the transducer, the bolts will, of course, have to take up additional large alternating forces. Table 6.1 shows that titanium alloy combines the highest fatigue strength with extremely low losses (even at large excursions), and is therefore the best material for the bolts. The threaded end of the bolt and the thread in the metal end piece must be perfect, though they are positioned in the vicinity of a nodal point. Repeated assembly and dismantling reduces the torque required.

High intensity transducers in operation

Water load, tank wall, and bonding layer all reduce the transducer frequency slightly (the water load alone causes a frequency decrease of about 0.5 kHz in a centre-bolt transducer). The characteristic frequency of the tank and the water load usually give rise to several additional resonances. With a properly designed generator circuit the transducer will always operate close to its own resonant frequency.

Since the transducer capacitance C_0 might lead to a high reactive current, it's useful to compensate this capacitance with an inductance (see Appendix A), usually shunted across the transducer, but series connection is also possible. The required inductance is given by:

$$L = \frac{1}{4\pi^2 f^2 C_0} \qquad (6.16)$$

where f is the operating frequency.

The impedance of a transducer thus compensated is almost real at the operating frequency. However, the tank and water resonances can again cause deviations. Cavitation occurring at high powers causes a reduction in impedance which becomes all the more pronounced when the radiating plane of the transducer is brought into direct contact with the water. The change of impedance due to cavitation is much reduced when the transducer is bonded to the tank wall and radiates through it into the water.

The maximum permissible operating power depends to a large extent on the operating conditions (temperature, coupling to the tank, type of tank and its contents, and so forth). Reliable performance is ensured at an (electrical) input power of 50 W; at higher powers one must carefully consider heat loss and the stresses and strains involved. The overall efficiency is also governed by the operating conditions, but is usually better than 90%.

6.1.6 Disc transducers (bonded to a cleaning tank)

Construction of a PZT disc transducer

Pre-stressed composite transducers are not absolutely necessary for effective ultrasonic cleaning, good results are also obtained with PZT disc transducers bonded direct to the tank wall. The transducer itself consists of a PZT disc alone (PZT8), or a PZT disc and a metal disc bonded together. In the latter case the metal disc is positioned against the tank wall. Figure 6.10 shows such an arrangement.

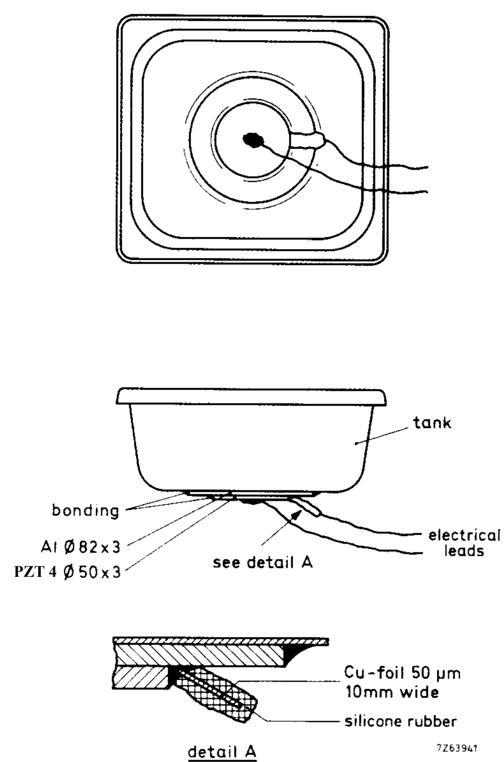

Fig.6.10 Disc resonator bonded to an aluminium disc and the cleaning tank. The connecting foil and stranded wire are protected from fatigue by an acoustic damping material (e.g. silicone paste, Silastic 731 RTV)

When bonding a PZT disc direct to the tank, bear in mind that, apart from involving considerable losses, a thick bond impedes heat removal. It's therefore essential that the bond be as thin as possible. On the other hand, a bond that's too thin is liable to fracture, especially if heavy objects are dropped into the tank. Obviously a compromise must be made. A bond of defined thickness can best be made by reinforcing it with a fibre-glass or metal gauze about 0.5 mm thick. The thickness of the PZT disc cannot be chosen independently of the thickness of the tank wall. Stainless steel tanks with the usual wall thickness of I mm used in conjunction with 3 mm thick discs provide a satisfactory compromise between mechanical strength and efficiency.

A metal plate between the PZT disc and the tank (Fig.6.10), will protect the PZT and reduce losses. The metal disc may be aluminium or steel. Size for size, aluminium gives a greater electro-mechanical coupling factor than steel (and a better matching).

The PZT disc and the metal disc are usually of the same thickness their diameters are chosen to give them the same radial-mode resonant frequency. For optimum results, a PZT disc of, say 50 mm diameter, requires a steel or aluminium disc of about 82 mm diameter.

With both transducer types it's advantageous to use a tank without sharp corners (which tend to impede the spreading out of the ultrasound). The connections to the free electrode must be made with a soldered stranded wire. and contact to the bonded electrode is made with a compression bonded or soldered metal foil (beryllium copper. for instance).

To ensure reliable operation, all free ends of the stranded wire and the foil must be acoustically damped with a damping agent (such as silicone rubber).

The PZT disc bonded to the tank vibrates in the radial mode ???ith an impedance of a few hundred ohms and radiates power mainly through the tank wall into the bath. On the other hand. transducers bonded to the tank with a metal plate in between exhibit various resonances between 40 kHz and 60 kHz and have impedances of several kilohms. The radial vibrations of the transducer apply shear forces to the tank wall, causing the wall to vibrate in flexure mode and thus radiating power into the liquid. Owing to mechanical feedback the transducer is caused to vibrate in a superimposed flexure mode.

Since the tank wall has in fact become part of the transducer, both form and thickness of the tank greatly influence the overall characteristics of the equipment.

Optimum results are possible only if the tank data is taken into account, which calls for a great deal of experimental work. The transducer data, such as operating frequency, impedance, and maximum efficiency, can be determined only after samples have been made.

Operating frequency and power

Ultrasonic cleaning tanks equipped with PZT disc transducers and constructed as shown in Fig.8.I0 operate at about 50 kHz, which is somewhat higher than the radial mode frequency of the freely suspended disc (radial vibration $f_s \approx 45$ kHz for a disc of 50 mm diameter). The transducer can be safely driven at an electrical input power of 50 W and it exhibits no irreversible changes, but between I00 W and 150 W the transducer begins to show signs of permanent damage.

6.1.7Driver circuits for high intensity transducers

The circuit described in this section is useful for laboratory experiments or during the design phase of a transducer. Operating frequency and output voltage are adjustable. The circuit is built up with three basic units (Fig.6.1](a)):

- power supply
- sine wave generator
- power output stage with matching transformer.

Fig.6.1 1(b) shows the supply circuit for generating the necessary DC voltages.

The sine-wave generator in Fig.6.11(c) comprises a free-runnin^{g} oscillator that generates a triangular wave, and a sine-shaping network. The frequency adjustment operates with a ten turn potentiometer and with an additional potentiometer for fine-tuning. The oscillator frequency depends linearly on the setting of the potentiometer. The advantage of this type of oscillator is its simple frequency adjustment and its stability in amplitude even during frequency changes.

The power stage (Fig.6.11(d)) operates like a normal Hi-Fi power amplifier (class B). Its output transistors are Power MOSFETs to guarantee the required power level over the full frequency range. The maximum output voltage is limited by the supply voltage level. Generally this level is much too low to drive PZT -transducers. An output transformer is therefore used which offers a choice of floating output voltages to suit the connected transducer. The power transistors arc protected by a current limiter. In overload situations, caused for instance by a mismatch between transducer and output, the current is limited to a prefixed level.

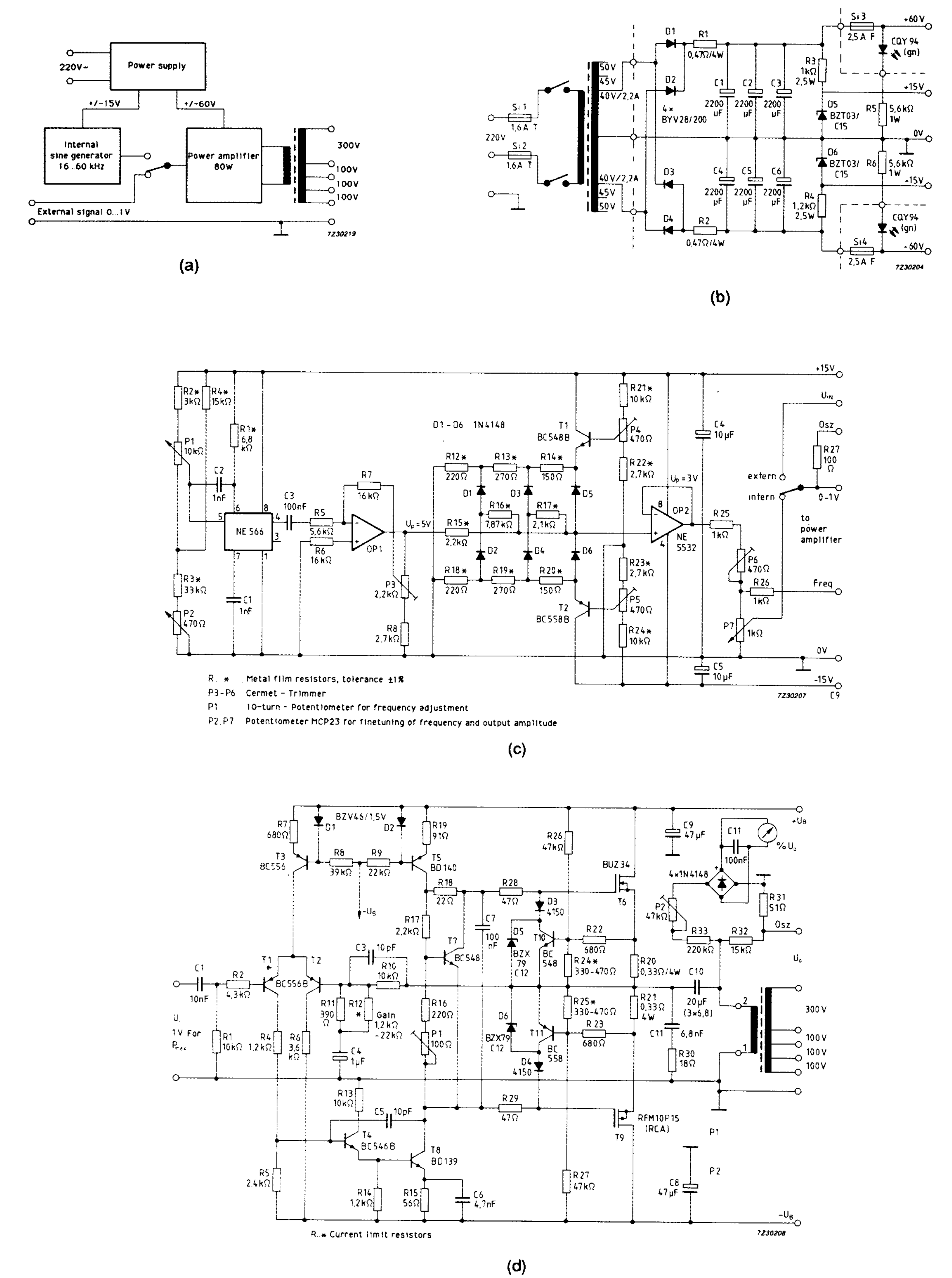

Fig.6.11 Drive circuit for high-intensity transducers.
(a) block diagram (c) sinewave generator
(b) power supply (d) power stage with output transformer