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HIGH POWER ULTRASONIC TRANSDUCERS

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Introduction The application of ultrasonic energy to industrial processing and scientific research has made progress during the past few years, mainly due to improvements in transducer design. The change from valve to semiconductor generators has enabled compact power sources to be produced, but this development is of secondary importance.

Two basic requirements must be met in most applications: a defined acoustic dissipation per unit area of transducer, and the total area over which energy is propagated. The first is limited by transducer and transmission line characteristics, while the second has only economic limitations.

When electrical energy is used as a primary power source the transducer efficiency is of some importance, as excess heat may impose problems of dissipation. Solid state transducer systems involving piezoelectric or magnetostrictive materials must be carefully designed to obtain maximum heat conduction or radiation away from the transducer, and it is essential to use the minimum mass of material compatible with the required power. Although piezoelectric ceramics exhibit a high conversion efficiency they are bad heat conductors, and have high temperature limitations. The lower efficiency of magnetostrictive metals is offset by better heat conduction and good high temperature characteristics.

To obtain an efficient transmission of energy into the required medium the acoustic impedance of the transducer must be comparable to the acoustic impedance of the medium. It is sometimes possible to provide an impedance matching coupler between the active element and the medium, and there are no great problems when propagating into solids and liquids. The large impedance ratio between solids and gases requires a different approach and with one major exception, the St. Claire electro magnetic transducer (Ref 1), it is usual to employ the medium itself as the motivator of the transducer. Whistles and sirens are obvious examples.

The type of propagating medium is a convenient classification for forms of transducers and it is proposed to consider the various available methods of high power generation in solids, liquids and gases.

Propagation in Solids Until the advent of ultrasonic welding techniques, little practical work on coupling high power transducers to solids was undertaken. The development of plastic welding equipment stimulated investigation into methods for achieving high vibrational amplitudes and mechanical transformers were rediscovered from the basic principles established by Rayleigh (Ref 2). Transducer elements operating in their economic power range have vibrational amplitudes too small to be effective for plastic welding applications. Mechanical amplifiers must be used to increase the amplitude and can be considered as resonant tapered stubs.

Any form of tapering will provide an increase in the particle motion, but the transformation ratio and the resonant dimensions will depend largely on the exact form of the taper. The well known velocity distribution equation for sinusoidal vibration applies to all forms of tapers in which only the taper profile function changes.

A taper consisting of a double quarter wave stepped stub is easily manufactured and gives the largest transformation function. However, it has a number of disadvantages in high gain, high power applications and in practice is limited to an amplitude gain of about 10. As the nodal plane coincides with the plane of maximum mechanical stress, metal fatigue eventually produces a breakage at this point.

The operation of several transformers in series is often employed, but the multiple half wavelengths provide a loss of stiffness and at high power the assembly may vibrate in flexure. An alternative is to use a Gaussian taper such as the fourth order Fourier curve described by Eisner (Ref 3). When it is practical to consider end diameters of less than 5 mms., amplitude gains of 25 to 50 are easily reached. In practice, it is possible to approach the ultimate tensile strength of the stub material. Using titanium alloy, amplitudes of 2 mm peak-to-peak at 20 KHZ have been measured (Ref 4). The high velocity and acceleration can materially alter crystal surface conditions and Fourier transformers are employed for gas diffusion studies on metal crystals.

A further design problem peculiar to plastic welding is in the provision of high amplitudes over a long rectangular face. This is required for the production of line welds and involves the suppression of transverse waves in a structure where the transverse dimension is larger than a $\frac{1}{4}$ wavelength. Vertical slots are used to break up the formation of a transverse wave, but a limit is reached where flexing in the structure prevents an even energy distribution along the entire length. To overcome this, an 'octopus' transducer assembly is being used with some success (Ref 5). Vibrational energy is supplied to a number of points along the length using waveguides from single or multiple transducer elements.

Similar problems are encountered in the design of large diameter tubular transformers and are not yet completely solved. The complex vibration of large cylinders generally necessitates the utilisation of anti-node circles on the face. Welding can be produced at these points of high amplitude and the work application must be chosen to suit these dimensions.

Propagation in Liquids The established use of ultrasonically induced cavitation for cleaning applications has resulted in considerable development activity on transducers for liquid propagation. It was realised that the power level required for the onset of cavitation increased with increasing frequency. For example, the threshold intensity at 1 MHZ is 500 w/cm^2 while at 10 KHZ it is only 0.5 w/cm^2. The advantages of low ultrasonic frequencies stimulated development of mass loaded piezoelectric transducers and these are now employed in most ultrasonic cleaning systems.

High power dissipation is often undesirable in an ultrasonic cleaner, as intense cavitation activity over the transducer face prevents energy transmission due to back reflection from the bubble interfaces. Energy levels are generally limited to about 1·5 w/cm^2 but higher intensities may be used if the liquid is pressurised. Large area coverage is obtained by employing a mosaic of ceramic sandwich transducers.

Magnetostriction transducers of dense stack or spaced lamination form are used in some systems (Ref 6) The open stack design allows areas as large as 1·5 $metres^2$ to be assembled.

Very high energy densities may be produced in liquids with focussing bowl radiators. As the power density per unit area of the radiating surface is of a relatively low level there is little cavitation masking. Bowls composed of ceramic mosaics have been built for very high powers, and intensities at the focus of $10^5 w/cm^2$ are reported (Ref 7). Tubular transducers with magnetostriction driving elements have been built for input powers of up to 10 KW. These operate in peripheral vibration modes in the 18-30 KHZ range.

The use of transducers fitted with velocity transformers for liquid irradiation has been established for organic cell disruption. The acoustic mismatch between transducer and liquid is lessened by impedance couplers and magnesium is used in one system to obtain up to 80% transfer efficiency. With exponential stubs, intensities of over 150 w/cm^2 have been measured at the tip. By taking advantage of the high efficiency it is possible to use a lumped mass stub in which the end face area is larger than the transducer element. The liquid column must constitute a tuned load if maximum efficiency is to be obtained.

Propagation in Gases To produce an acoustic intensity of 1 w/cm^2 at 8 KHZ in air, an amplitude of 0·1 mm is required. This prevents the employment of magnetostriction or piezoelectric transducers for gas propagation.

Aerodynamic systems in which the source of acoustic energy is a gas jet offer a practical alternative, but although high power is obtainable, the efficiency is low and there are difficulties in reaching true ultrasonic frequencies. Dynamic sirens in which the gas flow is mechanically interrupted can be built for power outputs in the kilowatt range, but reliability is poor, due to moving parts.

Whistles based on jet instability are simple in construction and some progress has been made in increasing efficiency. With simple systems this does not exceed 10%. A number of more complex assemblies such as the Gavreau tangential jet (Ref 8), the Jahn flat nozzle inclined jet (Ref 9) and the toroidal whistle of Levavasseur (Ref 10) use multiple entries into a resonant chamber

Power outputs of several hundred watts are possible, with efficiencies of 15 to 25%, but it is difficult to raise the operating frequency much above 10 KHZ.

The most promising system appears to be whistles of the Hartmann type and particularly the modification known as the stem jet generator. This overcomes the inherent low stability of the Hartmann whistle and is based on a solid rod coaxially placed within the jet and cavity. The work of Boucher materially advanced this technique and recent Russian reports show that radiated power can be as high as 1·5 KW with efficiencies of 20% (Ref 11).

However, high power ultrasonic transducers for gas propagation are still neglected despite promising industrial applications such as defoaming, particle precipitation and drying.

References

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