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1) ABSTRACT

Ultrasonic rotary motors have the potential to meet this NASA need and they are developed as actuators for miniature tele robotic applications. These motors are being adapted for operation at the harsh space environments that include cryogenic temperatures and vacuum and analytical tools for the design of efficient motors are being developed. A hybrid analytical model was developed to address a complete ultrasonic motor as a system. Included in this model is the influence of the rotor dynamics, which was determined experimentally to be important to the motor performance. The analysis employs a 3D finite element model to express the dynamic characteristics of the stator with piezoelectric elements and the rotor. The details of the stator including the teeth, piezoelectric ceramic, geometry, bonding layer, etc. are included to support practical USM designs. A brush model is used for the interface layer and Coulomb's law for the friction between the stator and the rotor. The theoretical predictions were corroborated experimentally for the motor. In parallel, efforts have been made to determine the thermal and vacuum performance of these motors. To explore tele robotic applications for USMs a robotic arm was constructed with such motors.
2) INTRODUCTION

What is an ultrasonic motor

An ultrasonic motor is driven by the vibration of piezoelectric elements, and produces force for rotation or horizontal movement by harnessing the elements ultrasonic resonant of over 20 KHz. An ultrasonic motor is a type of electric motor formed from the ultrasonic vibration of a component, the stator, placed against another, the rotor or slider depending on the scheme of operation (rotation or linear translation). Ultrasonic motors differ from piezoelectric actuators in several ways, though both typically use some form of piezoelectric material, and most often lead zirconate titanate and occasionally lithium niobate or other single-crystal materials. The most obvious difference is the use of resonance to amplify the vibration of the stator in contact with the rotor in ultrasonic motors. Ultrasonic motors also offer arbitrarily large rotation or sliding distances, while piezoelectric actuators are limited by the static strain that may well be induced in the piezoelectric element.

Piezoelectric ultrasonic motors are a new type of actuator. They are characterized by high torque at low rotational speed, simple mechanical design and good controllability. They also provide a high holding torque even if no power is applied. Compared to electromagnetic actuators the torque per volume ratio of piezoelectric ultrasonic motors can be higher by an order of magnitude.

The ultrasonic motor is characterized by a ‘low speed and high torque’, contrary to the ‘high speed and low torque’ of the electromagnetic motors. Two categories of ultrasonic motors are developed at our laboratory: the standing wave type and the traveling wave type.

The standing wave type is sometimes referred to as a vibratory-coupler type, where a vibratory piece is connected to a piezoelectric driver and the tip portion generates flat-elliptical movement. Attached to a rotor or a slider, the vibratory piece provides intermittent rotational torque or thrust. The travelling-wave type combines two standing waves with a 90°-phase difference both in time and space. By means of the traveling elastic wave induced by the thin piezoelectric ring, a ring-type slider in contact with the surface of the elastic body can be driven.
3) USM Prototypes

1. Linear ultrasonic motors

I) DOF planar pin-type actuator
The objective of this project is to design and develop a piezoelectric actuator based on the fundamental operating mechanism of ultrasonic motors. Two pin-type prototypes with piezoelectric bimorph plate and a contact pin for generating driving force in the X-Y direction were designed and fabricated. A test rig was also constructed for the evaluation of the two prototypes and basic characteristics of the actuators were investigated. The working principle of the actuator was verified and proven during the experiment. Basically, the optimal driving speed of an actuator is dependent on the driving frequency, the input voltage, the contact surface and the friction coefficient between the stator and motor. An analytical study of the prototypes has been carried out by means of finite element analysis utilizing ANSYS5.4. With comparison to the experimental results, it was proven that the optimal driving condition occurred at the specific resonant mode depending on the pin vibration. Maximum unloaded driving speed was obtained to be approximately 0.68 cm/s at a frequency of 14.8 kHz and the optimum input voltage was found to be approximately 70 V p-p.

II) Bi-directional linear standing wave USM

A standing wave bi-directional linear ultrasonic motor has been fabricated. This linear USM has very simple structure and can be easily mounted onto any commercially available linear guide. A high precision positioning x-y table was built by mounting these individual movable linear guides together. The basic parameters of our linear USM are: moving range 220 mm(variable depending on the linear guide), no-load speed 80mms/s, ratings 23mm/s at 3 00gf, stall force 700gf, starting thrust 500gf, resolution<50nm, response time of 12ms from stationary status to constant velocity(80mm/s) with a initial mass of 260g.
2. **Rotary ultrasonic motor**
   The characteristics of the rotary disc type motor will be investigated and theoretical model will be formed to relate the important components on the power of the motor. The scope includes designing different motor with various dimensions, formulation of the analytical model, experimental testing and ultimately, setting a standard for practical application of this particular type of USM. This project will lay the foundation of the characteristics and performance of the rotary disc type USMs for future application.

3. **Spherical ultrasonic motor**
   Presently a new type of spherical USM is under investigation. This particular USM consists of a thin square plate, 30x30 mm in area. It can rotate in more than 4 individual directions. Now we are trying to compile rotation in any direction by using a computer to control the 4 individual directions properly.
4) Ultrasonic micro motor drive principle

Fig. 1 shows an exploded view of a typical traveling wave ultrasonic motor, is discussed in this paper.

Fig. 1; An exploded view of a typical traveling wave ultrasonic motor It consists of two basic parts: the statically part vibration (stator vibration) with a frequency in the ultrasonic range, and the driven part (rotor) by the stator effect via frictional forces. Stator is composed of an elastic body and a thin piezo ceramic ring. The piezo ceramic ring is bonded under the elastic body. It has the function of exciting traveling bending waves and is shown in Fig. 2. The piezo ceramic ring is divided into two halves: phase A and phase B. These two phases are separated by sensor and ground parts which are a quarter and three quarters of a wavelength, respectively. Each phase (A or B) includes n segments. Each segment is a half wavelength and polarized adversely regarding the adjacent one. Phase A and phase B are a quarter of the wavelength out of phase, spatially. The phases are excited by two sinusoidal voltages which are temporally 90° out of phase [18]. Therefore, a traveling wave is generated and the particles of the stator surface move elliptically [19]. The sensor part is used for
measuring the amplitude and the phase of the traveling wave to control the excitation of the piezo ceramic ring. The rotor is pressed against the stator by means of a disk spring, and a thin contact layer is bonded to the rotor in the contact region [20]. Therefore, the vibration of the stator with high frequency and small amplitude is transformed into the macroscopic rotary motion of the rotor by friction.

Fig. 2: The piezo ceramic ring of the experimental ultrasonic motor.
Figure 1. Principle of Operation of a Rotary Traveling Wave Motor
5) Advantages of ultrasonic motor over electromagnetic motor:

1. Little influence by magnetic field:

The greatest advantage of ultrasonic motor is that it is neither affected by nor creates a magnetic field. Regular motors which utilize electromagnetic induction will not perform normally when subjected to strong external magnetic fields. Since a fluctuation in the magnetic field will always create an electric field (following the principle of electromagnetic induction), one might think that ultrasonic motors will be affected as well. In practice, however, the effects are negligible. For example, consider a fluctuation in the flux density by, say, 1T (which is a considerable amount), at a frequency of 50 Hz, will create an electric field of 100 volts per meter. This magnitude is below the field strength in the piezoelectric ceramic and hence can be ignored.

2. Low speed, high torque characteristics, compact size and quiet operation:

Ultrasonic motors can be made very compact in size. The motor generates high torques at low speeds and no reduction gears are needed unlike the electromagnetic motors. The motor is also very quiet, since its drive is created by ultrasonic vibrations that are inaudible to humans.

3. Compact-sized actuators:

The ultrasonic motor’s small size and large torque are utilized in several applications. The ultrasonic motors hollow structure is necessary for an application in several fields such as robotics etc where it would be very difficult to design a device with an electromagnetic motor and satisfy the required specifications.

Their main advantages over the conventional electromagnetic devices are:

4. Different velocities without gear-mechanisms,
5. High positioning accuracy due to the friction drive,
6. High holding torque (braking force without energy supply) [4],
7. Simplicity and flexibility in structural design [4 -5],
8. No magnetic noise [6],
9. High output torque at low speed[7],
10. High force density
6) APPLICATIONS

Ultrasonic micro motor

A wristwatch is essentially a high density micro mechanism that includes a power supply, oscillator, control and drive circuits, micro motor, micro transfer mechanism, micro sensor and display elements. The key technology behind this micro mechanism is the micro motor. SII successfully launched mass production of the world's smallest ultrasonic motor (4.5mm diameter by 2.5mm thick), and incorporated it in wristwatches as the actuator for the fully-automatic calendar. Highly evaluated for its small size, low voltage operation using a simple drive circuit, and application in wristwatches, the ultrasonic micro motor received the Aoki Award from the Horological Institute of Japan, the Technology Award from the Japan Society for Precision Engineering, and the Japan Society for the Promotion of Machine Industry Prize. We have also developed many types of ultrasonic micro-motors, with a focus on downsizing.

The technology has been applied to photographic lenses by a variety of companies under different names:

Canon ± USM, Ultra Sonic Motor
Minolta, Sony ±SSM, SuperSonic Motor
Nikon ± SWM, Silent Wave Motor
Olympus± SWD, Supersonic Wave Drive
Panasonic± XSM, Extra Silent Motor
Pentax± SDM, Silent Drive Motor
Sigma± HSM, Hyper Sonic Motor
Tamron- USD, Ultrasonic Silent Drive

7) FUTURE OF USM’S
Piezoelectric Materials Will Power Future Nano scale Devices

One of the most daring dreams that scientists have is to create a world that is completely self-sustaining, and which is not reliant on exterior sources of power for it to operate. This means that everything requiring electricity will have to reach a high-level of conservation abilities,

**Image comment:**
A small piezoelectric motor. In the future, these devices may also exist at the nano scale, powering others all around us.
8) Conclusion

The main contribution of the work presented in this paper consists in description development rotary traveling wave ultrasonic motor as structure, principle function and application form in according to its working characteristics.

As technical example of ultrasonic motor, Daimler-Benz AWM90-X motor is presented, using the measurements values obtained from the manufacturer data and it simulation implemented that we have developed.

After 25 years of active search and nowadays piezoelectric rotary motors have considerable advantages and represent a truth concurrent for conventional electromagnetic motors.

For the new needs of applications domains, several types of piezoelectric ultrasonic motors have been suggested and designed and developed, to be used as standard as efficient, particularly the rotary traveling wave ones which are now commercially available and applied as auto-focus cameras, in robotics, in medical domain and in aerospace.