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ULTRASONIC MOTORS

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Abstract—Ultrasonic motors represent an alternative to the conventional electromagnetic motor principle. They comprise a stationary resonator, which is excited to produce mechanical oscillations in the ultrasonic frequency range, and a passive rotor. The oscillating end of the resonator drives the rotor via a friction contact. Two newly-developed operating principles for ultrasonic motors based on rod-shaped resonators will be discussed. A single-mode drive utilizes the longitudinal oscillation of a tapered rod-shaped resonator, resulting in an ultrasonic motor with a single direction of rotation. The bimodal motor uses superimposed longitudinal and flexural oscillations and can easily be electronically driven in both directions. Ultrasonic motors are distinguished by high torques at low speed, a large holding torque when switched off and the absence of a magnetic field.

INTRODUCTION

Conventional motors convert electrical energy into mechanical energy by the electromagnetic principle: wires conducting an electric current in a magnetic field experience a mechanical force. Constant movement is achieved by current commutation techniques which produce a sequence of these effects.

Ultrasonic motors, on the other hand, are based on a completely different principle: a mechanical resonator is electrically excited to produce resonant oscillations at ultrasonic frequencies; the oscillating ends of the resonator drive a passive rotor via a friction contact.

This can be implemented as shown in Fig. 1, which represents the operating principle of an ultrasonic motors developed in the U.S.S.R. in the 1970s [1]. The asymmetric mounting of the longitudinally oscillating resonator causes the drum-shaped rotor to be driven continually in one direction. The oscillating frequencies remain above 20 kHz, the limit of perception of the human ear.

Rotor speeds of several hundred rpm can be achieved using ultrasonic motors, although no movement of the resonator ends can be detected with the naked eye. The following calculation shows how this is possible: the amplitude of motion of the resonator ends is in the order of several μm, i.e. a single oscillating period of the resonator can drive the rotor approximately 3 μm along its circumference. This process is repeated at a frequency of 30 kHz. Thus v, the circumferential speed of the rotor, is obtained from:

$$v = 3\ \mu\text{m} \times 30\ \text{kHz} = 540\ \text{cm min}^{-1}.$$

The rotor speeds quoted above are obtained from this result on the basis of a

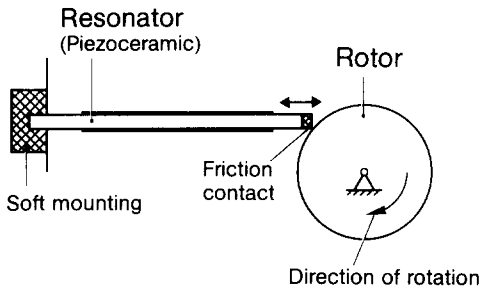

Fig. 1. Basic operating principle of an ultrasonic motor consisting of a stationary mechanical resonator and a passive rotor driven via a friction contact.

typical rotor diameter of 2 cm. Despite the intermittent driving force, constant rotation is possible due to the rotor's moment of inertia.

A completely different ultrasonic motor principle based on the flexural oscillations of an annulus has been developed in Japan. Figure 2 shows the natural oscillations of a typical annulus used here, represented in a calculation prepared by the authors using the finite-element method. When two of these natural oscillations are excited, rotating flexural waves are produced [2, 3]. They were named 'travelling waves' by the inventors. These waves turn a second annulus, placed concentrically on the resonator, about their common axis. The direction of rotation of the flexural waves can be reversed, so this motor has two directions of rotation. Other ultrasonic motor

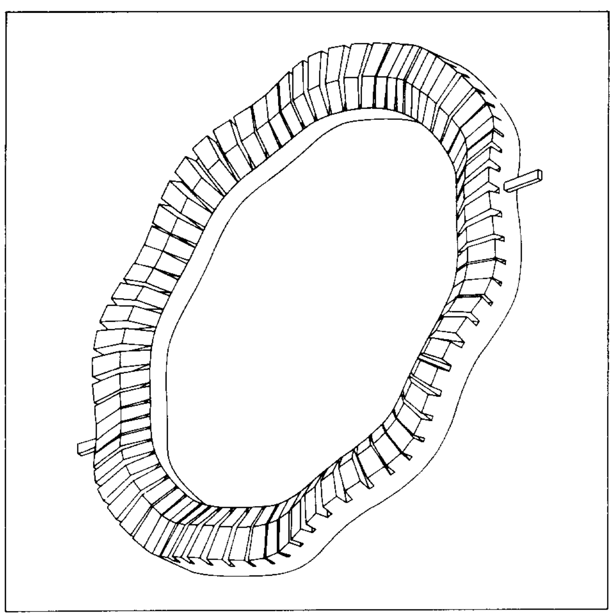

Fig. 2. Resonator oscillations in an annulus ultrasonic motor. The rotor consists of an identically sized concentric annulus in friction contact with the top of the teeth of the resonator. The teeth increase the resonator's amplitude of oscillation.

concepts differ in the way the resonators oscillate. An overview is given in the references [4–7].

EXCITATION OF OSCILLATIONS IN THE RESONATOR

In ultrasonic motors, electrical energy is converted into mechanical energy via the inverse piezoelectric effect [8]: a piezoelectric material subjected to an electric field extends or contracts depending on the orientation of the field to the piezoelectric polarization. The periodic change in shape due to the alternating current causes oscillations to be excited in the mechanical resonator.

The piezoelectric materials used here are lead–zirconate–titanate ceramics (PZT ceramics). They exhibit a much greater piezoelectric effect than natural piezoelectric materials such as quartz. PZT ceramics are brittle; pure PZT ceramic oscillators would be ripped apart by the high restoring forces accompanying the oscillations. Therefore the oscillators are constructed from metal with piezoceramics embedded or cemented at suitable points.

The following text describes recently developed ultrasonic motors based on the oscillations of optimized rod-shaped resonators. Here, two concepts have proved to be applicable: a single-mode drive using the longitudinal oscillations of the rod, and a bimodal drive based on superimposing a longitudinal and flexural oscillation.

SINGLE-MODE DRIVE

The single-mode principle is based on the longitudinal oscillation of a rod (compare the schematic sketch, Fig. 3a): the resonator's oscillation nodes and the support lie at the center of the rod, while the excursion maxima occur at its ends. One end is pressed asymmetrically against a steel drum. During expansion (primary movement A), the end of the resonator hits the hard drum. The tip retracts sideways (secondary movement B) due to its asymmetrical position, and this motion is significantly amplified by the bevel on the resonator end. A motion occurs tangential to the rotor which drives the motor due to the frictional connection. During the contraction which follows, the friction contact between the rotor and resonator opens up and the lateral deformation of the tip is elastically returned.

This operating principle employs a complete '$\lambda/2$ resonator', the mounting of the resonator is oscillation-free, in contrast to the design shown in Fig. 1.

INCREASING THE AMPLITUDE OF THE RESONATOR END

In order to achieve good performance data with ultrasonic motors, the greatest possible movement is required at the resonator end. This can be achieved by tapering the resonator toward its end. Here, various shapes capable of analytical description have been discussed, the best known being the exponential and Gaussian cross-sec-

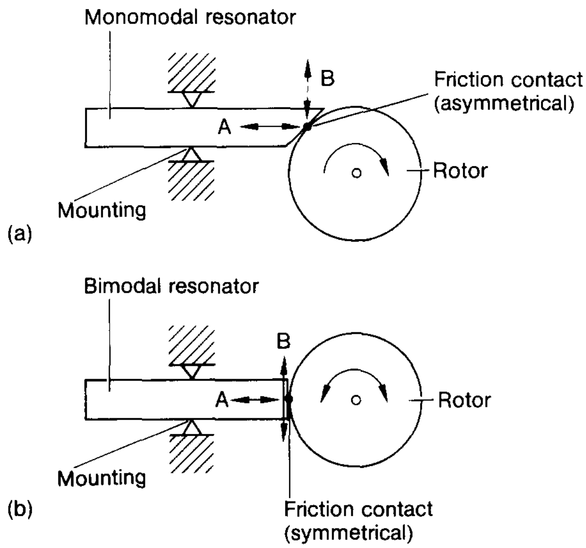

Fig. 3. Operating principle of ultrasonic motors based on rod-shaped resonators. (a) Monomodal motor with pure longitudinally oscillating resonator for one direction of rotation. (b) Bimodal motor with the longitudinal (A) and a flexural harmonic oscillation (B) of the resonator (reversible direction of rotation).

tional reductions, see, for example [9, 10].

The resonator shown schematically in Fig. 4a, whose right-hand section consists of a tapered piece of light and relatively soft material (e.g. aluminium) emerged as the preliminary optimum [11]. The left-hand section has a larger cross-section and is constructed from a heavier and harder material (steel) than the right-hand section. The greater amplitude of the motion at the right-hand end in comparison to the left-hand end can be seen from the two-dimensional finite-element model calculation in Fig. 4b. The amplitude of motion is amplified in a similar way for the longitudinal and flexural oscillations.

The longitudinally oscillating resonator, bevelled at the front, is pressed by springs against a steel drum 2 cm in diameter with a force of approximately 20 N [11]. This principle requires the drum to be harder than the resonator. The resonators possess natural frequencies of approximately 25 kHz and were driven by alternating voltages of approx. 250 V_{rms}. Lower driving voltages can be obtained by replacing the solid piezo-ceramics with multi-layered 'piezo-stacks' [7, 12].

The performance data of these motors with a single direction of rotation are shown in the 'motor diagram' in Fig. 5, i.e. plotted against the delivered torque. Unloaded motors reach speeds of 300 rpm and an efficiency of 35% can be achieved in the best operating range of the motor. In this context, efficiency refers to the conversion of 25 kHz drive signal energy to mechanical power available at the shaft. The efficiency of the drive electronics which generate the 25 kHz drive signal from the supply voltage (12 V D.C. or 220 V A.C.) also needs to be taken into account in real applications. With optimized drive electronics, this has a value around 90%. Overall efficiencies of around 30% are typical for ultrasonic drives.

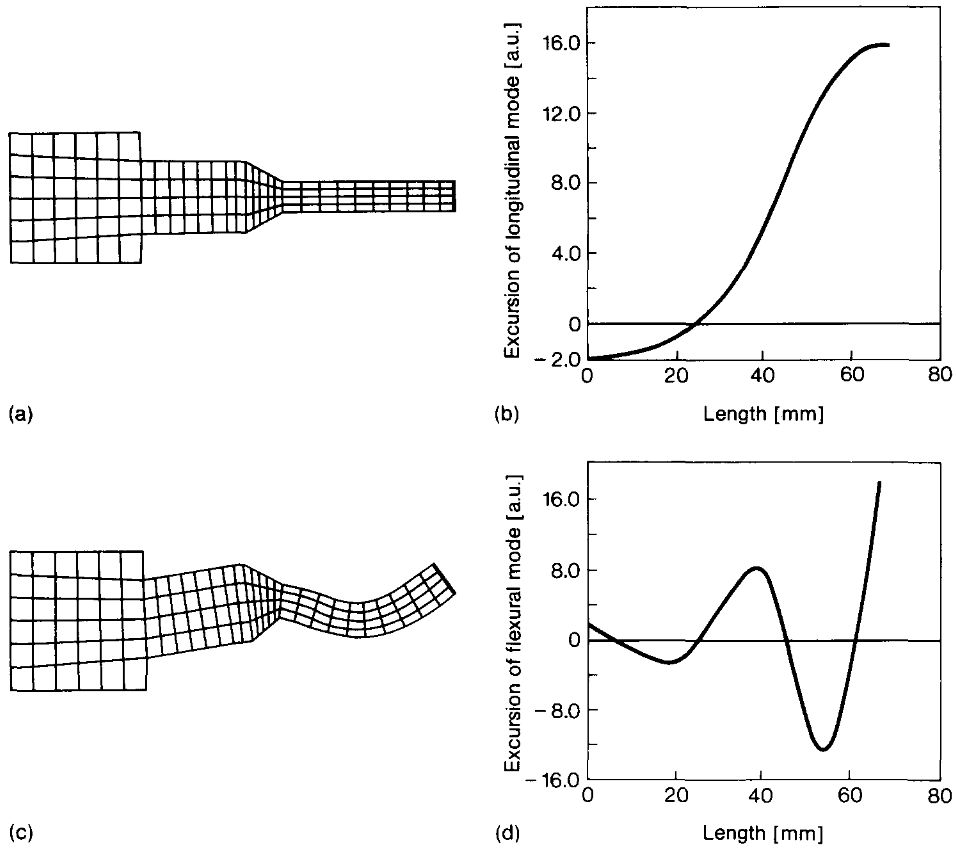

Fig. 4. Increase of the amplitude of oscillation at the end of the resonator in the finite-element model: (a) longitudinal oscillation of the resonator; (b) associated excursion; (c) flexural harmonic; (d) associated excursion.

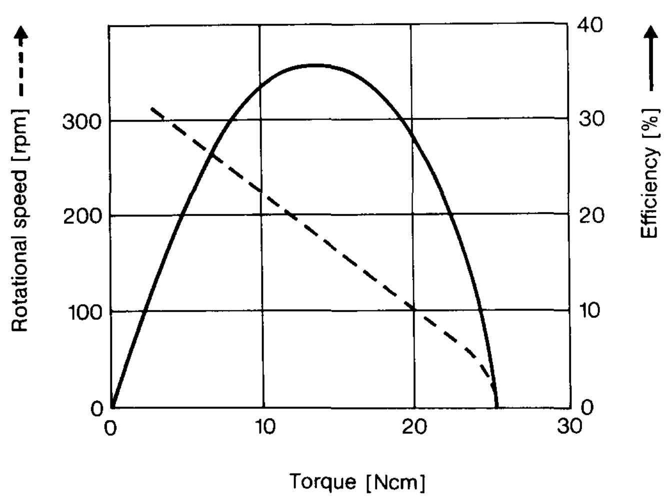

Fig. 5. 'Motor diagram' showing performance data of the single-mode ultrasonic motor.

BIMODAL DRIVE

By superimposing two oscillating modes with mutually orthogonal components of motion, rotary motion of the resonator ends is achieved directly. The longitudinal mode and one flexural harmonic mode of the rod are suitable for this purpose. The longitudinal mode causes movement A as shown in Fig. 3b and the flexural mode causes movement B. When the frequencies are in an integral ratio, superimposition results in closed rotary movements (Lissajou's figures) which can be used to 'gently' drive an attached rotor. The heavy impact of the resonator against the rotor to instigate the sideways retraction process is not necessary.

Both types of oscillation must be independently excitable. However, due to deviations of a real resonator from the ideal symmetrical shape, the two modes of oscillation are in fact coupled.

The behavior of coupled mechanical oscillators is described by a system of two spring–mass–pendulum arrangements coupled by an additional spring k_3 (see Fig. 6a). The solution of the equation of motion for this system shows that in the general case the coupled system will exhibit beat oscillations (see Fig. 6b). This cannot be used to construct a bimodal ultrasonic motor. A measure for the effective coupling between the two modes can be derived from this model [13]. It can be seen from Fig. 7 that this effective coupling is at a maximum when the frequency ratio of the uncoupled natural modes is 1:1, but is reduced by 2 orders of magnitude at a ratio of 1:2. This prediction has been confirmed by experiments using suitably tuned metal bars [13]. Therefore, undesirable mutual interference can be avoided with a 1:2 ratio of the two oscillation frequencies, where the flexural mode frequency is twice the longitudinal frequency.

The motion of the resonator end can be described as follows:

$$x = x_0 \cdot \sin(2\pi f_0 \cdot t)$$

$$y = y_0 \cdot \sin(4\pi f_0 \cdot t + \Theta),$$

where x is the direction of motion of the longitudinal oscillation (natural frequency f_0) and y the direction of motion of the flexural oscillation (natural frequency $2f_0$).

The shape of the motion curve is determined by the phase angle Θ (see Fig. 8). When $\Theta = 0$, a curve shaped like a horizontal figure of eight is produced. The bold section of the curve indicates the time during which the resonator end is in frictional contact with the rotor. At a phase angle $\Theta = 0$ in the configuration shown, the rotor rotates anti-clockwise at its maximum speed of rotation. As Θ increases, the motion curve changes such that it becomes less favorable for driving the rotor, i.e. the speed is reduced (see the curve for $\Theta = \pi/4$, for example). At $\Theta = \pi/2$ the driving moment is reduced to nil. As Θ increases further, the direction of rotation is reversed. In this way, the phase angle between the two oscillations can be used to change the direction of rotation of the rotor, and to control the speed.

Ultrasonic motors lock up in the switched-off state because the resonator is usually pressed onto the rotor with a spring. For this reason, the operating state $\Theta = \pi/2$ (stationary) is of particular interest (cf. Fig. 8): it is a freewheeling state, in which the friction between the resonator and rotor is cancelled by the oscillation of the resonator end.

Implementation of the bimodal motor concept required specific alterations in shape of the resonator in order to tune the natural frequencies of the longitudinal and flexural modes to a ratio of 1:2. Absolute precision was unnecessary, a value within the half-value width of the resonance (100 Hz) being sufficient. Data from finite-element model calculations were used for tuning. The dependence of the natural frequencies of the relevant oscillation modes on the geometric dimensions of the resonator was calculated and is shown in Fig. 9. The oscillations arising from the mutually tuned modes are shown in Fig. 10.

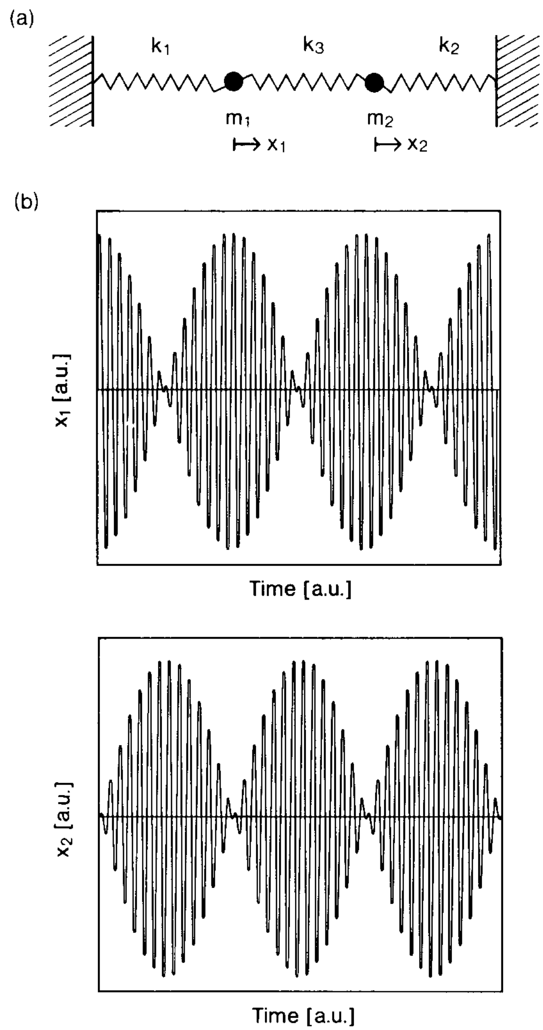

Fig. 6. (a) Mechanical model demonstrating the behavior of coupled oscillating modes. The spring–mass–pendulum arrangements k_1/m_1 and k_2/m_2 correspond to the two intrinsic modes. They are coupled by an additional spring k_3 ($k_3 \ll k_1, k_2$). (b) General form of oscillation (beat oscillation) of the system shown above.

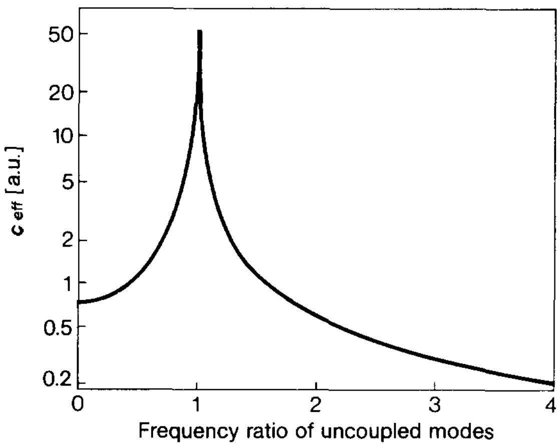

Fig. 7. Strength of effective coupling c_{eff} of the two oscillating systems of Fig. 6 as a function of the ratio of the uncoupled natural frequencies.

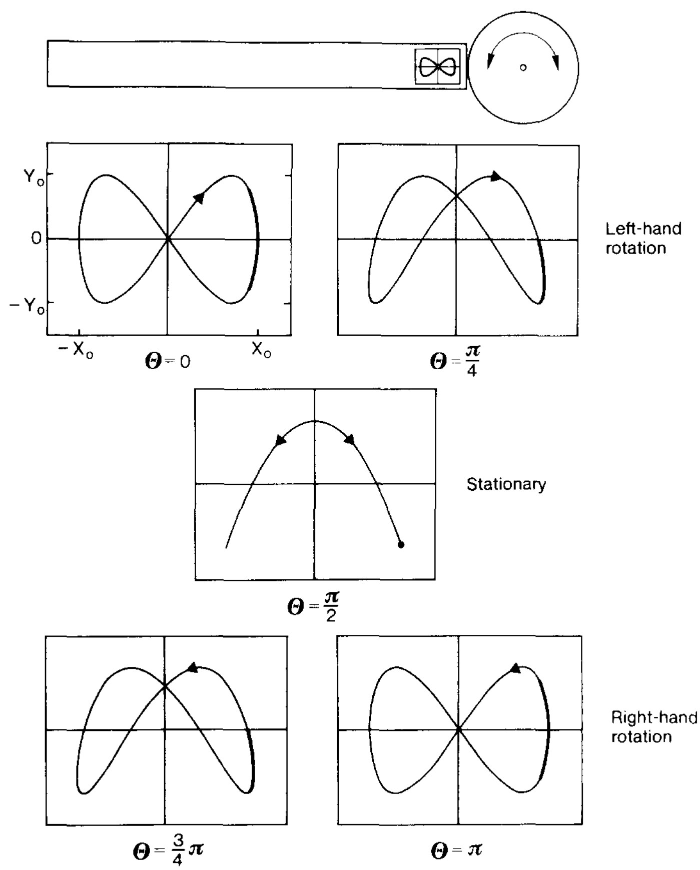

Fig. 8. Motion curves of the resonator end of a bimodal motor as a function of the phase angle between the two oscillations. The period of driving contact between resonator and rotor is emphasized. The direction of rotation applies to the set-up shown schematically above.

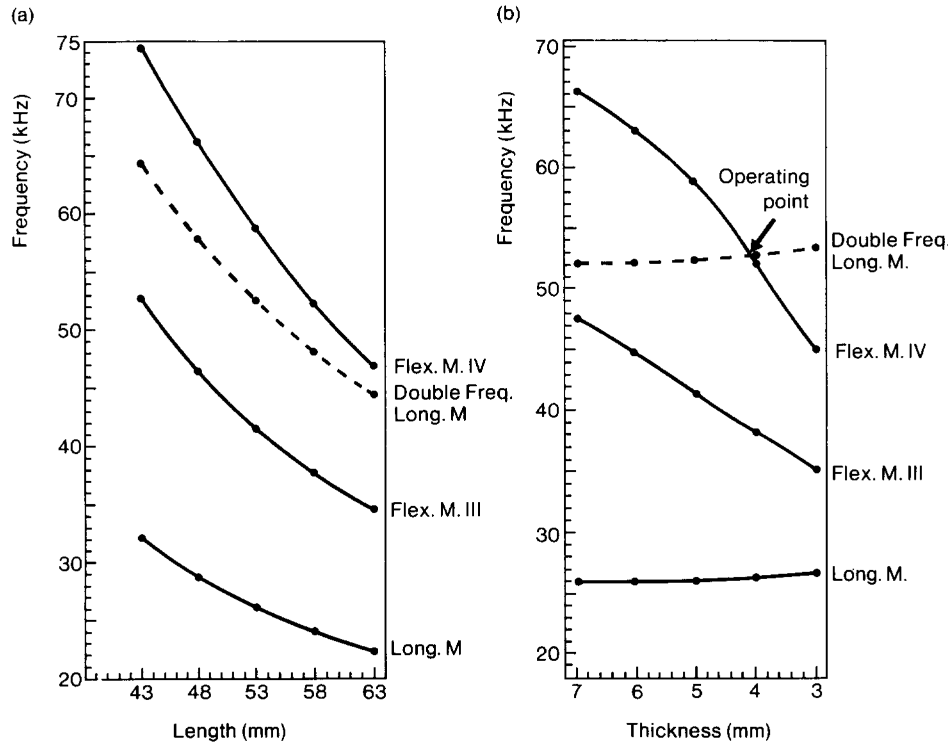

Fig. 9. Dependence of the natural frequencies of the longitudinal and flexural harmonic oscillations on the thickness and length of the flat section of the resonator (from finite-element calculations). Tuning is possible by varying the thickness.

ELECTRICAL DRIVING OF THE BIMODAL MOTOR

This requires a signal of frequency f_0 and a phase-coupled signal of frequency $2f_0$. The electrical drive of this motor can be simplified: the two phase-coupled drive signals are electronically added at low voltage, brought up to the required energies via a power amplifier and the summed signal is applied in parallel to all the piezoceramics (see block diagram in Fig. 11). The large difference in frequency between the two signals means that the individual piezoceramics only react to the corresponding spectral components. Electrical driving of the motor then requires only one (expensive) electric power amplifier. The motors with the annulus-shaped resonator and the reversible direction of rotation discussed earlier must be driven by two signals of the same frequency but different phases, i.e. two electrical power amplifiers are required in this case. Implementation of the bimodal drive resulted in the first ultrasonic motor with a reversible direction of rotation that can be controlled by a single phase signal. This is significant in economic terms, taking into account the relatively high cost of power electronics.

When the motors are in use it must be taken into account that the natural frequency of the resonator can change slightly due to heating effects, abrasion in

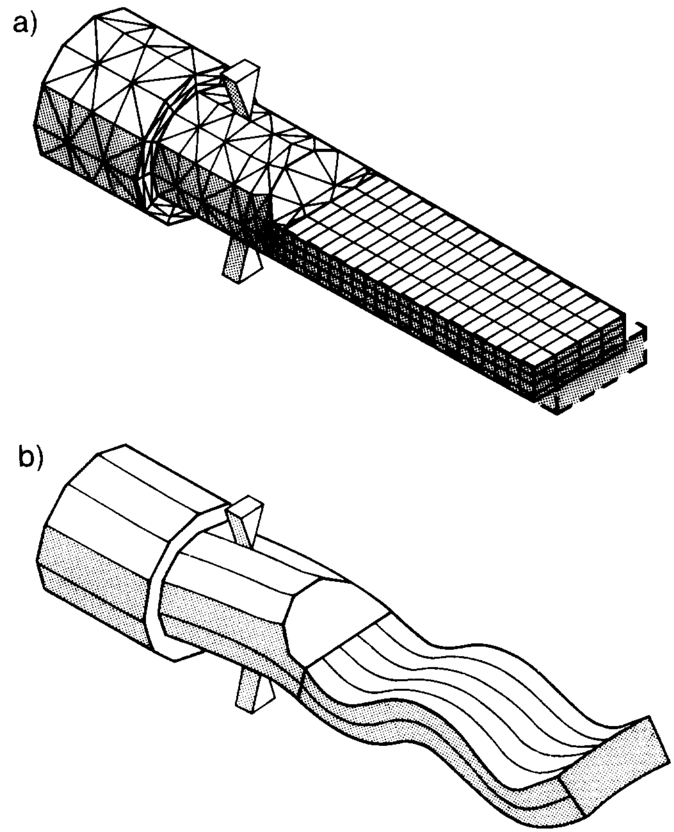

Fig. 10. The oscillating modes used in the bimodal motor: (a) longitudinal oscillation (24 kHz) and (b) flexural harmonic oscillation (48 kHz). The total length of the resonator is about 8 cm.

frictional contact or under different loading conditions. This can be compensated by attaching an extra piece of piezoceramic that detects the actual oscillating state of the resonator and sends a signal to control the sine-wave generators. A PLL technique (such as that described in [14]) could also be used.

The amplitude of the voltage component that excites the longitudinal oscillation was approx. 200 V_{rms}, and that of the flexural component approx. 300 V_{rms}. The typical speed characteristic with respect to the phase relationship of the mechanical oscillations is shown in Fig. 12. The maximum speed n_{max} is a linear function of the diameter of the rotor (within certain limits). Speeds of 300 rpm are obtained with rotors 2 cm in diameter.

The bimodal operating principle enables the resonator end to be placed gently on the rotor. Thus, with an optimal system, a long service life can be expected from the motor. The time delay between the start of the electrical drive signal and the initial rotary motion is less than 1 msec, and after approx. 25 msec maximum speed is reached (see Fig. 13). The start-up response of the motor is determined ideally by the transient behavior of the resonators (dependent on the mechanical oscillation quality). High mechanical oscillation quality causes high amplitudes of motion at the tip of the

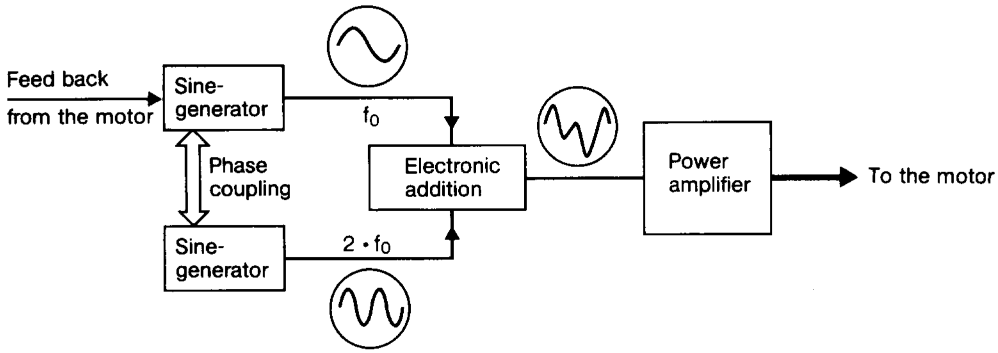

Fig. 11. Block diagram showing the electrical driving of the bimodal motor.

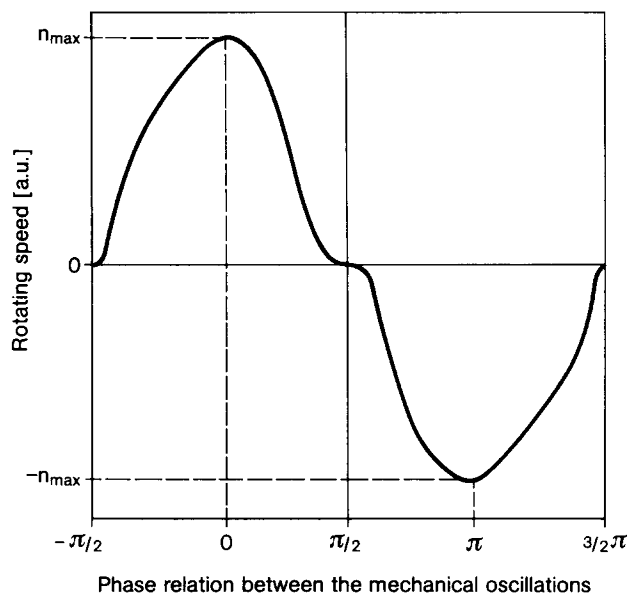

Fig. 12. Speed of a bimodal ultrasonic motor as a function of the phase difference of the oscillations.

resonator and therefore high efficiency, but at the cost of a slower start-up time of the motor.

CONCLUSIONS—CHARACTERISTICS OF ULTRASONIC MOTORS

Ultrasonic drives represent a new method for the conversion of electrical energy into mechanical energy. The basic principle, mentioned in the U.S.S.R. as long ago as the early 1970s, offers realistic applications today, due to the availability of

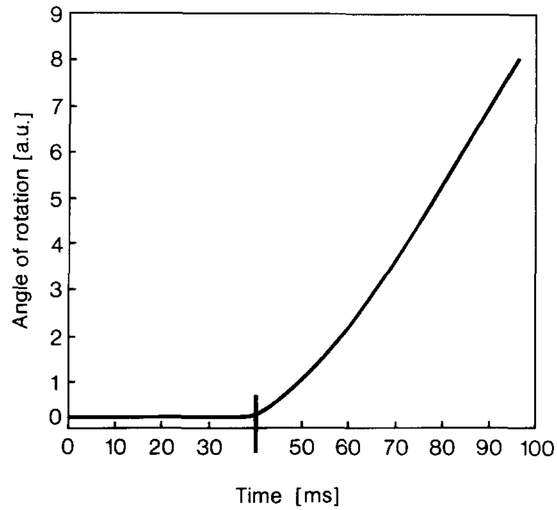

Fig. 13. Start-up characteristic of a bimodal piezomotor. The curve of the angle of rotation plotted against time becomes a straight line after maximum speed has been reached.

powerful, mechanically stable and inexpensive piezoelectric materials. Another significant point is the development of microelectronics, which has simplified implementation of the necessary drive electronics. In certain applications, ultrasonic motors have significant advantages over electromagnetic drives.

Depending on the oscillation mode of the resonator, drives can be constructed that rotate in one or both directions. The main drawback of ultrasonic motors is the mechanical wear at the friction contact between the resonator and rotor, which is the usual cause of their limited service life. Wear-reducing surface treatments, such as those used on high quality tools, are helpful. With the bimodal motor concept presented here, a rotor drum can be made from a softer material than the resonator end (e.g. hard PVC), thus transferring the wear from the resonator to the rotor.

Linear drives can also be implemented with most design concepts by replacing the rotor by a rail. If a rotor is used, it need not carry windings or permanent magnets as is the case with electromagnetic drives. Mechanical moments of inertia are thus low, resulting in short starting and stopping times for the rotor. The start-up response can be precisely controlled by the drive electronics.

Optimized ultrasonic motors produce greater torques than electromagnetic motors of the same physical size. In contrast to the latter, large torques can be produced at low speed (100 rpm) without a gearbox. The precise control of the rotary motion by the drive electronics would suggest the application of ultrasonic motors as a new type of fast positioning and control drive, especially as these motors have a large holding torque in the switched-off state. Examples of initial applications would be paper feeds in printers, positioning of plotter pens or the auto-focus drives of camera lenses. The service life of ultrasonic motors, typically several hundred hours, would suffice for these positioning applications.

Ultrasonic motors do not use field windings and therefore do not generate a magnetic scatter field; this would suggest their use in areas where such fields would cause interference: in special scientific applications or with NMR measurements, e.g. in the magnetic field of computer tomographs in medical engineering. Currently possibilities of miniaturization of these motors using micromachining techniques are under discussion; this may yield a new generation of micromachining motors [15].

REFERENCES

1. Hjiev I. and Ivanow Z., *Feingerätetechnik* **36**, 65 (1987).
2. Akiama Y., *J. Electron. Engng* **24**, 76 (1987).
3. Inaba R. *et al.*, IEEE 1987 *Ultrasonics Symposium Proceedings*, New York, USA, pp. 747–756 (1987).
4. Schoenwald J. S. *et al., Proc. IEEE Conference on Robotics and Automation*, Philadelphia, USA, April (1988).
5. Osamu O. *et al., Jap. J. appl. Phys.* **28**, 1 (1989).
6. Ueha S., *Jap. J. appl. Phys.* **28**, 3 (1989).
7. Uchino K., Kato K. and Tohda M., *Ferroelectrics* **87**, 331 (1988).
8. Jaffe B., Cook W. R. and Jaffee H., *Piezoelectric Ceramics*. Academic Press, New York (1971).
9. Mason W. P. and Wick R. F., *J. Acoustic Soc. America* **32**, 209 (1951).
10. Eisner E. and Sarger J. S., *Ultrasonics* **3**, 88 (1965).
11. Fleischer M., Stein D. and Meixner H., *IEEE Trans. Ultrason., Ferroel. Freq. Contr.* **36**, 607 (1989).
12. Shuo H. C. and Wang H.-C., *Sensors Actuators* **A24**, 239 (1990).
13. Fleischer M., Stein D. and Meixner H., *IEEE Trans. Ultrason., Ferroel. Freq. Contr.* **36**, 614 (1989).
14. Komatsu K., *Jap. J. appl. Phys.* **24**, 159 (1985).
15. Muller R. L., *Sensors Actuators* **A21**, 1 (1990).