Design and analysis of a travelling wave ultrasonic motor for space applications
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Abstract

The design of a rotary ultrasonic motor for space applications is considered. First the working principle of such device is examined. The dynamics of the stator and the rotor is then studied by means of modelling approaches proposed in the recent literature. A special attention is devoted to geometry of the piezoelectric actuating layers and the relevant electrodes pattern. A preliminary design and verification process is then set up based on general performance indices determined for particular space applications.

1 Introduction

New demanding objectives in terms of cost and performances of space systems have favoured the development of a new generation of devices and components. Some of them are based on the use of active materials, such as piezoelectrics, combined with passive metal structures for different purposes as vibration and shape control or power transduction (1). The last is the case of ultrasonic motors which are attracting more and more attention for their limited volume, high precision and low weight (2,3). The range of applications of such motors is rapidly increasing and many commercial applications are already developed especially for the case of high precision mechanisms.

The working principle of these motors is based on the interaction between a fixed vibrating part (the stator) and a moving part (the rotor) which carries the load. The friction between the stator and the rotor allows...
It is easy to understand that many alternative geometries of the stator and the rotor and many relevant vibration patterns can be considered for different applications and purposes (linear or radial motors, flexural, longitudinal or torsional vibration modes). Here we will restrict the analysis to rotary motors for which numerous versions have been already used in practice.

In space applications, especially for the case of deployment and pointing mechanisms, ultrasonic motors can play in the next future a very interesting role for the absence of reduction devices, which are in general necessary for electromagnetic motors, and for the possibility of generating a reasonably high torque at low angular velocity.

Recently, there has been a significant effort in the development of analytical and numerical tools for the analysis and design of ultrasonic motors and the prediction of their performance. Some authors concentrated their attention on the dynamics of the stator, including the modelling of the piezoelectric material and the relevant geometry of the electrodes along the annular plate (4,5,6). Another group of studies aimed at the general analysis of the performances of the motor. In this case not only the dynamics of the rotor but also an accurate modelling of the friction mechanism between stator and rotor needs to be included. A description of these developments can be found in the work by Wallaschek (7). Among the most recent contributions Hagood and McFarland (8) proposed a general approach for predicting a priori motor performances as a function of design parameters. In their study they also include the non linear effect of the dynamics of the rotor on the dynamics of the stator which is usually neglected in the analysis.

The present study aims at applying the approach derived by Hagood and McFarland (8) by verifying its suitability for preliminary design purposes. The analysis proposes the development of a B08 ultrasonic motor with two alternative geometries for the electrodes by means of which the piezoelectric layers are actuated.

The predicted performance are then studied in terms of angular velocity, torque and power. The effect of the intensity of the axial load applied in order to maintain the contact and of the presence of teeth along the edge of the stator are also examined.
The working principle of a travelling wave ultrasonic motor

The first basic element of the operation of the motor is the excitation of a travelling wave along the annular direction of the stator which assumes usually the shape of a circular plate with a distribution teeth along the area close to its external edge.

The presence of the travelling wave can be induced by exciting two stationary waves opportune shifted in space and time (3). The frequencies of these waves are usually chosen among the resonant ones with the purpose of enhancing the vibrating response. For the annular plates two eigenmodes with the same natural frequencies are usually chosen for obtaining the travelling wave. A natural bending mode of the plate with \( n \) nodal diameters and \( m \) nodal circles will be denoted by \( B_{nm} \). The same is true for the motor which usually borrows the name from the mode excited in the stator in the form of a travelling wave.

The kinematics of the annular plate in presence of the travelling wave is such that (8) the points at the top and bottom surface (or the corresponding tooth) undergo an elliptic motion with the instantaneous velocity described in figure 1. This vibration pattern of the stator can be used for producing a rotary motion in another plate in friction contact with the stator. Of course some axial load in the direction normal to the plates needs to be applied to maintain the contact. Moreover the contact with the top edge point should be maintained only for the time interval during which the local elliptic motion has a component along the direction of the expected rotation of the rotor.

The angular velocity that can be obtained from the motion at ultrasonic frequencies of the stator can be estimated as four orders of magnitude lower than the exciting frequencies. This will allow the possibility of exciting resonant frequencies of the order of 10 kHz obtaining low angular velocities, which are interesting for many practical space applications.

3 The piezoelectric forcing

The generation of the travelling wave in the stator is provided to the motor by the excitation of a piezoelectric actuation mechanism. In fig. 2 the geometry of the stator is illustrated. The annular plate is constructed by assembling to a metal substrate two piezoelectric wafers. The piezoelectric
The piezoelectric wafers are covered by two groups of electrodes A and B, separated by two sectors which are not covered by any. Each group shows the presence of small subsectors, denoted by "+" or "-" where the polarisation of the piezoelectric substrate is opposite in sign. This will generate a distribution of bending moments in the plate which will induce, for each group of electrodes, one of the two stationary waves which are needed to produce the travelling one (8). The presence of the area C not covered by electrodes will create the necessary shift in space, while the area D is in connection with the other side of the wafer and assures the reference level to the potential at the opposite side of the piezoelectric wafer.

4 Preliminary design and analysis of a Bo8 motor

In this section a possible eight-wavelength motor is proposed for attaining performances of the order of 1 Nm for the torque at relatively low angular speed. This order of magnitude is considered as a good requirement for possible pointing and deployment motors for parabolic antennas mounted on telecommunication satellites.

The analysis was conducted based on the work by Hagood (8), which accounts for an accurate modelling of the friction interface between the stator and the rotor. The effect of the motion of the rotor on the vibration of the stator was also accounted for.

Two alternative patterns of the electrode geometry are proposed. The first one corresponds to the case of a Bo8 travelling wave (fig.4) of the classical distribution illustrated in the previous section and proposed in (8) for a Bo4 motor. In this case the two piezoelectric wafers have the same geometry of electrodes except for the sign which is the opposite, which creates a pure out-of-plane behaviour of the stator. In this kind of geometry (Type I, fig.5), every wafer excites both the stationary waves which are needed for producing the travelling one. In the second proposed case (Type II, fig.6) the electrodes cover completely the surface of the wafer, apparently with an absence of the shift in space. This is obtained by shifting the bottom wafer with respect to the top one. In fact in this case each wafer will excite one stationary wave only. One possible drawback of this solution (not examined in the simulations proposed in this paper) is the induction of a membrane vibration as well, with possible loss of efficiency.
5 Performances

The performances of the motor are illustrated in some diagrams the first of which (fig. 7) shows the values of the angular velocity as a function of the obtained torque for type I and type II motors. In fig. 8 the same diagram is obtained with a reduction of 20% of the axial normal load with respect to the case of fig. 7. From both diagrams the order of magnitude of the expected torque is almost reached for the low angular velocity required. In both cases the second type of vibrating mechanism seems to be more efficient.

In fig. 9 the effect of the presence of teeth disposed along the edge of the plate is shown for several heights of teeth as compared to the thickness of the passive substrate. The kinematic effect of teeth can be explained as the one of a rigid link between the (deformable) plate and the contact point on the rotor. In practice the elliptic motion of the contact point will be transformed accordingly. The most significant effect illustrated in the picture is a notable increase of angular velocity. In fig. 10 the performances of the motor are described in terms of power as a function of torque for different heights of the teeth.

6 Conclusions

A preliminary design and analysis of a B08 ultrasonic motor was performed based on a modelling approach proposed in the open literature for B04 motors. Two different mechanisms of excitation were also studied and compared. The analysis has shown that performance indices very close to the design requirement, established for some space applications concerning deployment and pointing mechanisms, can be reached by the proposed motor.

Acknowledgements

The financial contribution of ASI (Italian Space Agency), contract n. ARS-96-19, and of CNR (National Research Council), research contract n. 96.02342.07, is gratefully acknowledged. The authors would like to thank Prof. R. Barboni for his support and for the useful discussions.
References


Figure 1. Principle of operation of a travelling wave ultrasonic motor

Figure 2. Assemblage of the stator (piezoelectric wafers and metal substrate)

Figure 3. Covering electrodes pattern of piezoelectric wafers
Figure 4. Bos modeshape

Type I: upper piezoelectric wafer  Type II: upper piezoelectric wafer

Type I: lower piezoelectric wafer  Type II: lower piezoelectric wafer

Figure 5. Electrodes for Type I  Figure 6. Electrodes for Type II
Figure 7. Angular velocity-torque diagrams for the proposed motor for Type I and Type II motors.

Figure 8. Same as figure 6 with a reduction of 20% of the axial load.
Figure 9. Angular velocity-torque diagram for different teeth heights $h'$ (Type I)

Figure 10. Power-torque diagram for different teeth heights $h'$ (Type I)