Ultrasonics 54 (2014) 1610–1619

Contents lists available at ScienceDirect

Ultrasonics

journal homepage: www.elsevier.com/locate/ultras

A curved ultrasonic actuator optimized for spherical motors: Design and experiments

Edouard Leroy *, José Lozada, Moustapha Hafez

CEA, LIST, Sensorial and Ambient Interfaces Laboratory, 91191 Gif-sur-Yvette CEDEX, France

ARTICLE INFO

Article history:
Received 20 February 2014
Received in revised form 19 March 2014
Accepted 23 March 2014
Available online 1 April 2014

Keywords:
Curved actuators
Multi-degree-of-freedom
Ultrasonic
Piezoelectric
Modal analysis

ABSTRACT

Multi-degree-of-freedom angular actuators are commonly used in numerous mechatronic areas such as omnidirectional robots, robot articulations or inertially stabilized platforms. The conventional method to design these devices consists in placing multiple actuators in parallel or series using gimbals which are bulky and difficult to miniaturize. Motors using a spherical rotor are interesting for miniature multidegree-of-freedom actuators. In this paper, a new actuator is proposed. It is based on a curved piezoelectric element which has its inner contact surface adapted to the diameter of the rotor. This adaptation allows to build spherical motors with a fully constrained rotor and without a need for additional guiding system. The work presents a design methodology based on modal finite element analysis. A methodology for mode selection is proposed and a sensitivity analysis of the final geometry to uncertainties and added masses is discussed. Finally, experimental results that validate the actuator concept on a single degree-of-freedom ultrasonic motor set-up are presented.

1. Introduction

Ultrasonic motors are devices that convert ultrasonic vibrations into a continuous motion of a rotary or linear rotor. They offer several advantages as compared to electromagnetic motors that make them particularly suitable for the fabrication of miniature actuators. Their working principle, based on friction forces offers tunable speed/torque capabilities and built-in guidance that limits the required number of mechanical parts and increases their potential for miniaturization.

The use of friction forces is interesting for the design of multidegree-of-freedom actuators. Spherical motors which can move a load in the three angular directions of space are suitable for application in mechatronic devices using optical components such as mirrors or cameras. The use of a spherical rotor reduces the inertia and increases the dynamic capabilities of the actuator while providing a compact motor design. This paper proposes a new actuator for spherical motors. The proposed ultrasonic actuator is based on an adaptation of the contact surface to a spherical rotor, offering improved stress distribution and rotor guidance as compared to existing tip-based ultrasonic motors. The presented work is divided into four different parts. First, the actuator concept is presented and a design method based on modal analysis is proposed. The next part is dedicated to the sensitivity of the geometry to perturbations. The last section presents the experimental results of the actuator.

2. Actuator concept

Spherical ultrasonic motors found in literature can be classified into two main categories:

- Single-stator ultrasonic spherical motors: These motors are based on the generation of several different vibrations in a single mechanical part. Their monolithic design is adapted to the manufacturing of miniature actuators while coupling between the different vibration modes make the direction of rotation difficult to control. Multiple examples of single-stator ultrasonic spherical motor are found in literature. Rogers [1] presents a motor with a 350 μm in diameter rotor that uses multiple vibrations modes of a cylinder to actuate the motor. Zhang et al. [2] base their prototype also on vibration modes of a cylinder but they use the association of a non-resonant and a resonant vibration resulting in more flexibility in the actuator structure. Tjeung et al. [3] propose a motor that uses surface acoustic waves in a single stator to actuate a sphere. Lu et al. [4] designed a spherical motor based on the vibration modes of a disk-like structure.

---

* Corresponding author. Tel.: +33 (0)1 69 08 01 78.
E-mail addresses: edouard.leroy@cea.fr (E. Leroy), jose.lozada@cea.fr (J. Lozada), moustapha.hafez@cea.fr (M. Hafez).

http://dx.doi.org/10.1016/j.ultras.2014.03.009
0041-624X/

- Multi-stator ultrasonic spherical motors: These motors associate three or more mechanical vibrators in parallel. They require an assembly of the different parts and are not suited to miniaturization below the centimeter scale. On the other hand, the use of independent parts limits the coupling of vibrations and offer numerous possibilities for the stator design. Examples of single-stator ultrasonic spherical motors include an association of multiple traveling wave motor proposed by Hoshina et al. [5], a spherical motor based on four asymmetric standing wave actuator described by Shen and Huang [6] and a motor combining multiple standing waves in four individual plates presented by Otokawa et al. [7].

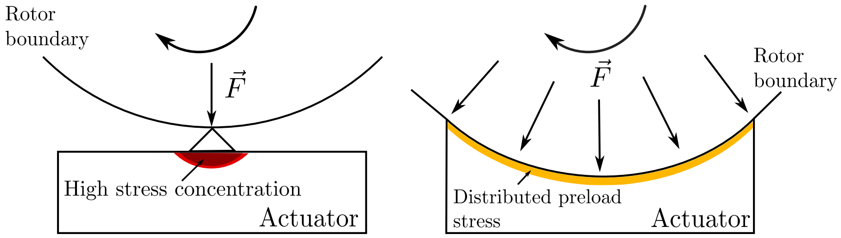
In this paper, a multi-stator configuration is proposed. It provides a high versatility in the actuator geometry. Although a traveling wave design such as proposed in [5] offers a built-in rotor guidance, it is difficult to build a compact system with this approach. On the other hand, standing wave prototypes such as presented in [6] are interesting since they offer great compactness and ability to be miniaturized. One limitation is the rotor guidance that requires additional mechanical parts and make the actuator difficult to integrate. A substantial improvement would be the design of a standing wave ultrasonic actuator that allows good miniaturization and compactness while providing an excellent rotor guidance and easy integration.

Since ultrasonic actuators are friction-based actuators, they are subjected to wear and stresses. The common use of friction tips as contact transmission mechanism in standing wave linear actuators generates localized stresses around the friction head and therefore causes wear of the contact layer. An enlarged contact area could be interesting to obtain a better pressure distribution and reduced wear of the contact layer (Fig. 1a). In addition, this increased area could also be used to improve rotor guidance and to offer a completely constrained sphere similarly to the concept used in radial-bending single-stator motors [8,4]. A fully constrained rotor can be obtained by the association of three or more actuators as shown in Fig. 1b. A curved contact surface of the same radius as the rotor is proposed for our application.

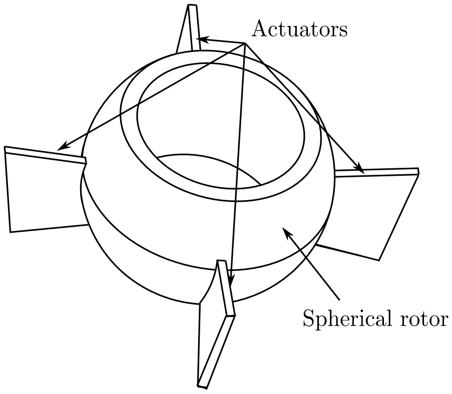
Two major working principles can be used to drive a rotor from standing waves:

- Single-mode asymmetric actuation: A single vibration mode of a structure is excited asymmetrically. This causes the formation of linear oblique motions at the interface that drive the rotor. Inversion of the asymmetry causes reverse motion of the rotor. An example of single-mode asymmetric actuation is the PI Line motor [9].
- Multi-mode actuation: Two different modes of a structure are excited at the same frequency with a temporal phase shift in order to generate elliptical movements at the interface. A change in the phase shift causes reversed motion.

An extended contact surface for the actuator implies the interaction of multiple friction forces along the stator/rotor interface. Although these interactions can be constructive, some of the generated forces could also act against each other causing a reduction in the actuator efficiency. To our knowledge, only few literature has discussed the influence of the contact extent on standing wave ultrasonic actuators. Spanner and Koc [10] discussed briefly the use of an extended contact surface on an asymmetric single-mode actuator. However, the use of a single vibration resulted in non-constructive movements that limited the performance. Lu et al. [11] developed a multi-mode actuator with several contact points at the interface. Proper operation of the motor is reported although no explicit comparison with a single contact point motor is made. The use of a multi-mode actuation principle presents an improved control over the trajectories produced at the interface that could be used to produce constructive motions. In this work, it is proposed to use a combination of two vibration modes as the working principle for the developed actuator.



(a) Reduction of stress concentration.



(b) Fully constrained spherical rotor.

Fig. 1. Expected improvements using an extended contact area for the ultrasonic actuator.