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Rotary Ultrasonic Motors: Daimler-Benz AWM 90–X TWUSM motor, Experimental and Simulation mechanical characteristics

Rotary ultrasonic motors have now been investigated for several years. Their key features are high thrust forces related to their volume and good position-accuracy. This study is consisted by two main parts. In the first we describe the development of the structure and working principle of the piezoelectric motors. In second we present Daimler –Benz AWM90-X Motor as technical example of ultrasonic motor by their data information's delivered by the manufacturer and as simulation of the implementation of functional mathematical model on Matlab/Simulink software results. Results of the simulation are validated using the measurements made by other researchers on traveling wave piezoelectric motor AWM90-X Daimler-Benz type and a prototype USM (AWM-90).

Keywords: Rotary Ultrasonic motor, Traveling Wave, Daimler –Benz AWM90-X Motor, Mathematical Model.

1. Introduction

The first scientific document concerning piezoelectric motors has been applied in 1942**.** It proposes a motor that is based on piezoelectric excited vibrations which should be transformed to rotary motion by gear wheel mechanism. After progresses in material science and power electronics first rotary and later the linear ones have been developed in the 1970s. Their operating principle is based on piezoelectric actuators that convert electric energy to mechanical energy in the form of vibrations of an elastic body [1- 2]. This body is excited by the inverse piezoelectric effect in such a manner that points of its surface perform elliptic motions with a frequency in the ultrasonic range. Another body is pressed beside the vibrating body by a static normal force F_N and thus the microscopic small vibrations are transformed to continuous motion by friction forces [3]. Based on this operating principle many different types of ultrasonic piezoelectric motors have been developed. Their main advantages over the conventional electromagnetic devices are:

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

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These properties make ultrasonic motors suitable to a direct-drive mechanism. Today ultrasonic piezoelectric motors are used in applications where in their characteristic advantages balance their costs, which are still too high for high volume applications, like robotic, medical, space and automotive applications [8].

In the following of study, one of commercial ultrasonic motors and prototypes with outstanding operational characteristics, the AWM-X 90 by Daimler-Benz will be presented. We start in this paper from detailing its characteristics and application requirements. The second section one specifies its behavior simulation result related to its features, implemented on the software MATLAB / SIMULINK [9].

The third section of study include a comparison between the experimental results of Daimler–Benz AWM90 Motor, and theoretical simulation study realized by our work group [9], which show how the motor-characteristics can be adjusted for a particular task by choosing appropriate operating parameters like amplitude and frequency of the electrical excitation or forces between stator and moving part [10-11].

2. Ultrasonic Motor

Several types of piezoelectric ultrasonic motors have been suggested and designed in the last 25 years [12-13]. The large family of USMs can be categorized by various criteria: based on their functionality into two types, linear and rotary motor [14], also, by the exploitation of the piezoelectric material to adjust the propagation of its vibration wave in the static part of the USM motors (stator). With this classification, standing wave and traveling wave USMs can be identified. Following to the advantages and various applications of rotary type ultrasonic motors [15], and in particularly the traveling wave ones, compared to the other types of USMs, have attracted more research attention to them [16-17].

2.1. Principal of Operation of Rotary Traveling Wave Ultrasonic Motor

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

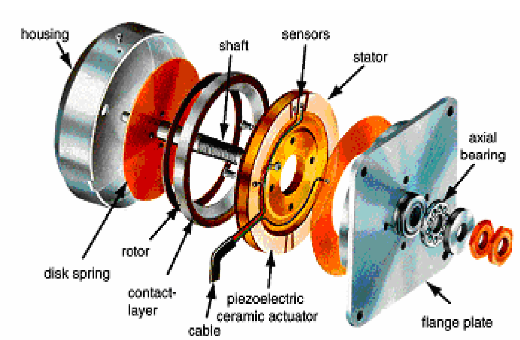


Fig. 1; An exploded view of a typical traveling wave ultrasonic motor

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 piezoceramic ring. The pizoceramic ring is bonded under the elastic body. It has the function of exciting traveling bending waves and is shown in Fig. 2.

The piezoceramic 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 90^0 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 piezoceramic 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.

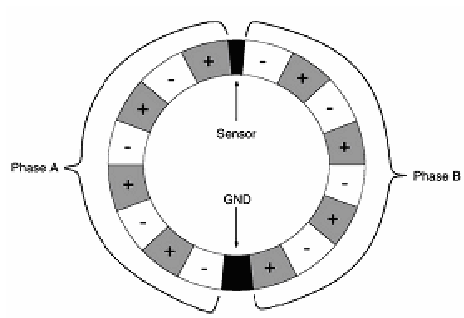


Fig. 2: The piezoceramic ring of the experimental ultrasonic motor.

2.2. Forces Action in Traveling Wave Rotary Ultrasonic Motor

In the interface part between stator and rotor we find the truth source of displacement in the rotor. Since this later is fixed by means of a normal force F_N on the surface of the stator, and in contact zone, the friction forces appear [11]. F_N force has as role to maintain the holding torque without supply, and the friction ones ensure transmission of horizontal movement of external point of the stator, based on the vibration of the piezociramic element, into traction forces on rotor part [10]. The effect of traction forces is accompanied by the effects of the feedback forces which are made by the axial displacement of the stator and the reaction of the interface (rotor/stator).

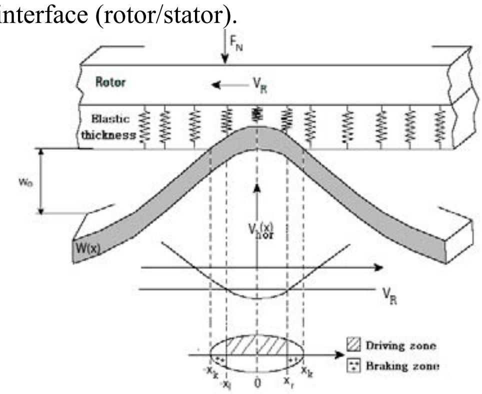


Fig.3: Drive of the traveling wave piezoelectric motor by the force of friction

In the layer of contact the stator creates normal pressure along the zone of contact. The line of distribution of force along the zone of contact is:

$$\mathrm{f}_z = c_N \cdot \Delta \mathrm{W} = c_N \cdot \mathrm{W}_0 \cdot (\cos(k\tilde{x}) - \cos(kx_k)) \qquad (1)$$

Where x_k is the half of length value of the contact surface, $\tilde{x}$ is the new coordinate system moving with traveling wave., W_0 is Amplitude of the traveling wave n and c_N is the equivalent rigidity of the contact layer .

The overlapping between the stator and the rotor, and the forces details in the stator-rotor interface [10- 11], is showed in Fig. 3.

The normal force of the working rotor can be calculated corresponding to the contact zone:

$$F_n = n \int_{-X_K}^{X_K} f_Z(\tilde{x})\, d\tilde{x} \qquad (2)$$

Where n represents the peaks number of the wave.

The friction force which actuates the rotor can be calculated as follows:

$$\mathrm{F}_{\mathrm{antr}} = \mathrm{n}\mu \int_{-\mathrm{x}_k}^{\mathrm{x}_k} \mathrm{sign}(\mathrm{v}_{\mathrm{hor}}(\tilde{x}) - \mathrm{v}_R) \cdot \mathrm{f}_z(\tilde{x}) d\tilde{x} \qquad (3)$$

The feedback effect in the interface (stator/rotor) is determined by the tangential and normal feedback forces:

- Feedback tangential forces:

$$F_T = -\mathrm{n}\mu a \int_{-\mathrm{x}_k}^{\mathrm{x}_k} \frac{\partial \Phi_x^T}{\partial x} \mathrm{sign}(\mathrm{v}_{\mathrm{hor}}(\tilde{x}) - \mathrm{v}_R) \cdot \mathrm{f}_z(\tilde{x}) d\tilde{x} \qquad (4)$$

- Feedback normal forces:

$$F_{Tnorm} = -n \int_{-\mathrm{x}_k}^{\mathrm{x}_k} \Phi_x^T\ \mathrm{f}_z(\tilde{x}) d\tilde{x} \qquad (5)$$

With mathematical simplification vector:

$$\Phi_x^T = \begin{bmatrix} \sin(kx) & \cos(kx) \end{bmatrix} \qquad (6)$$

3. Daimler –Benz AWM 90 Motor

In this section we present the Daimler–Benz ultrasonic motor AWM90, this type of motor is classed in the categories of traveling wave ultrasonic motor. Our work groups have realized a functional simulation on Matlab/Silmulink environment [9-10], based on a refinement of mathematical model proposed by [21]. The Fig. 4 represents dimension description of Daimler-Benz ultrasonic motor AWM90-X.

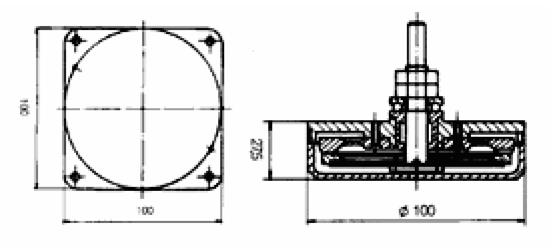


Fig.4: Dimension description of Daimler-Benz AWM90 traveling wave motor

For validation of the model, measurements on an actual motor have to be performed, and simulation results have to be compared with the measurements made by other researchers on traveling wave piezoelectric motor AWM90-X Daimler-Benz type [21] and a prototype USM (AWM-90) [22].

3.1. Measurements Mechanical Characteristics

In order to give to the studied ultrasonic motor a practical use, application and a good technical description, the mechanical characteristic (torque-speed correspondence) must be performed by experimental measurements.

3.1.1 Test of First Validation Rest in Experimental Data

For Daimler-Benz AWM90-X motor the mechanical characteristic is evaluated by Forschungs institute in Frankfurt [21], these measurements represent validation support for the simulation results of our realized implementation [9].

One of test bench for measurement of torque-speed mechanical chrematistic of traveling wave motors is presented in the Fig.5, taken from Lummer's work [23].

The table-1 gathers experimental values for some point's torque-speed correspondence characteristic.

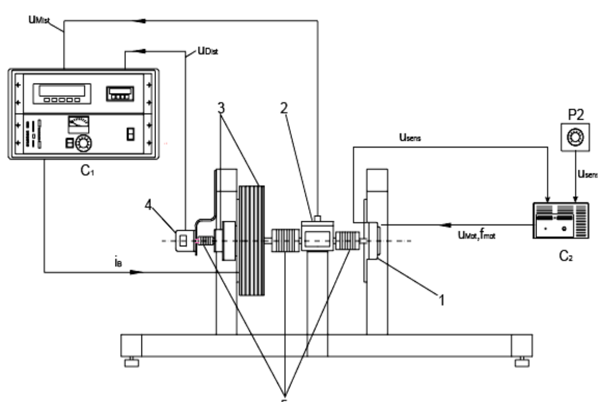


Fig.5: Working principle and experiment system of ultrasonic motor : (a) Test bench for measurement of speed-torque curves of traveling wave motors (1) Traveling wave; (2) Torque sensor; (3) Magnetic powder brakes; (4) Incremental optical encoder; (5) Metal clutch.

Table1: Measured and Simulated Speed-Torque Characteristics of the AWM90-X Motor with Various Loads [21]

Torque [Nm]	Rotor speed [rpm]	Rotor speed [rpm] measure 1	Rotor speed [rpm] measure 2
0	45.6	53	*
0.25	44.52	44.5	*
0.375	43.96	44	*
0.75	42.1	41	45.5
1.2	39.6	42	*
1.25	39.3	39	39.5
1.4	38.4	39.7	*
2.06	34	33.5	*
2.25	32.58	34	*
2.75	28.53	29	31.5
2.875	27.43	27	*
3.25	23.864	28.5	*
4.22	12.65	19.8	*
4.25	12.2	20.8	*
4.3	11.5	13	*
4.55	7.9	11.25	*
4.7	5.3	11	*
4.75	4.55	12.5	*
5	0	*	*

3.1.2 Test of Second Validation Rest in Experimental Data

In this section, the experimental measurements made by other researchers [22] on traveling wave piezoelectric motor AWM90 type have been used by Z .Boumous and al [24] in order to confirm the validity of the simulation results. In this recent paper [24], the mathematical model has been improved. The detail of shearing deformation impact has been analyzed.

The table-2 gathers experimental values for some point's torque-speed correspondence chrematistic.

Table2: Measured and Simulated Speed-Torque Characteristics of the AWM90-X Motor with Various Loads [22-24]

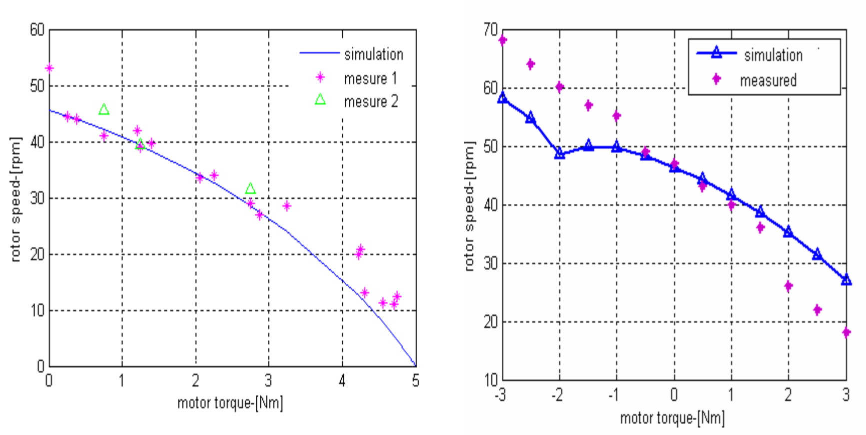
Torque [Nm]	Rotor speed [rpm]	Rotor speed [rpm] measure
-3	58	68
-2.5	54.7	64
-2	48.43	60
-1.5	50	57
-1	49.6	55
-0.5	48.2	49
0	46.34	47
0.5	44.1	43
1	41.5	40
1.5	38.5	36
2	35.1	26
2.5	31.35	22
3	27	18

3.2 Simulation

Considering the parameter values of the motor [21] used for the simulation (see table-3), the steady and transitory state motor is simulated. For the first test, the optimal parameters of the excitation voltages frequency have been tracked and evaluated to 46.65 kHz as frequency, 570 volt as excitation voltages amplitude and the shift between the two excitations $\pi/2$ rd. In the second test the simulation parameters are the same except that the excitation voltages amplitude was 595 Volts. The work carried out in [22] was investigated only the torque range located between -3Nm and 3Nm, because it was to be used in a speed control and the optimization of the performance of the drive system because generally, in this torque range the analytical values of the precedent model are close to measured values, for a torque between 0 and 3 Nm.

The values of speed-torque, was represented in table -1, table -2, Fig.6 ((a), (b)). By comparing the results obtained with the data of the manufacturer [21-22]. We can say that implementation [9] performed, on the software Matlab/Simulink, of refined model reflects the true behavior of the motor. The simulation results compared with experimental measurements are presented in Fig. 6.

On Fig.6 ((a), (b)), (*) represent the points of measurements of the manufacturer, and the solid lines the interpolation ensured by the points extracted from the simulation results. This shift between the measured values and the analytical curve is due to the effect of the temperature of ceramics following friction stator/rotor.



a) **b)**

Fig.6: Measured and simulated speed-torque characteristics of the AWM90-X motor with various loads a) * Gregor Kandare et al.'s measurements, b) * Thomas Schulte et al.'s measurements.

4. 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.

Table3: Parameters of the AWM90-X Motor [21]

Name	Symbol and value
Resistances of entries	$Rp_1 = 5\ \Omega$ $Rp_2 = 5\ \Omega$
Ceramics capacity	$Cp_1 = 7.8e\text{-}9\ F$ $Cp_2 = 7.87e\text{-}9\ F$
Capacity of stator	$Cp_{s1} = 0.42e\text{-}9$ $Cp_{s2} = 0.428e\text{-}9$
Inertia of Rotor	$J_R = 3.4367e\text{-}004\ Kgm^2$
Ray	$R_w = 40.5e\text{-}3\ m$
Effective mass	$m_{eff} = 40.5\ Kg$
Mass of rotor	$m_R = (m_{eff}+22.8+3)*1e\text{-}3\ Kg$
The rigidity of Rotor	$c_R = 300e3\ N/m$
Attenuation of Rotor	$d_R = 50*1e3$ Ns/m
Coefficient of Coulomb of friction	$\mu = 0.21$
The distance enters the points of surface of stator	$a = 4.5e\text{-}3\ m$
Peak of wave numbers	n=11
Frequency of Resonance	Wres2=wres1 wres1=2*pi*43.365*1e3 Hz
Wavelength	$\lambda = 2*pi*R_w/n\ m$
Wave numbers	$k = 2*pi/\lambda$
The rigidity of the zone of contacts	$c_N = 8500*1e6\ N/m^2$
Frequency of Antiresonance	$w_{ant2} = w_{ant1}$ $w_{ant1} = 2*pi*46.65\ e3$ Hz
Modal mass of Stator	$m = 0.082\ Kg$
Report/ratio of transfer	$A1 = (m*C_{p1}*(w_{ant1})^2 - w_{res1})^2))^{1/2}(kgFs^{-2})^{1/2}$ $A2 = (m*C_{p2}*(w_{ant2})^2 - w_{res2})^2))^{1/2}(kgFs^{-2})^{1/2}$
Rigidity of the stator	$c_{S1} = (w_{res1})^2*m\ N/m$ $c_{S2} = (w_{res2})^2*m\ N/m$
Factor of disturbance	$\varepsilon 1 = \varepsilon 2, \varepsilon 1 = 0.02$
Damping ratios	$d_{S2} = d_{S1}$, $d_{S1} = 10\ Ns/m$

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