Rotary Ultrasonic Motors Actuated By Traveling Flexural Waves

Shyh-Shiuh Lih, Yoseph Bar-Cohen,
Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109
yosi@jpl.nasa.gov

and

Willem Grandia,
Quality Manufacturing Inspection (QMI), Costa Mesa, CA 92627

ABSTRACT

Ultrasonic rotary motors are being developed as actuators for miniature spacecraft instruments and subsystems. The technology that has emerged in commercial products requires rigorous analytical tools for effective design of such motors. An analytical model was developed to examine the excitation of flexural plate wave traveling in a rotary piezoelectrically actuated motor. The model uses annular finite elements that are applied to predict the excitation frequency and modal response of the annular stator. This model allows to design efficient ultrasonic motors (USMs) and it incorporates the details of the stator which include the teeth, piezoelectric crystals, stator geometry, etc. The theoretical predictions and the experimental corroboration showed a remarkable agreement. Parallel to this effort, USMs are made and incorporated into a robotic arm and their capability to operate at the environment of Mars is being studied.

Key Words: Actuators, Active Materials, Piezoelectric Motors, Ultrasonic Motors (USMs), Stators and Rotors, Modal Analysis

2. INTRODUCTION

The recent NASA efforts to reduce the size and mass of future spacecraft are straining the specifications of actuation and articulation mechanisms that drive planetary instruments. The miniaturization of conventional electromagnetic motors is limited by manufacturing constrains. Generally, these type of motors compromise speed for torque using speed reducing gears. The use of gear adds mass, volume and complexity as well as reduces the system reliability due the increase in the number of the system components. The recent introduction of rotary piezoelectric motors is offering potential drive mechanisms for miniature instruments [1-5]. These motors offer high torque density at low speed, high holding torque, simple construction, can be made in annular shape (for optical application, electronic packaging and wiring through the center), and have a quick response. A study is underway to develop such motors for operation at space environment, namely, operate effectively and reliably at temperatures down to cryogenic levels and vacuum.

Ultrasonic motors [5] can be classified by their mode of operation (static or resonant), type of motion (rotary or linear) and shape of implementation (beam, rod, disk, etc.). Despite the distinctions, the fundamental principles of solid-state actuation tie them together: microscopic material deformations (usually associated with piezoelectric materials) are amplified through either quasi-static mechanical or dynamic/resonant means. Several of the motor classes have seen commercial application in areas needing compact, efficient, and intermittent motion. Such applications include: camera auto focus lenses, watch motors and compact paper handling. To obtain the levels of torque-speed characteristics of USMs using conventional motors requires adding a gear system to reduce the speed, thus increasing the size, mass and complexity of the drive mechanism. USMs are fundamentally designed to have a high holding force, providing effectively zero backlash. Further, since these motors are driven by friction the torque that would cause them to be backdriven at zero power is significantly higher than the stall torque. The number of components needed to construct the motor is small minimizing the number of potential failure points. The general characteristic of USMs makes them attractive for robotic applications where small, intermittent motions are required.

In Figure 1 the principle of operation of an ultrasonic motor (flexural traveling wave ring-type motor) is shown as an example. A traveling wave is established over the stator surface, which behaves as an elastic ring, and produces elliptical motion at the interface with the rotor. This elliptical motion of the contact surface propels the rotor and the drive-shaft connected to it. The teeth, which are attached to the stator, are intended to increase the moment arm to amplify the speed. The operation of USM depends on friction at the interface between the moving rotor and stator, which is a key issue in the design of this interface for extended lifetime.

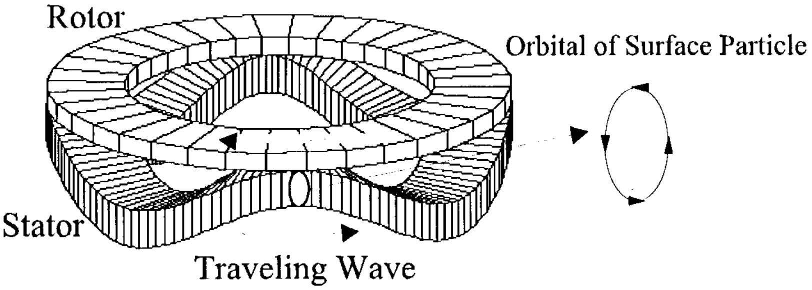

Figure 1. Principle of Operation of a Rotary Traveling Wave Motor.

3. PRINCIPLE OF OPERATION

The general principle of the operation of ultrasonic motors is to generate gross mechanical motion through the amplification and repetition of micro-deformations of active material. The active material induces an orbital motion of the stator at the rotor contact points and frictional interface between the rotor and stator rectifies the micro-motion to produce macro-motion of the stator. This mechanism is illustrated in shown in Figure 1. The active material, which is a piezoelectric material excites a traveling flexural wave within the stator that leads to elliptical motion of the surface particles. Teeth are used to enhance the speed that is associated with the propelling effect of these particles. The rectification of the micro-motion an interface is provided by pressing the rotor on top of the stator and the frictional force between the two causes the rotor to spin. This motion transfer operates as a gear leads to much lower rotation speed than the wave frequency.

A stator substrate is assumed to have a thickness, t_S, with a set of piezoelectric crystals that are bonded to the back surface of the stator in a given pattern of poling sequence and location. The thickness of the piezoelectric crystals is t_p. The total height, h, is the sum of the thickness of the crystals and the stators (bonding layer is neglected). The overall height of the stator is also allowed to vary with radial position. The outer radius of the disk is b and the inner hole radius is a. To generate traveling wave, the piezoelectric crystals poling direction is structured such that quarter wavelength out-of-phase is formed. This poling pattern is also intended to eliminate extension in the stator and maximize bending. The teeth on the stator are arranged in a ring at the radial position.

To generate a traveling wave within the stator two orthogonal modes are activated simultaneously. These modes are induced by constructing the drive solid-state crystal actuators in the form of two sections of poling pattern that are bonded to the stator. Geometrical examination of this pattern shows that driving the two sections using $cos(\omega t)$ and $sin(\omega t)$ signals, respectively, will produce a traveling wave with a frequency of $\omega/2\pi$. Also, by changing the sign on one of the drive signals, the traveling wave would reveres its direction.

4. THEORETICAL MODELING

The equation of motion of the ultrasonic motor can be derived from Hamilton's principle. The analytical model has been derived by many authors (e.g. Hagood and A. McFarland [5], Kagawa et al [6]). The generalized equation of motion of the stator can be summarized as

$$[M]\{\ddot{\xi}\} + [C]\{\dot{\xi}\} + [K]\{\xi\} = [P]\{\varphi\} + \{F_N\}+\{F_T\}$$
$$[P]^T\{\xi\} - [G]\{\varphi\} = \{Q\}$$

where [M], [C], [K], [P], [G], are the mass, damping, stiffness, electromechanical coupling, and capacitance matrices, respectively. The vectors $\{\xi\}$, $\{\varphi\}$, $\{F_N\}$, $\{F_T\}$, and {Q} are the model amplitude, the electric potential vectors the normal external force, the tangential external force and the charge vectors, respectively. The modal amplitude $\{\xi\}$ and other generalized coordinates can be defined through energy methods such as Rayleigh Ritz method [5]. However, this method smears the contribution of the teeth and the variation of the stator ring as well as the support disk along the radial direction and may lead to undesirable results. Even though, 3-D finite element method (FEM) was reported [6] to be used to accurately predict the modal frequencies and transient response of the stator, it is computational intensive process. Further, the calculated response modes and associated frequencies that are determined by the 3-D FEM needs to be identified visually to find the designed mode. Due to the disadvantages for the methods mentioned above the modified annual finite element described in [7] is used and it is based on the symmetrical characteristics of the ultrasonic motors. The annular finite element is shown as in Fig. 2, where w_1, w_2 ψ_1, and ψ_2 are the degree of freedoms. The transverse displacement w across each element is assumed to be of the form given by the equation

$$w(r,\theta,t) = (a_0 + a_1 r + a_2 r^2 + a_3 r^3)\cos m\theta \cos(\omega_n^m t), \text{ for } R_1 < R_2$$

where ω_n^m is the radial resonance frequency and the index m, n are mode along the θ and r direction, respectively. If we assume that the transverse shear and rotary inertial effects are negligible, the elemental mass, stiffness can be derived using the standard variational methods. Thus, the natural frequency and modal shape can be found by solving the eigenvalue problem.

$$\{[K] - (\omega_n^m)^2[M]\}\{\xi_n^m\} = \{0\}$$

Using consistent mass formulations, the effect of the stator teeth can also be included. Details of the formulation of other generalized coordinate are treated similar to those in [7] and will be presented by the authors' in a future publication.

5. ANALYSIS OF PIEZOELECTRIC MOTORS

The analysis of the nonlinear, coupled rotor-stator dynamic model discussed above has demonstrated the potential to predicting motor steady state and transient performance as a function of critical design parameters such as interface normal force, tooth height, and stator radial cross section. A finite elements was incorporated into the analysis and a MATLAB code was developed to determine the modal characteristics of the stator. The model accounts for the shape of the stator, the piezoelectric poling pattern, and the teeth parameters. Once the details of the stators are selected the modal response is determined and is presented on the computer monitor, as shown for example in Figure 3, where the mode (m, n) = (4, 0) is presented. An electronic speckle pattern interferrometry was used to

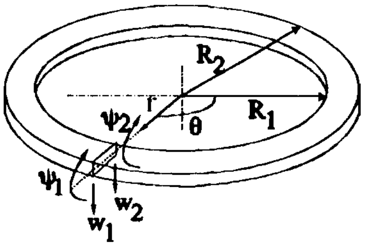

Figure 2: An annular finite element.

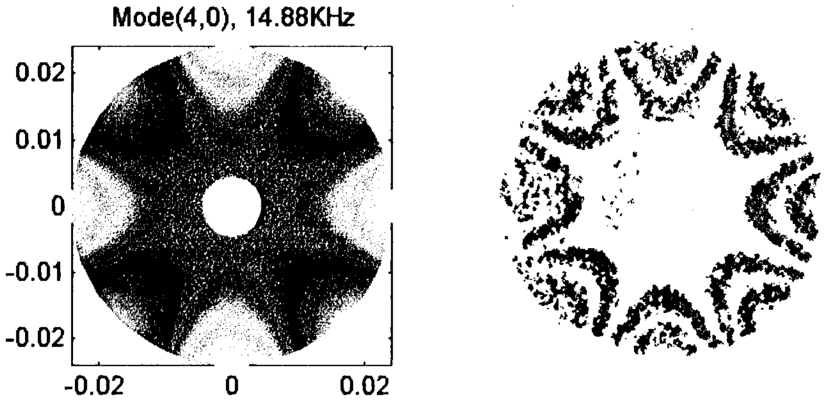

Figure 3: Modal response and resonance frequency (left) and experimental verification (right).

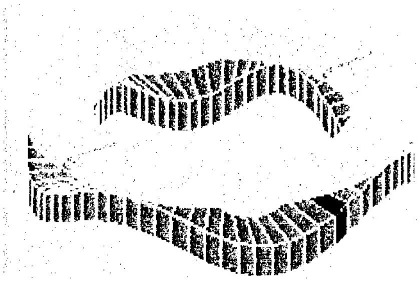

Figure 4: Animation tool for viewing the operation of USM. The stator is shown with traveling wave and the rotor is rotating above the stator.

Using this analytical model that employs finite element analysis, motors were constructed. The predicted resonance and measured resonance frequency for a 1.71-in diameter steel stator are represented in Table 1. The results that are presented in this table are showing an excellent agreement between the calculated and measured data. To examine the effect of vacuum and low temperatures, a 1.1 inch USM was also tested in a cryovac chamber that was constructed using a SATEC system and the torque speed was measured as shown in Figure 7. The motor that was servo-controlled showed a remarkable stable performance down to about -48°C and vacuum at the level of 2×10^{-2} Torr. This result is very encouraging and more work will be done in the future to determine the requirements for operation of USMs at Mars simulated conditions.

Table 1. The measured and calculated resonance frequencies of USM's stator.

Mode (m,n)	Calculated Frequency (KHz)	Measured Frequency
(4,0)	14.88	14.55
(5,0)	22.48	22.37
(6,0)	31.45	31.34

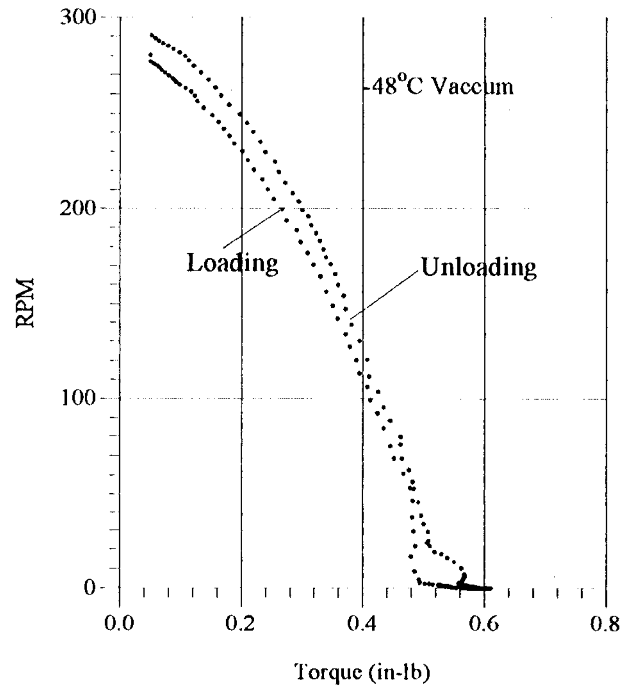

Figure 7. Measured torque-speed curve for a 1.1-inch diameter USM at -48C and $2x10^2$ Torr.

6. CONCLUSIONS

A finite element model was developed to analyze the spectral response of ultrasonic motors with various geometrical configurations and construction materials. The modal response and the predicted resonance conditions were corroborated experimentally using spectral measurements and interferometric analysis. Further, user interface interactive tools were developed for a MATLAB platform simplifying the analysis of the modal behavior of USMs and allowing the study of their response to various stator parameters.

ACKNOWLEDGMENT

The authors would like to thank Nesbitt. W. Hagood IV, Aeronautics and Astronautics, MIT, for his assistance in this study under a TRIWG contract. The results reported in this manuscript were obtained under a TRIWG task that is

ACKNOWLEDGMENT

The authors would like to thank Nesbitt. W. Hagood IV, Aeronautics and Astronautics, MIT, for his assistance in this study under a TRIWG contract. The results reported in this manuscript were obtained under the Planetary Dexterous Manipulator Task, that is managed by Dr. Paul Schenker and it is a TRIWG task that is funded by a JPL, Caltech, contract with NASA Headquarters, Code S, Mr. David Lavery and Dr. Chuck Weisbin are the Managers of TRIWG.

REFERENCES

1. M. Hollerbach, I. W. Hunter and J. Ballantyne, "A Comparative Analysis of Actuator Technologies for Robotics." In Robotics Review 2, MIT Press, Edited by Khatib, Craig and Lozano-Perez (1991).
2. A. M. Flynn, et al "Piezoelectric Micromotors for Microrobots" J. of MEMS, Vol. 1, No. 1, (1992), pp. 44-51.
3. E. Inaba, et al, "Piezoelectric Ultrasonic Motor," Proceedings of the IEEE Ultrasonics 1987 Symposium, pp. 747-756, (1987).
4. J. Wallashek, "Piezoelectric Motors," J. of Intelligent Materials Systems and Structures, Vol. 6, (Jan. 1995), pp. 71-83.
5. N. W. Hagood and A. McFarland, "Modeling of a Piezoelectric Rotary Ultrasonic Motor," IEEE Transactions on Ultrasonics, Ferroelectrics and Frequency Control, Vol. 42, No. 2, 1995 pp. 210-224.
6. K. Kagawa, T. Tsuchiya and T. Kataoka, "Finite Element Simulation of Dynamic Responses of Piezoelectric Actuators,", J. of Sound and Vibrations, Vol. 89 (4), 1996, pp. 519-538.
7. D. G. Gorman, "Natural Frequencies of Transverse Vibration of Polar Orthotropic Variable Thickness Annular Plates, " J. of Sound and Vibrations, Vol. 86 (1), 1983, pp. 47-60.