Research Journal of Applied Sciences, Engineering and Technology 4(20): 3923-3929, 2012
ISSN: 2040-7467
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Submitted: December 20, 2011 Accepted: April 23, 2012 Published: October 15, 2012

Structure Design, Dynamic Simulation and Characteristic Measurement of a Thin-Disc Ultrasonic Actuator

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Abstract: In this study, we constitute and propagate a three-phase reflected wave based on the purpose locations of constraints. The wave configuration could convert electrical energy to actuate the kinematical power for rotating the rotor. Moreover, in mechanical design, the benefits of this novel ultrasonic actuator are the separated design in both of rotors and stators, convenient arrangement in mechanism, manufacturing cost in cheap and simple structures in thin. Since the high rotary speed is closed to 3500 rpm, the motor keeps the potential and developed commercialization in future.

Keywords: ANSYS, piezoelectric buzzer, three-phase eccentric, three-phase symmetric, ultrasonic actuator

INTRODUCTION

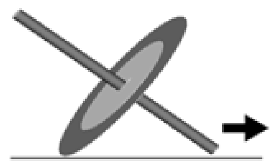
Since technology is developing rapidly, a thin driving device with smaller size, lower noise, huge driving force, good heat dissipation, precise positioning capabilities and the ability to be applicable in 3C products is in dire need of development in our industry now; examples are the thin motor and thin cooling fan (Chen and Ouyang, 2004). The electromagnetic motor has been developed for a long period of time and it has been successfully applied in many related fields. However, there are still some problems that are difficult to overcome, for example, high interference by electromagnetism, fixed size, inability to provide high torque while lower rotating and operating noise, etc. Sashida and Kenjo (1993), Ueha *et al*. (1993), Uchino (1997) and Huang and Huang (2001) Nevertheless, these problems of the electromagnetic motor can be overcame by using an ultrasonic motor or ultrasonic actuator instead because they do not need winding or phase splitting (Uchino, 1998). Therefore, an ultrasonic motor or ultrasonic actuator can be a perfect substitute for the electromagnetic motor in many applications.

Piezoelectric buzzer (Mou and Ouyang, 2004; Yang and Ouyang, 1999) is one kind of product with the simplest structure and cheapest price among the piezoelectric components. It is composed of one layer of piezoelectric membrane and a flexible sheet metal with the characteristics of high coupling factor, high dielectric constant and low quality factor Q (Wu, 1994). The buzzer is principally designed as a buzzer or an acoustic component in the audio-frequency range. The audio source is induced by the vibrating expansion and extraction of the piezoelectric ceramic material, resulting to the stirring air from the flexible sheet metal back-plate. So the metal back-plate has the functionality of signal amplification and this portion is just the difference of the buzzer from the general piezoelectric materials. Thus, it's desired to have the different structural design and vibration analysis according to the metal back-plate of the buzzer; as a result, there'll be a revised thin-disc ultrasonic actuator with the characteristics of high speed and low power consumption.

The buzzer, model OBO-TE41208-26, that we used in this experiment is purchased from OBO INC., Taiwan. The buzzer is mainly designed to work within audio range; therefore, the buzzer should be kept away from the first resonance frequency point ((0.8±0.3) kHz) of the audio range and the second resonance frequency point within ultrasonic frequency range should be selected in order to avoid dissipating or consuming input energy in the process of transferring energy into sound wave (Mou and Ouyang, 2004).

The design of a thin-disc ultrasonic actuator stator is mainly composed of geometric asymmetry (Mou and Ouyang, 2004; Wen *et al*., 2004) metal back-plate of the buzzer that achieves the rotating effect by vibration mode of stator. According to the different structures of the buzzer that the thin-disc ultrasonic actuator can be divided into single-phase thin-disc ultrasonic actuator (abbreviated as 1P-USA), dual-phase thin-disc ultrasonic actuator (2P-USA), three-phase eccentric thin-disc ultrasonic actuator (3P-EUSA) and three-phase symmetric thin-disc ultrasonic actuator (3P-SUSA) and so on.

This study constitutes and propagates a three-phase reflected wave based on the purpose locations of constraints. The wave configuration could convert electrical energy to actuate the kinematical power for rotating the rotor. In addition, in mechanical design, the benefits of this novel ultrasonic actuator are the separated design in both of rotors and stators, convenient arrangement in mechanism, manufacturing cost in cheap and simple structures in thin. Since the high rotary speed



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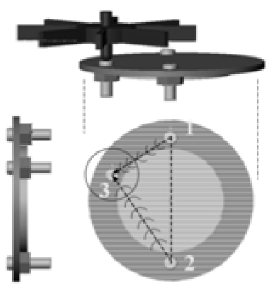

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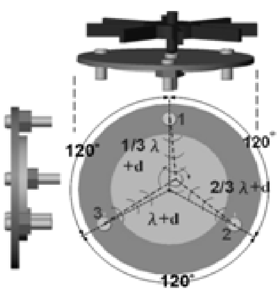

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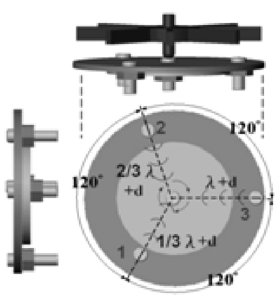


(d)

Fig. 1: The wave illustration and stator structure, (a) 1P-USA, (b) 2P-USA, (c) 3P-EUSA, (d) 3P-SUSA

is closed to 3500 rpm, the motor keeps the potential and developed commercialization in future.

METHODOLOGY

The structure of actuator: The diagram of the 1P-USA is as shown in Fig. 1a (Chen and Ouyang, 2004). When one stick-like mechanism positioned at the center of a buzzer as a rotating shaft, it will form a 1P-USA. Thus, Deformation would result in the shaft-axial extension vibration and edge-radial wing vibration of the piezoelectric buzzer. It could be able to generate a linear movement similar to step-indexing method, while shaft-axial movement extension is large enough to overcome the friction between contact surfaces. However, at the same time, the edge-radial vibration magnitude of metal back-cover metal plate would also make the actuator to rotate. Though the mechanism design and related movement theory of the 1P-USA was quite simple, its linear and angular mixed movement pattern was too difficult to control the movement direction. (This was caused by the ceramic material of the buzzer not able to be polarized in single direction.) Its application would not have high practical value.

At the piezoelectric metal back-plate, three screws with 2 mm diameter are mounted separately at the angle of 60-120-180ºC, respectively and the position of the screw 3 is used to be the driven point of direct contact point, by which it will replace the shaft that pass through the center of the piezoelectric plate in the 1P-USA. Because the screw is a fixed point and it will becomes a reflection point at the progressing of the wave and based on the different distance from screw 1 and 2 to screw 3 separately, so when the progressing waves to screw 1 and 2 along the radical direction and the curve-direction will form a wave with time difference when they arrive the position of screw 3. And the design concept of the 2P-USA is to use this alternative wave to achieve the rotation result on the shaft at the position of screw 3. In Fig. 1b (Chen and Ouyang, 2004), the position of screw 1 and 2 will have the same alternative wave from other two screws, but the measured rotation speeds that we place shaft at the position of screw 1 and 2 are less than the rotation speed that we place the shaft at the position of screw 3, so we can define screw 3 as the driven position of the shaft of the 2P-USA and the meaning named “dual-phase” is that each pulse wave input will have two alternative waves to drive the shaft to rotate. But the different CW or CCW direction of the wave along curve-direction from screw 1 and 2 will affect will influence the rotation direction of the shaft, so the 2P-USA is similar to the 1P-USA and not easy to control the motion of the rotation direction to CW or CCW.

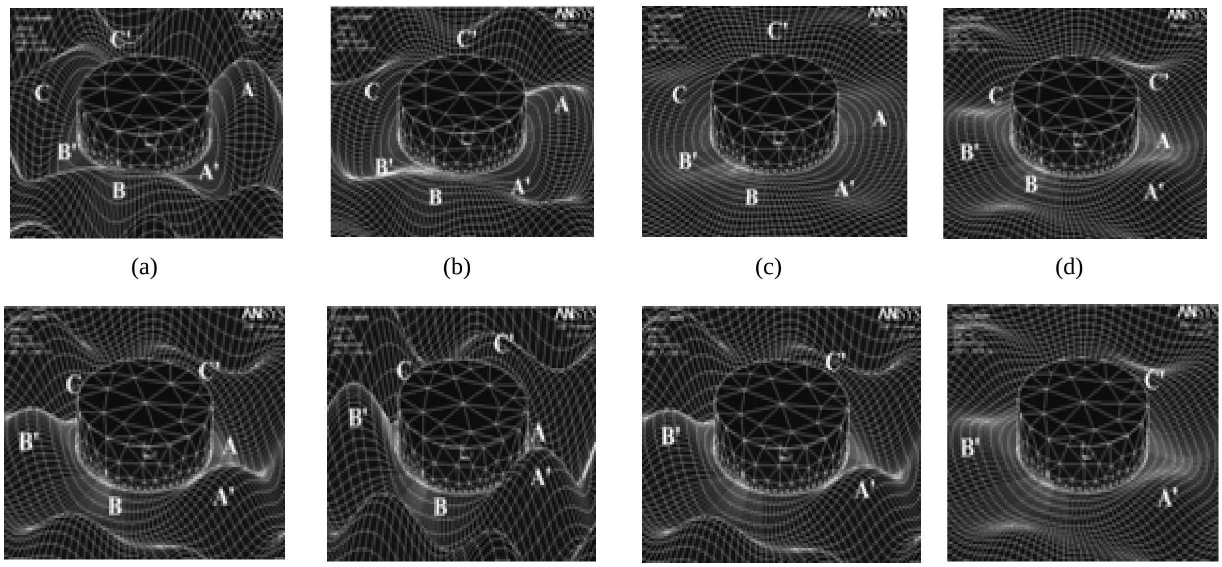
The stator structure and the wave description chart of the 3P-EUSA is as shown in Fig. 1c (Mou and Ouyang, 2004; Wen *et al*., 2004). On the metal back- plate of the buzzer, three screws are separately mounted at the same distance and the same angle of 120-120-120ºC, respectively (as shown in 1, 2, 3 of Fig. 1c), the screw positions is likely to divide the circular plate of the buzzer into three segments (Wen *et al*., 2004; Idogaki *et al*., 1996) and one screw of the same size is also mounted at the eccentric position near the center, this position is used to be the driven position of the shaft. Obviously, the 3P-EUSA is the extension of the 2P-USA. From the description of previous study, at the same pulse signal, three alternative waves are better than two waves. But we also have to consider whether the driven energy of each reflected wave is uniform or not and whether the total driven energy of three-phase waves is greater than two-phase waves or not. Otherwise, it will be helpless to increase the shaft rotation speed and to raise the system stability.

On the 3P-EUSA, the principle of movement is to utilize the reflection point constructed by the three screws' positions located at the metal back plate of the buzzer. It guides the outward energy to return back to the center of the circle. (Because the other designs of the 2P-USA does not separate the buzzer into a symmetrical structure of three equal-angle distances, so there is no mechanism about the energy reflection back to the circle center.) Because the reflection wave generated by the three screws will reach the circle center at the same time stamp, so the three progressing waves at the circle center will not construct an elliptic trace of movement with circulation of driven point. But at this design, even when the three symmetrical energy wares reach at circle center, it will also construct an alternatively progressing three-phase wave due to different travelling distance of three waves and the existence of phase difference (or travelling distance difference) when the reflection waves reach the eccentric point. Finally it could fulfill the purpose of driving the shaft and rotor to rotate.

As shown in Fig. 1c, from the stator structure illustration of the 3P-EUSA, it could be revealed that the outer three screws at the metal back plate to the eccentric screw are screw 3, screw 2 and screw 1 in turn by distance. So when the reflection wave from screw 1 (the nearest position to the eccentric screw) gradually disappears, the followed reflection wave to drive the shaft to rotate is from screw 2. And then it follows the reflection wave from screw 3. In this order the three alternative waves to drive the shaft to rotate are continuously generated, so the rotation direction of this 3P-EUSA is defined after the confirmation of the eccentric screw and it could only rotate toward the uni-direction. In the 3P-EUSA as shown in Fig. 1c (Mou and Ouyang, 2004), the shaft rotation on the point of the eccentric screw is clock-wise. If we want to change the rotation direction to CCW, we could only change to position of eccentric screw by adjusting the distances from the three screws on the metal back-plate to be in the order of screw 1, 2 and 3. Because the 3P-EUSA could rotate in one direction, so it only needs one source to drive the circuit. And because we do not have to cutting the electrodes in the structure and the electrodes are alternative polarization, so the driven voltage is very low, just a little more than ten volts (with benefit in the application of 3C product). It could tremendously simplify the circuit design of traditional ultrasonic motor of actuator (driven by two source and high voltage amplitude of 100-150 V).

The stator structure and the wave description chart of 3P-SUSA are as shown in Fig. 1d (Mou and Ouyang, 2004), which is a modified structure. According to the 3P-EUSA shown in Fig. 1c, because its eccentric position is not easy to be accurately found during manufacturing, this cause that the three segments based on the eccentric position is not completely symmetric at the structure of 120-120-120ºC, therefore, the driven force of the three alternative waves generated by each pulse signal input will have variation of some level. To overcome the above issue, we consider moving the position of the eccentric screw to the right center of the buzzer and we keep the distances of three screws at the metal back-plate to the center position (shaft position) as $\lambda/3+d$, $2\lambda/3+d$ and $\lambda+d$, this is for remaining the traveling distance of one-third wavelength (phase difference of 120ºC). Base on the two modifications, the completely symmetric structure of 120-120-120ºC on the buzzer could be easily designed.

ANSYS dynamic simulation: In the development history of ultrasonic motor or actuator, because of the large variation in developing the structure-shape and many nonlinear factors which are hardly to predict, such as the tensile effect, wave conduction, electro-mechanical exchange, non-uniformity of material, hysteresis, back-gap, energy dissipation (heat loss), contact abrasion, temperature increase, which are non-linear time-variation physical variables, so we suffer many difficulties in doing the mathematical description and derivation on the systems. To effectively analyze problems of the structure deformation by external force and the dynamic vibration behavior on the system, usually some special assumption are established to simplify original system to become linear system, so that the mathematical ODE or PDE could be used to describe and find the solution. And the parameter setting of the boundary condition and the initial condition and the assumption of material uniformity are often given and based on a special condition that the analytical solution could be found. Its result could not effectively reflect the true situation of real problem. For some simple engineer issues or systems, maybe there is not too much inaccuracy generated by this approximate solution of simplified assumption. (At certain level, it may have the accuracy.) But for most real systems that are complicated, un-regular and difficult to be described by mathematics, the usage of traditional analytical method will hardly find the actual and accurate solution and often lead to in-correct solution. To solve the complicated system that is difficult to be analyzed on engineering, some numerical analysis methods are introduced to solve this kind of issues and finite element analysis is the often-used numerical analysis method among all. Finite element method is a numerical analysis technique to change the



(a) (b) (c) (d)

(e) (f) (g) (h)

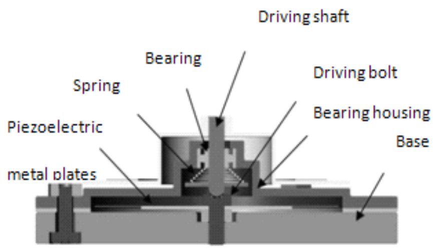
Fig. 2: An ANSYS dynamic simulation conducted nearby a shaft driving point of the 3P-SUSA

continuous system in real engineering to an equivalent discrete system for handling, that is, it separates continuous body to the combination of finite elements. By this kind of combination model, it could analyze, simulate or approach the area the desired solution. Due various kinds of the elements, it could be different composition by different linking method. And because of the different geometric shape and degree of freedom that exist in the elements, so it could be used to solve the engineering issues of high complexity and un-regularity. The most obvious advantage of finite element method is its high flexibility to system geometric shape. In this study, we use ANSYS software as the imitational and analytical tool for dynamical simulation of the thin-dick ultrasonic actuator.

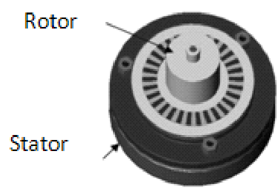
By combining the five pictures of Fig. 2d, e, f, g and h, we could monitor that the first reflection wave marked, B, C already do not have the effect of the effect to drive, the rotation of shaft and the driven-shaft is completely driven by the second reflection wave marked 2, B2, C2 The actuation result has the proportional relation about the sequential increase and decrease of the wave amplitude. For the same reason, the effect of third reflection wave will also has that same result. And from the analysis result of each drawing in Fig. 2, we could know that the rotation-shaft will have the ration at CW direction. And we have to make a description of a special phenomenon: when the first reflection wave has already lost the actuation effect, even it has no capability to drive the shaft to rotate, actually the second reflection wave do not successively continue to drive the shaft to rotate. From the experimental observation about the rotation speed of the shaft, the speed variation does not change dramatically, that is, during the period of driven-loss, the shaft will be supported by the original rotation inertia to achieve the purpose of continuing rotation.

In the dynamic simulation graph shown in Fig. 2a to h, we have following important conclusions: The design of three-phase symmetrical structure and un-equal distance from the three screws to circle will actually generate a three alternatively progressing wave around the shaft driven point of the ultrasonic actuator. And the consistent change of the three phases will form a spin force surround the rotation shaft and finally they drive the rotation shaft to rotate.

Characteristic measurement: About the rotation speed measurement of the structure of the designed 2P-USA, 3P-EUSA and 3P-SUSA, the frequency sweeping of system resistance by using HP 4194A Impedance/Gain-Phase Analyzer should be done before actual measurement. In the experimental progress of rotation speed measurement, the HP 4194A is first used to do the frequency scanning of the resistance, to make sure the approximate position of the system resonance frequency of various types of thin-disc ultrasonic actuator. And then by fine-tuning the frequency variation, for the original system resonance frequency measured by HP 4194A, we can measure the rotation speed at the frequency range with ±1~2 kHz around the frequency and use the driven frequency with maximum rotation speed as the real system resonance frequency of the actuator.



(a)



(b)

Fig. 3: The section of thin-disc ultrasonic actuator prototype

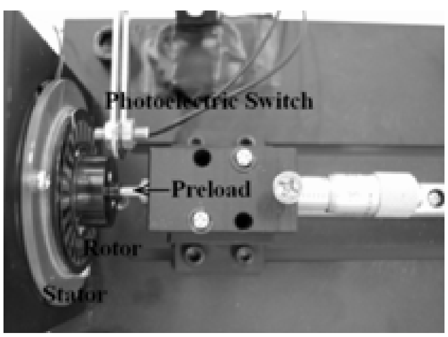


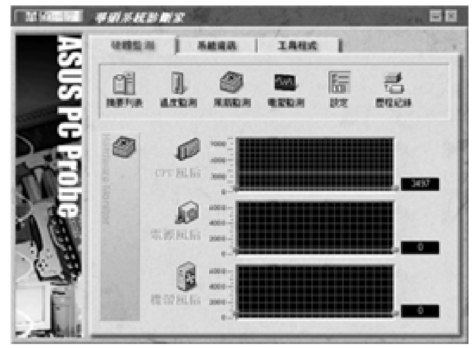
Fig. 4: The photo of an experimental structure for rotation speed measurement

About the speed measurement of various types of thin-disc ultrasonic actuator, we attach the light-reflection plate at its rotor and use OMRON E3X-A11 Photoelectric Switch as the detection device to send and detect the UV light on the light-reflection plate. The pulse signal gained by OMRON E3X-A11 is calculated and shown by the HP 34401A Multimeter and then we can get the actual rotation speed of various types of thin-disc ultrasonic actuator. The prototype structure of thin-disc ultrasonic actuator is shown in Fig. 3 (Chen and Ouyang, 2004) and the photo of experimental structure of rotation speed measurement is shown in Fig. 4 (Chen and Ouyang, 2004).

The comparison of rotation speed of various types of thin-disc ultrasonic actuator is shown in Table 1. The measurement of the rotation speed is based on the input impulse signal which is set as the system resonance frequency in Table 1. The result is got under the condition that the input voltage is 15 V, input current is 0.2 A and rotor-weight is approximately 100 g and preload id 30 gf. About the structure of 2P-USA, 3P-EUSA and 3P-SUSA which are designed in this study, the consumption power is about 1.5 W.

Table 1: The rotation speed to each type of thin-disc ultrasonic actuator

Actuator type	Resonance frequency (kHz)	Rotation speed (rpm)
2P-USA	68.3	1900
3P-EUSA	72.5	3400
3P-SUSA	72.5	3500



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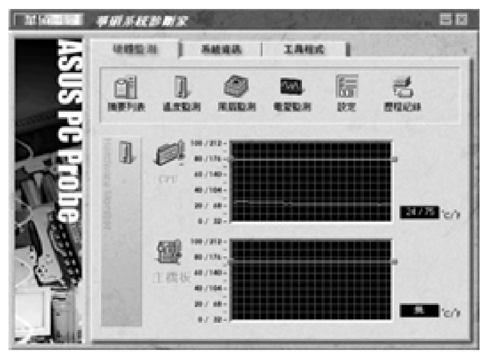
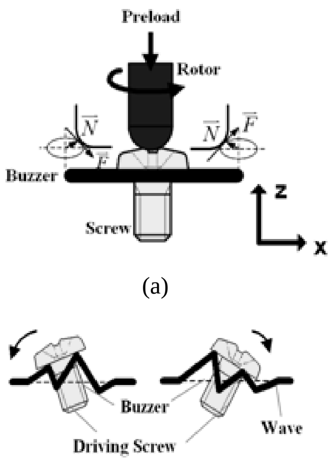


(b)

Fig. 5: (a) The fan rotation speed dynamic curve detected with ASUS PC probe, (b) A dynamic temperature curve detected with ASUS PC probe

By the example of the temperature and rotation test in the ASUS P4S533-MX motherboard of Intel Pentium 4, we find that under normal operation of the computer, the rotation speed of the CPU fan only needs to be kept at 3497 rpm (as shown as the yellow curve in Fig. 5a) to achieve the effect of stabilizing the operation temperature (as shown as the yellow curve in Fig. 5b).

As shown in Fig. 5a, it is the dynamic curve of CPU fan that use the ASUS PC Probe to detect. In the picture, the lower curve is the minimal threshold rotation speed of the CPU fan (program use 600 rpm as default). And as shown in Fig. 5b, the upper curve is the highest temperature threshold value (program use 80ºC/176ºF as default). In this picture, the operation temperature of the CPU is always kept at 24ºC/75ºF which is caused by the



(a)

(b)

Fig. 6: (a) The diagram for the elliptical motion profile of the contact point between rotor and stator of the 3P-SUSA, (b) the diagram for the tilt/deflection behavior of the screw on the rotor driving point

environmental temperature. The designed thin-disc ultrasonic actuator in this study already has the capability to be the rotation speed standard of CPU fan.

RESULTS AND DISCUSSION

At the original design of the thin-disc ultrasonic actuator, the screw position is considered as the completely fix point, but if we do the ANSYS dynamic behavior simulation and analysis about the screw position at the rotation shaft, we will find that it is not completely fix. Here we only consider the screw position at the driven-point, not including the piezoelectric buzzer and

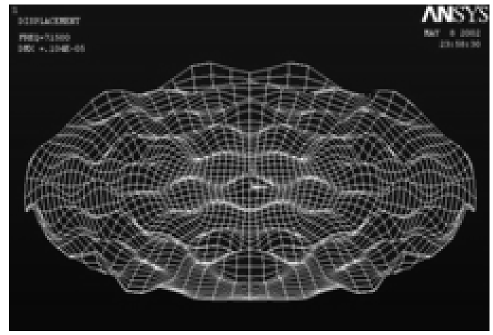
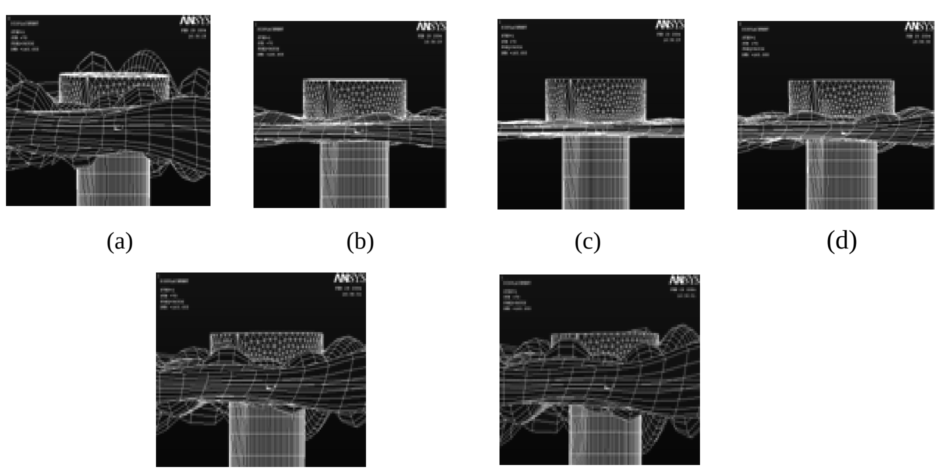


Fig. 7: The simulation diagram of ANSYS dynamic behavior in the buzzer by the converse piezoelectric effect

the three screws at the metal back-plate, it is due to the fact that the screw at the driven-point of rotation shaft is constructed on the piezoelectric ceramic material and the metal back-plate and the piezoelectric ceramic plate is the vibration source of whole the thin-disc ultrasonic actuator and the other three screws are only mounted at the metal back-plate, not directly contact with the piezoelectric ceramic material.

The chart of the elliptical movement trace of the contact point between the stator and the shaft on the 3P-SUSA is as shown in Fig. 6a (Chen and Ouyang, 2004). When the screw of the driven point of the shaft sustains the influence of the reflection wave generated by other three screws on the outer metal back-plate, it will have the behavior of deflection at an angle as shown in Fig. 6b (Chen and Ouyang, 2004). The root cause of this deflection behavior is due to that the created mechanical deformation of the piezoelectric material by the piezoelectric effect will cause the buzzer unable to sustain at plate-state as the plate is static, so it will become the shape of wave-ripple as shown in Fig. 7. Therefore, even



(a) (b) (c) (d)

(f) (g)

Fig. 8: The simulation diagram of ANSYS dynamic behavior in accordance with the tilt/deflection phenomenon of the screw on the rotor driving point of the 3P-SUSA

the driven-point of shaft is firmly locked at the buzzer, but the total piezoelectric plate is continuing deform (wave-ripple), so the screw at driven point will have obvious behavior of deflection at an angle and this will indirectly cause the shaft on the screw have the effect of the same deflection at the same angle.

Fig. 8 a to f shows a serial of dynamic simulation charts of ANSYS, it is an example by the 3P-SUSA. By the dynamic simulation of the screw position at the rotation shaft, we can get the continuous charts about the phenomenon of deflection. From the picture we could clearly see that the screw position of the driven-point on the rotation shaft is not completely fix and the tilt angle at the inner side of the screw will have the trend to gradually go down, but the outer side of the screw will have the trend to gradually go up. And this tilt variation will have periodical deflection behavior along with the wave period. This dynamic simulation result is the completely same as the description in Fig. 6b. At the experimental structure as shown in Fig. 4, the purpose of the design of preloaded mechanism is to provide appropriate contact pressure to the shaft and to avoid the eccentric deflection rotation by the shaft, in order to reduce the rotation speed.

CONCLUSION

In this article, among a series of thin-disc ultrasonic actuators developed from the buzzer, the resulting 3P-SUSA under the continuous design and modification process has not only so many characteristics compared to the traditional electromagnetic motor or actuator as mentioned above but also provide below advantages:

- Simple system architecture and capable of separation design on stator and rotor.
- Small volume with flat outline and quite low price.
- Single phase power driven with low voltage level (around ten or more volts).
- Unnecessary to divide or exchange the direction of polarization.
- High speed and low power consumption.

At the dynamic simulation of the 3P-SUSA, by using the finite element analysis software ANSYS to do the simulation analysis of vibration modes at the area near the shaft-driven point in the structure of the actuator stator, we could clearly know that there are three-phase alternative progressing waves near the shaft-driven point and the waves continue changing and forming a rotation driven-force surrounding the shaft-driven point to achieve the purpose to drive the shaft to rotate. And for the dynamic simulation about the screw position of the shaft-driven point, it shows that the screw position of the shaft-driven point is not totally fix, but has the property of periodical deflection along with the wave cycle.

The 3P-SUSA with the voltage amplitude of 12 V, input current amplitude of 0.2 A, rotor weight of 100 g, preload of 30 gf and consumption power of 1.5 W has the performance of high stable speed of above 3500 rpm, then this rotation speed is enough to compete with the Pentium 4 PC-2.67 GHz CPU fan. Although the 3P-SUSA could only rotation at single direction, but if for consideration of high-speed rotation fan, then the characteristic of single-direction will not impact the aspect of application. The 3P-SUSA in this study has the advantages of low voltage input, low power consumption and high-speed rotation, especially the low voltage up to 12~15 V could easily be obtain from the circuit system of the 3C product, which could dramatically simplify the circuit design and save the space of driving circuit. It has a very great outlook at the future application on the 3C product.

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