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Scientific Research

A Study on the Multiple Composite Piezoelectric Motor

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Abstract

In this study, we major discuss a multiple composite piezoelectric motor. It is made by the base, the multiple composite piezoelectric stator and the preload adjusting module. The multiple composite piezoelectric stator is composed of the base, the first actuating element, the second actuating element and stator. The first actuating element is composed of the longitudinal and the first bending vibration modules, in which the first bending vibration module includes the horizontal and vertical bending vibration modules. And the second actuating element or bending vibration modules, wherein the second actuating element also includes the horizontal and vertical bending vibration modules. In addition, the preload adjusting module includes the limiting element, spring, washer and nut. In order to obtain the best vibration modes of the multiple composite piezoelectric motor, we use the ANSYS code to simulate. And so as to get the better performance and efficiency relate to the previous similar type's motor under the same driving conditions, we try to use different vibration modules or modes to drive the multiple composite piezoelectric motor, including the longitudinal, the first bending, the second bending and the multiple vibration modules or modes by experiments. According to the results of the simulations and experiments, we found that the multiple composite piezoelectric motor has better rotational speed, loading ability and conversion efficiency of direction relate to the previous similar type's motor. Where the maximum rotational speed multiple composite piezoelectric motor is up to 600 rpm under conditions of 180 $V_{p\text{-}p}$ driving voltage, 37.8 kHz driving frequency, 0^0 driving phase angle and 12.1 gw loading. And the maximum loading ability is 2500 gw under conditions of 180 $V_{p\text{-}p}$ driving voltage, 37.8 kHz driving frequency, 0^0 driving phase angle and 6rpm rotational speed.

Keywords

Multiple Composite Piezoelectric Motor (MCPM), Longitudinal Vibration, Bending Vibration, Multiple Vibration, Conversion Efficiency of Direction

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1. Introduction

Since 1898, the piezoelectric motor has been studied by the Ohnishi *et al.*; so far there are about 33 articles of the rotary type piezoelectric motor in the discussion, shown as **Table 1** [1]-[33]. In which the rotational speed and torque of the initially rotary type piezoelectric motor is 64 rpm and 3.92 mNm separately. Until 1993, the rotational speed of the rotary type piezoelectric motor increased dramatically to 1200 rpm. However, it did not increase in torque [3]. When the torque increased from 3.92 mNm to 69 mNm, but the rotational speed is reduced to 30 rpm [5]. If only the torque point of view, the 2004's ultrasonic motor is the highest, wherein the torque is up to 13.2 Nm [13]. And simply to the rotational speed point of view, the 2009's ultrasonic motor is the fastest, where the rotational speed is up to 7500 rpm [21]. Moreover, if we look at loading ability of ultrasonic motor, the 2013's ultrasonic motor is the highest, in which the loading is up to 41 N [31]. If we look at the ratio of the torque with respect to rotational speed, the 2009's piezoelectric linear motor is the highest, wherein the ratio is 1.06 [13]. Furthermore, if we only care about the ratio if the loading ability relative to the rotational, the 2013's ultrasonic motor is the highest, in which the ratio is 0.205 [31].

Table 1. The performance table of the rotary type piezoelectric or ultrasonic motors.

Years	Rotational Speed (rpm)	Torque (Nm) or Loading (N)	References
1898	64	0.00392 Nm	[1]
1989	40	0.00049 Nm	[2]
1993	1200	0.00245 Nm	[3]
1993	64	0.000392 Nm	[4]
1994	30	0.069 Nm	[5]
1995	30	0.069 Nm	[6]
1996	30	0.069 Nm	[7]
1997	880	0.000007 Nm	[8]
1998	880	0.000007 Nm	[9]
1998	680	0.00000067 Nm	[10]
2000	183	0.005 Nm	[11]
2003	430	0.0005 Nm	[12]
2004	12.5	13.2 Nm	[13]
2006	660	0.0000000027 Nm	[14]
2006	300	0.8 Nm	[15]
2007	990	0.0000055 Nm	[16]
2007	450	0.0006 Nm	[17]
2008	840	0.00017 Nm	[18]
2008	247	0.0001 Nm	[19]
2008	90	0.1 Nm	[20]
2009	7,500	0.0003 Nm	[21]
2009	30	1.8 Nm	[22]
2009	4	5 Nm	[23]
2010	187	0.00047 Nm	[24]
2010	15	7.96 Nm	[25]
2011	407	4.9 N	[26]
2011	400	0.0003 Nm	[27]
2011	156	0.75 Nm	[28]
2011	58	0.0095 Nm	[29]
2011	3.6	0.0001 Nm	[30]
2013	200	41 N	[31]
2013	53	5.8 N	[32]
2013	480	23 N	[33]

From the above the piezoelectric or ultrasonic motors [1]-[33], the most important performance is the rotational speed and torque or loading ability separately, followed by the driving voltage and the conversion efficiency of energy or direction, and finally the noise may be generated by the piezoelectric or ultrasonic motor. However, the conversion efficiency of energy or direction and noise of each article has not been mentioned. In this study, we will describe the rotational speed, loading ability, driving conditions in detail, and we will also mention the conversion efficiency of direction and noise of the multiple composite piezoelectric motor.

2. Composition, Operation Principle and Trajectory

In this study, the multiple composite piezoelectric motor is made by the multiple composite piezoelectric stator, rotor, preload adjusting module and shaft, shown as **Figures 1-3**. In which the multiple composite piezoelectric stator is composed of the base, the first actuating element, the second actuating element and stator, shown as **Figure 3**. In addition the preload adjusting module includes the limiting element, spring, washer and nut. As for the first actuating element is composed of the longitudinal vibration module and the first bending vibration module (which the first bending vibration module includes the horizontal bending vibration module and the vertical bending vibration modules), shown as **Figures 3-4**. And the second actuating element or bending vibration module (which the second bending vibration module includes the horizontal bending vibration module and the vertical bending vibration modules), shown as **Figure 3** and **Figure 5**. Finally, we can found the motion trajectory or behavior of the multiple composite piezoelectric stator or motor, when we applied different driving voltage, frequency and phase angle to the actuating elements. In particular, we can find an elliptical trajectory occurs at the top or free end of the stator, shown as **Figures 6-7**. The approximate solution of the elliptical trajectory can be expressed as [31] [33]:

$$\left(\frac{u}{U_m}\right)^2+\left(\frac{v}{V_m}\right)^2+\left(\frac{w}{W_m}\right)^2=1. \tag{1}$$

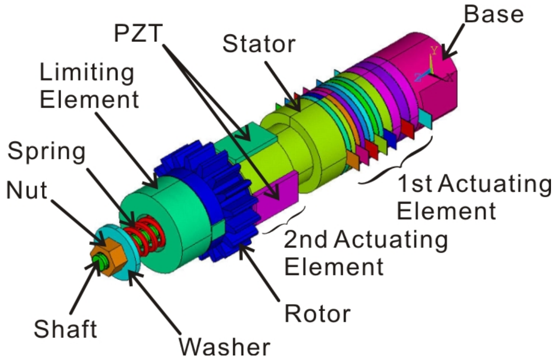

Figure 1. The composition of the multiple composite piezoelectric motor.

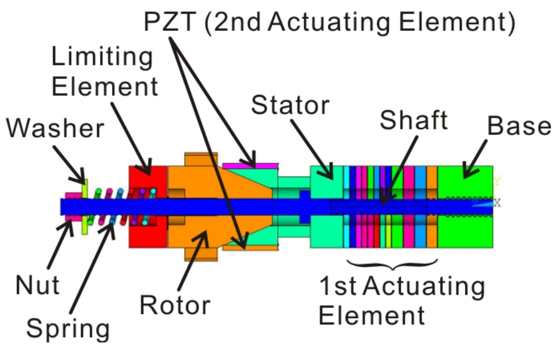

Figure 2. The cutaway view of the multiple composite piezoelectric motor.

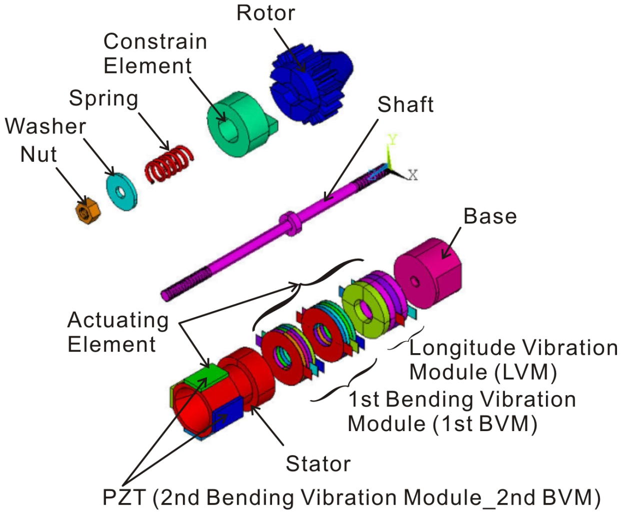

Figure 3. The exploded view of the multiple composite piezoelectric motor.

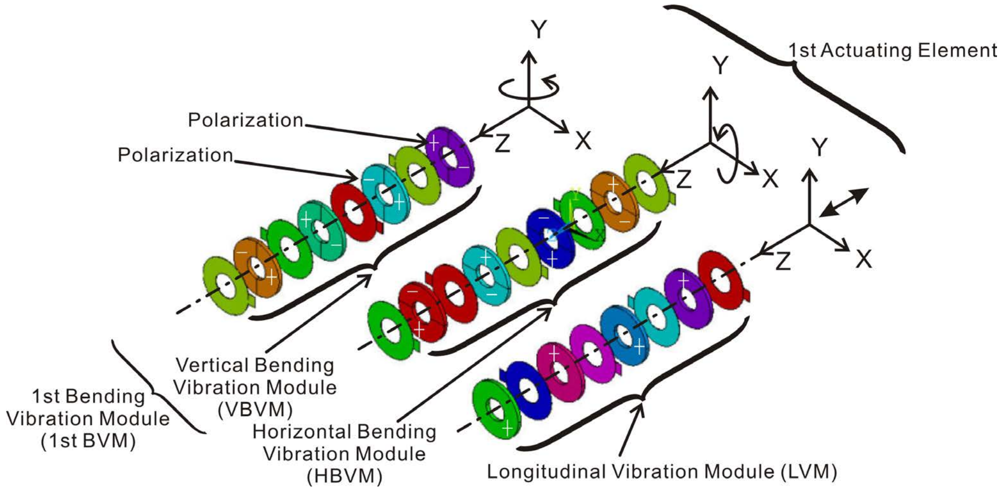

Figure 4. The operation principle of the 1st actuating element (Which it includes the Longitudinal Vibration Module_LVM and 1st Bending Vibration Module_1st BVM).

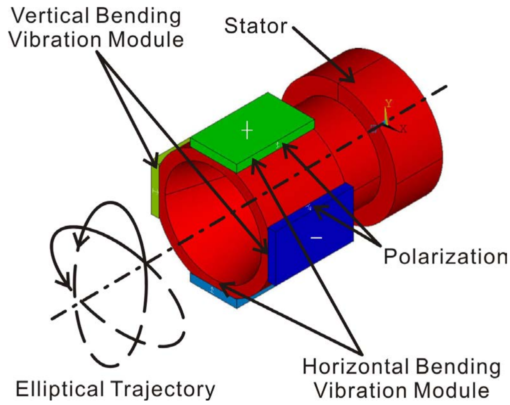

Figure 5. The operation principle of the 2nd actuating element (So called the 2nd Bending Vibration Module_2nd BVM).

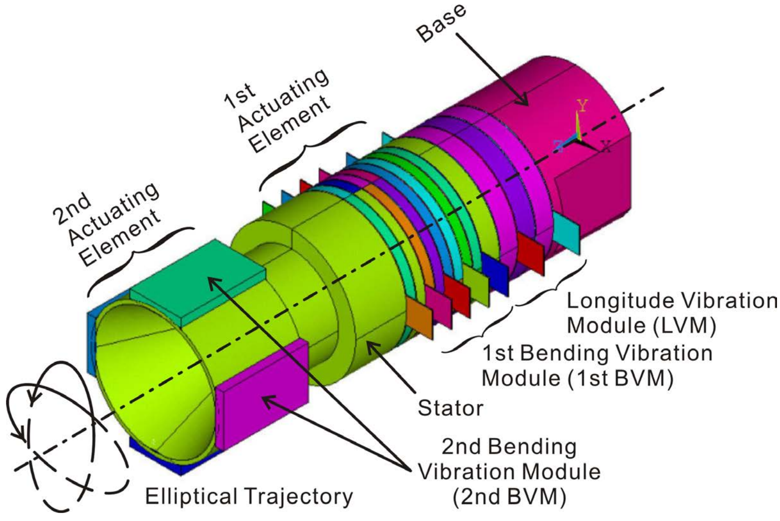

Figure 6. The operation principle of the multiple composite piezoelectric stator.

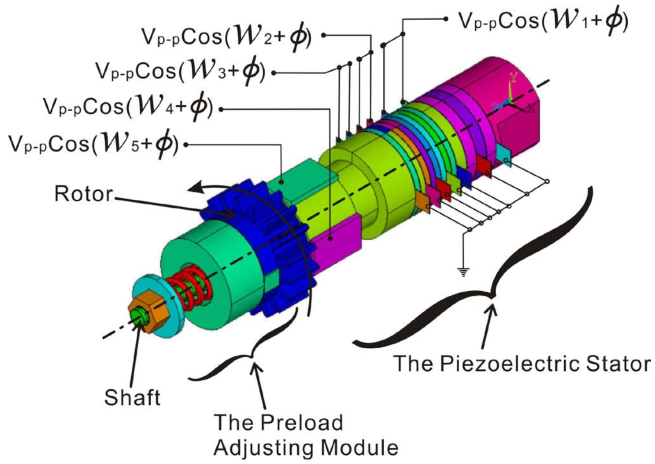

Figure 7. The operation principle of the multiple composite piezoelectric motor.

Where

$$u = U_m \sin\left(\omega_m t + \phi\right) \sin \omega_m t\ . \tag{2}$$

$$v = V_m \cos\left(\omega_m t + \phi\right) \sin \omega_m t\ . \tag{3}$$

$$w = W_m \cos \omega_m t\ . \tag{4}$$

And

$$U_m = c_{xi} d_{3i} V_{p\text{-}p}\ . \tag{5}$$

$$V_m = c_{yi} d_{3i} V_{p\text{-}p}\ . \tag{6}$$

$$W_m = c_{zi} d_{3i} V_{p\text{-}p}\ . \tag{7}$$

where u, v, and w represents the vibration displacement of the horizontal, vertical and longitudinal direction separately. And where U_m, V_m and W_m represents the vibration amplitude in different direction separately. $\omega_m\left(=2\pi f_m\right)$ represents driving angle velocity, where f_m representatives driving frequency. And ϕ driving phase angle (such as 0˚ - 180˚). Where c_{xi}, c_{yi} and c_{zi} represents the constant coefficient tensor in different direction separately, and where the subscript i = 1, 2, 3. d_{3i} represents constant piezoelectric strain of d-form. Such as

d_{31}, d_{32} and d_{33}.

3. Simulation and Experiment

We choose five different sizes of the multiple composite piezoelectric motors or stators to simulate by convention in order to compare with the previous papers [1]-[33] or [31] [33], shown as **Figures 8-9** and **Table 2**. Wherein the base and stator is made of copper and aluminum separately. Which the first actuating element is made of PZT and copper slices. And the second actuating element is directly attached to the side of the stator by the PZT under different polarization direction, shown as **Figure 6**. As for the physical properties of the multiple composite piezoelectric stator is expressed in **Table 3**.

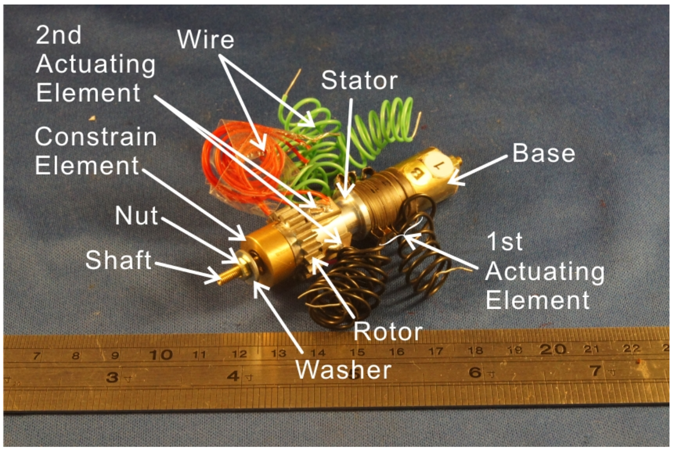

Figure 8. The prototype of the multiple composite piezoelectric motor.

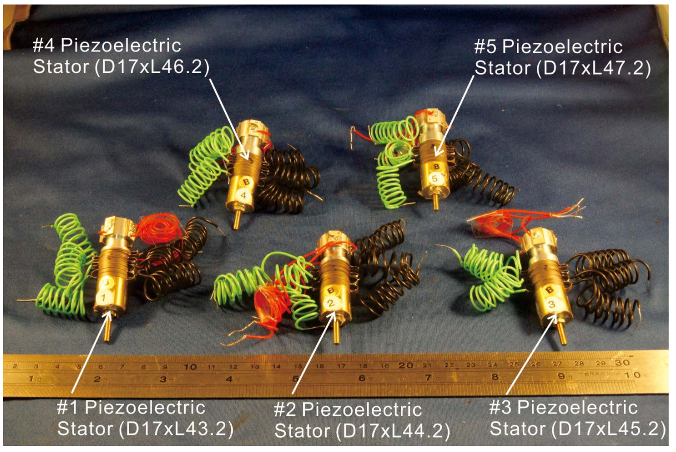

Figure 9. The prototype of the #1 - #5 multiple composite piezoelectric stators.

Table 2. The net weight and size of multiple composite piezoelectric stator.

Type	Net Weight (gw)	Size (mm)
#1	48	D17 × L43.2
#2	50	D17 × L44.2
#3	52	D17 × L45.4
#4	54	D17 × L46.2
#5	56	D17 × L47.2

Table 3. The physical properties of multiple composite piezoelectric stator.

Material	Physical name	Physical Quantities
Actuating Element (Piezoelectric Ceramic Slice_PZT5)	Piezoelectric Strain Constants	d31 = d32 = −274 (pm/V), d33 = 593 (pm/V) d15 = d24 = 741 (pm/V)
	permittivity	ε11 = ε22 = 15.3 (nF/m), ε33 = 15.1 (nF/m)
	Piezoelectric Stress Constants	e31 = e32 = −5.3 (N/Vm), e33 =15.8 (pm/V) e15 = e24 = 12.3 (pm/V)
	Stiffness Constants	c11 = c22 = 120 (GPa), c33 = 111 (GPa) c44 = 30 (GPa), c55 = c66 = 26 (GPa), c12 = c21 = 75.2 (GPa) c13 = c31 = c23 = c32 = 75.1 (GPa)
	Density	ρ = 7700 (kg/m^3)
Stator (6061_Al)	Young's Modulus	E = 73Gpa
	Poisson Ratio	v = 0.33
	Density	ρ = 2700 (kg/m^3)
Base (Copper)	Young's Modulus	E = 117Gpa
	Poisson Ratio	v = 0.30
	Density	ρ = 8900 (kg/m^3)

We use the ANSYS code to simulate in this study. And the simulation procedure includes modeling (show as **Figure 10**), meshing (show as **Figure 11**), solving and post-processing. We choose the element type of solid 98 for all materials in modeling operation process. We choose the number 6 - 10 of smart size for all materials in meshing operation process. The mechanical boundary condition is set to clamped-free. As regards the electrical boundary conditions is set to open circuit (That is V_{in} = 0 or $V_{p\text{-}p}$ = 0.) and closed circuit (That is V_{in} = 100 - 180 $V_{p\text{-}p}$ or $V_{p\text{-}p}$ = 100 - 180 $V_{p\text{-}p}$) for all piezoelectric materials in solving operation process.

In this experiment, we used two sets of the dual channel arbitrary function generator (Model: A-303, AA Lab. Systems Ltd. Co.) and four sets of the power amplifier (Model: AFG-3022, Tektronix Co.) to control or drive the multiple composite piezoelectric motor. In addition, we used the digital tachometer (Model: RM-1501, TES Electrical Electronic Co.) and the sound level meter (Model: TES 1350A, TES Electrical Electronic Co.) to measure the rotational speed and noise of the multiple composite piezoelectric motor separately. Furthermore, we are using the mass or rotor with two different materials to test the loading ability of the multiple composite piezoelectric motor, shown as **Figure 12**.

4. Results and Discussion

According to the results of simulations by the ANSYS code and experiments, we found:

1) The resonance frequency is inversely proportional to the length of the multiple composite piezoelectric stator. Wherein the first resonance mode frequency is 9.174 kHz of the #1 multiple composite piezoelectric stator. And the first resonance mode frequency is 7.565 kHz of the #5 multiple composite piezoelectric stator, shown as **Figure 13**.

2) The maximum deformation is inversely proportional to the length of the multiple composite piezoelectric stator. The maximum deformation and best vibration modes which appear in 38 - 39 kHz or the seventh vibration mode for the #1 - #5 multiple composite piezoelectric stator, shown as **Figures 14-19**.

3) The maximum rotational speed is inversely proportional to the length of the multiple composite piezoelectric motor. The #1 multiple composite piezoelectric motor has a maximum rotational speed of 600 rmp under conditions of 180 $V_{\text{-}p\text{-}}$ driving voltage, 37.8 kHz driving or resonance frequency, 0^0 driving phase angle and 12.1 gw loading. It is 1.25 and 3.0 times of the maximum rotational speed for the rod type ultrasonic motor [31] and the composite type piezoelectric motor [33], shown as **Figure 20**.

4) The noise range is between 60 and 100 dB of the multiple composite piezoelectric motor, where the higher noise appears before 20 kHz. And the noise values are independent of the driving frequency, shown as **Figure 21**.

5) The conversion efficiency of direction of the multiple composite piezoelectric motor is inversely proportional to the length of stator. Wherein the best conversion efficiency of direction is the #1 multiple composite

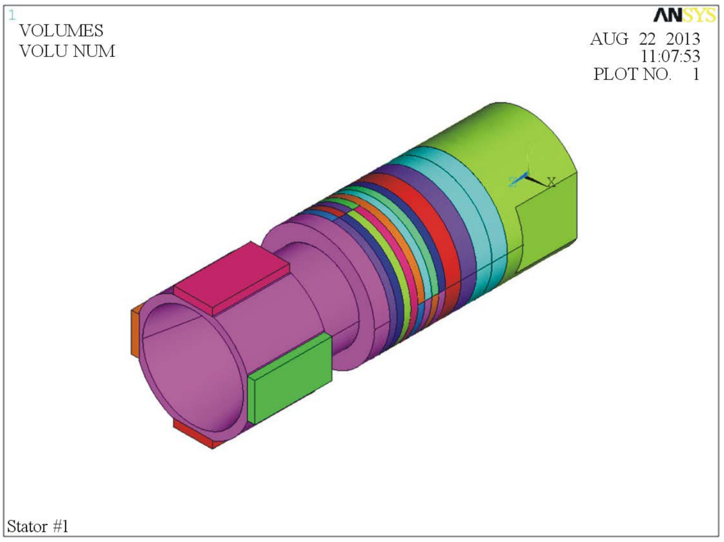

Figure 10. The modeling operation process of the #1 multiple composite piezoelectric stator in the simulation procedure.

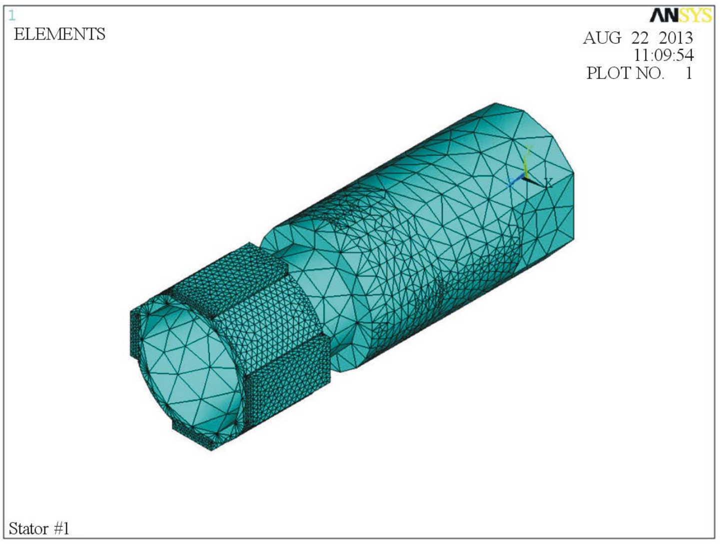

Figure 11. The meshing operation process of the #1 multiple composite piezoelectric stator in the simulation procedure.

piezoelectric motor. In addition, we also the poor conversion efficiency of direction is the rod type ultrasonic motor [31], shown as **Figure 22**.

6) The rotational speed of the multiple composite piezoelectric motor is proportional to the driving voltage. On average, the rotational speed of the multiple composite piezoelectric motor is higher than the rod type ultrasonic motor and the composite type piezoelectric motor, shown as **Figure 23**. Moreover, according to the experimental results shown in **Figure 23**, we can find a linear relationship between rotational speed and driving voltage. As:

$$y_i = a_i x + b_i. \tag{8}$$

where x, y represents the driving voltage and rotational speed respectively. In addition, the constants of a_i, b_i represent the slope and intercept of different type piezoelectric motors, shown as **Table 4**.

7) And rotational speed of the multiple composite piezoelectric motor is inversely proportional to the loading ability under the same driving conditions. Which has a maximum loading ability is the #1 multiple composite

piezoelectric motor which is 2500 gw, shown as **Figure 24**. Where the loading ability of the multiple composite piezoelectric motor is 1.68 and 1.08 times of the maximum rotational speed for the rod type ultrasonic motor and the composite type piezoelectric motor.

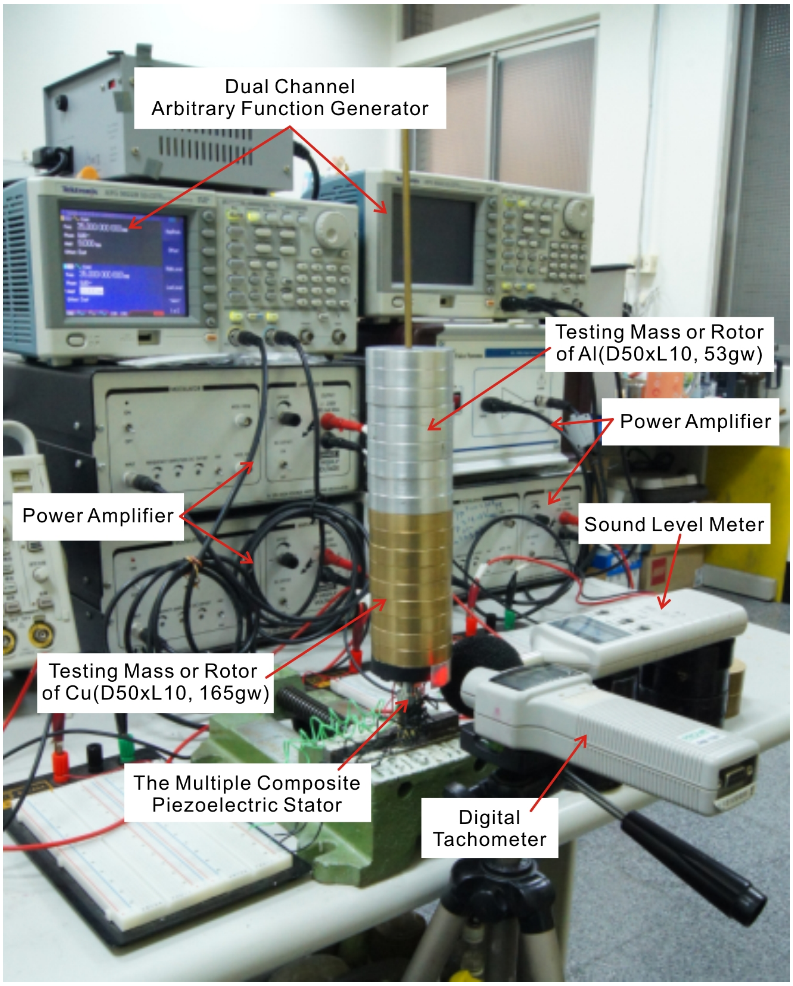

Figure 12. The experimental structure of the multiple composite piezoelectric stator.

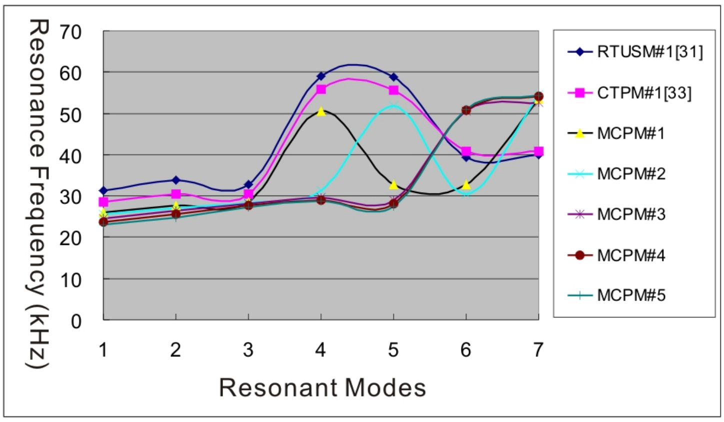

Figure 13. The driving frequency relative to the resonant modes of the #1 - #5 multiple composite piezoelectric stator.

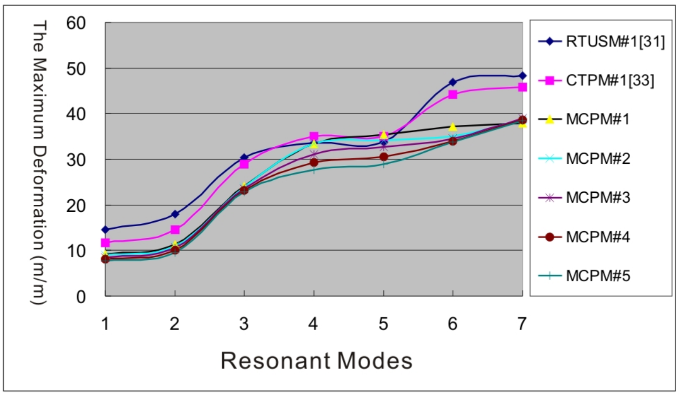

Figure 14. The maximum deformation relative to the resonant modes of the #1 - #5 multiple composite piezoelectric stator.

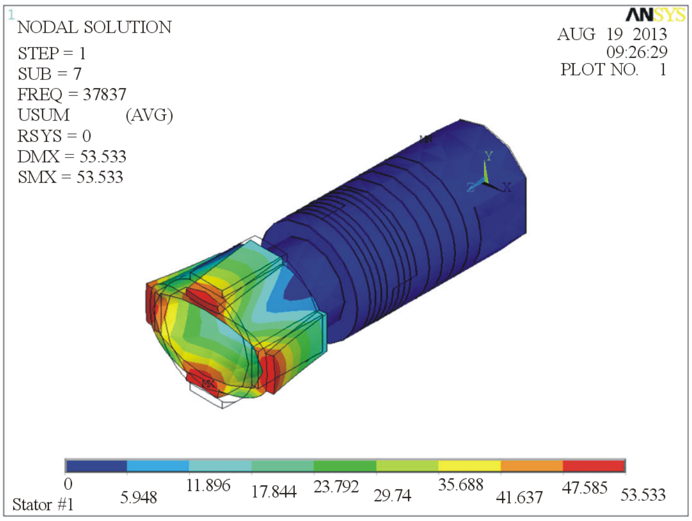

Figure 15. The best vibration mode of the #1 multiple composite piezoelectric stator.

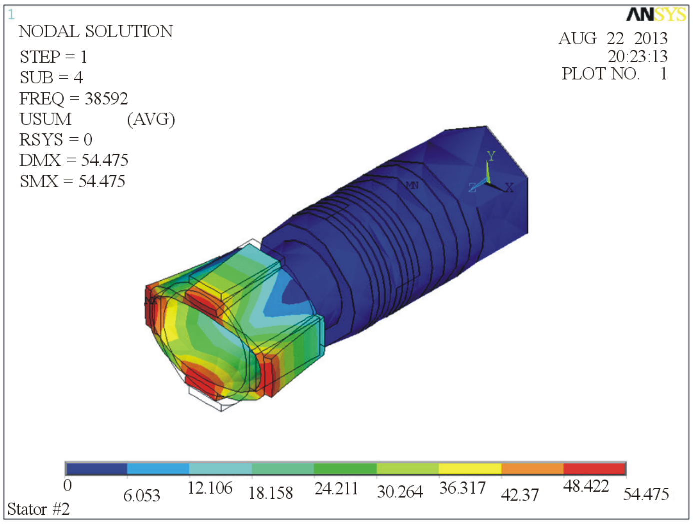

Figure 16. The best vibration mode of the #2 multiple composite piezoelectric stator.

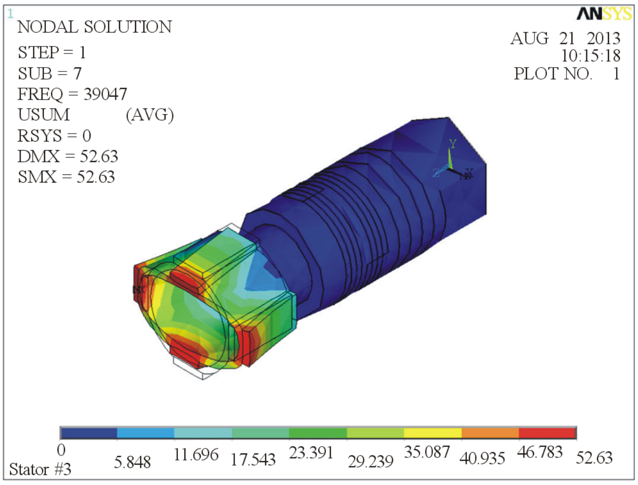

Figure 17. The best vibration mode of the #3 multiple composite piezoelectric stator.

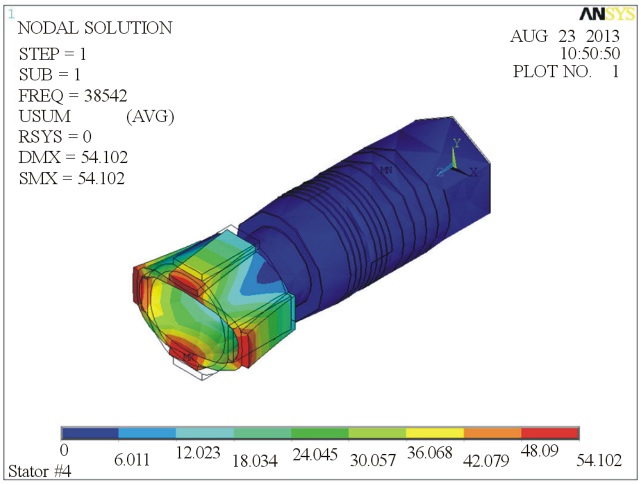

Figure 18. The best vibration mode of the #4 multiple composite piezoelectric stator.

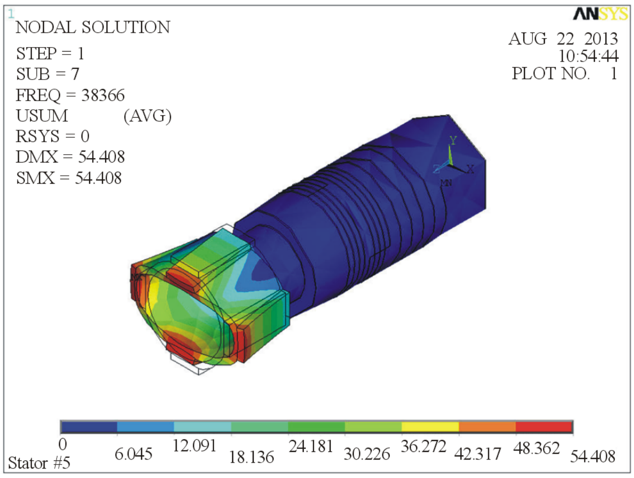

Figure 19. The best vibration mode of the #5 multiple composite piezoelectric stator.

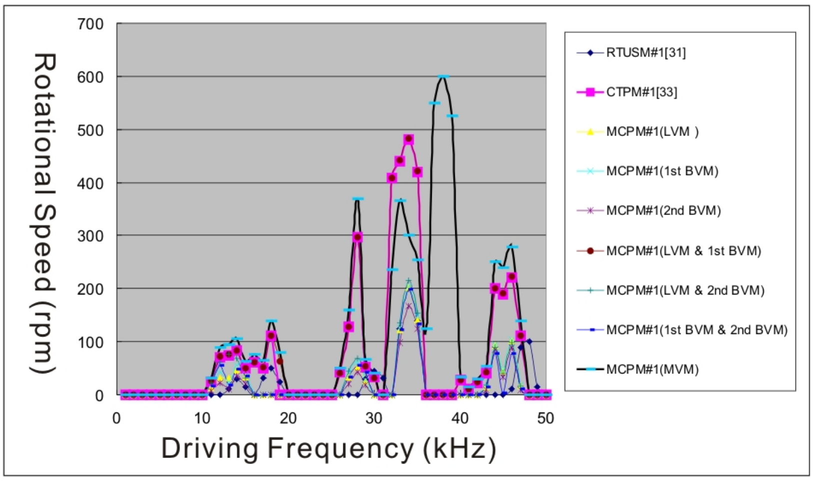

Figure 20. The rotational speed of different type motors relative to the driving frequency under conditions of 180 $V_{p\text{-}p}$ driving voltage and 12.1 gw loading.

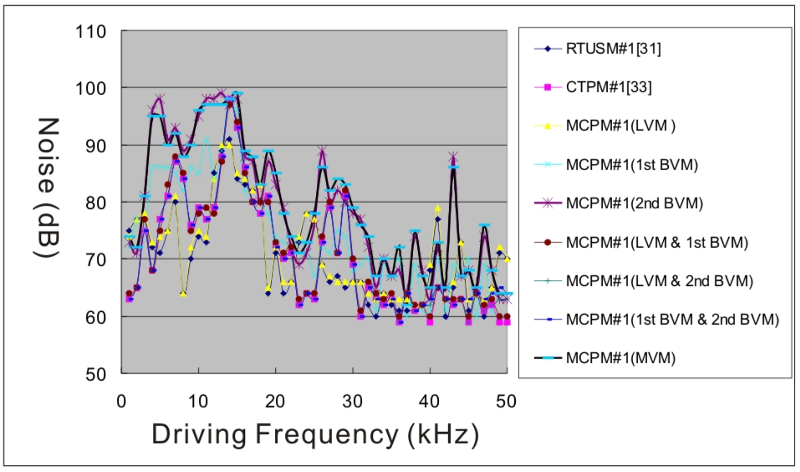

Figure 21. The noise of different type motors relative to the driving frequency under conditions of 180 $V_{p\text{-}p}$ driving voltage and 12.1 gw loading.

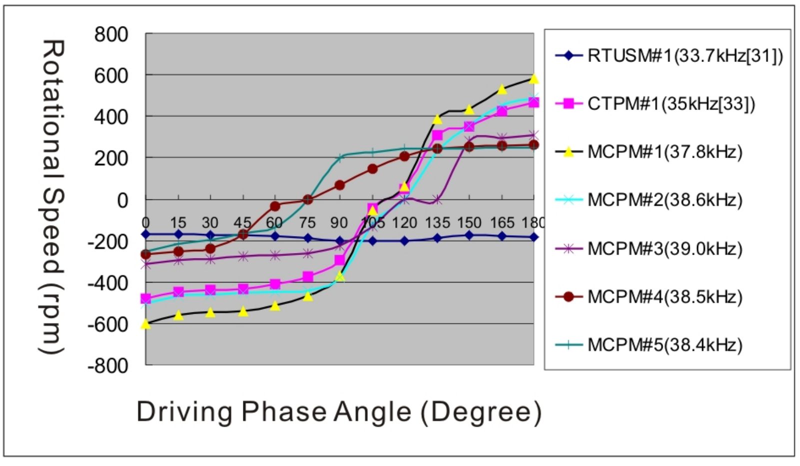

Figure 22. The rotational speed of different type motors relative to the driving phase angle under conditions of 180 $V_{p\text{-}p}$ driving voltage and 12.1 gw loading.

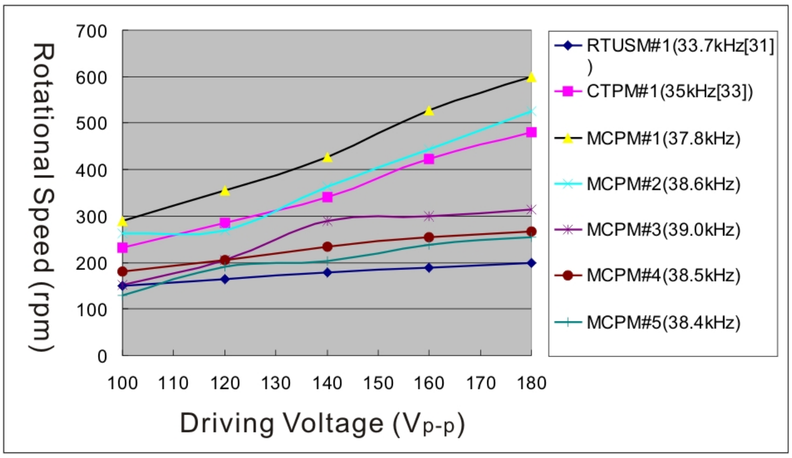

Figure 23. The rotational speed of different type motors relative to the driving voltage under conditions of 180 $V_{p\text{-}p}$ driving voltage and 12.1 gw loading.

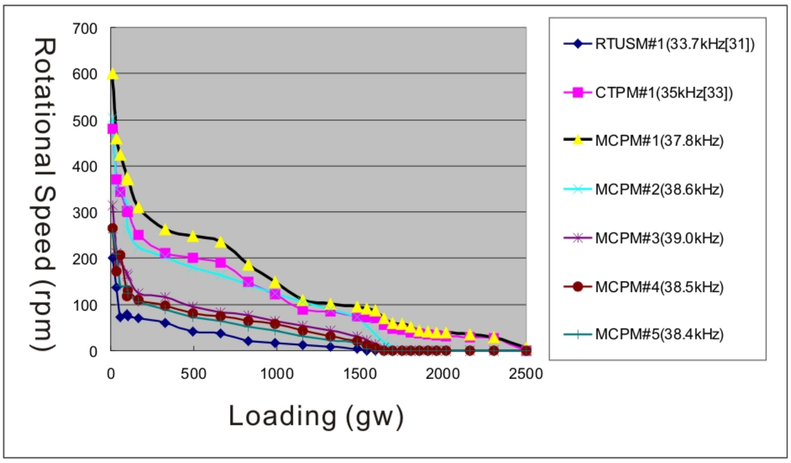

Figure 24. The rotational speed of different type motors relative to the loading under condition of 180 $V_{p\text{-}p}$ driving voltage.

Table 4. The slope and intercept of different type piezoelectric motors.

Type	a_i	b_i
RTUSM#1 [31]	0.62	89.6
CTPM#1 [33]	3.175	−92.7
MCPM#1	3.97	−116
MCPM#2	3.5	−117.4
MCPM#3	2.105	−42.7
MCPM#4	1.11	72.4
MCPM#5	1.49	−4.8

5. Conclusion

In this study, we found that the multiple composite piezoelectric motor has better rotational speed, conversion efficiency of direction and loading ability relate to the previous similar type's motor under the same driving conditions. The most special, when we use the multiple vibration modes to drive the motor, so that the above functions and efficiency achieve significant improvement and upgrade. Especially the maximum rotational speed of the multiple composite piezoelectric motor is 1.25 and 3.0 times of the composite type piezoelectric motor and the rod type ultrasonic motor respectively. Furthermore, the maximum loading ability of the multiple composite piezoelectric motor is 1.08 and 1.68 times of the composite type piezoelectric motor and the rod type ultrasonic motor respectively under conditions of the same driving voltage and loading or preload.

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Notes

RTUSM: Rod Type Ultrasonic Motor.
CTPM: Composite Type Piezoelectric Motor.
MCPM: Multiple Composite Piezoelectric Motor.
LVM: Longitudinal Vibration Module or Mode.
1st BVM: the first Bending Vibration Module or Mode.
2nd BVM: the second Bending Vibration Module or Mode.
MVM: Multiple Vibration Module or Mode.