Research on a New Composite Ultrasonic Energy Transmission Mechanism with Parallel Structure

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Abstract—A composite two-dimension ultrasonic vibration system with parallel structure is presented in this paper for the wire bonding application. Compared with other conventional structures, this one uses the structure of the clamping beam, weakening the horizontal deflection stiffness, instead of the clamping ring, which weakens the coupling effects existing in most parallel structures. By means of the self-locking wedge, the piezoelectric ceramics are effectively preload. The length of the horn is optimized according to the relationship between the magnification ratio and the ratio of the horn length. Through the vibration characteristic analysis and FEA verification, it is proved that this parallel structure can increase the composite output amplitude of the ultrasonic horn and the density of ultrasonic energy, and can complete the bonding at a larger area range so that it will shorten the bonding time and improve the bonding efficiency.

***Keywords*—Wire bonding, parallel composite vibration, horizontal deflection stiffness , energy density, bonding efficiency**

I. INTRODUCTION

Ultrasonic technology is widely used in many fields such as the micro-electronics, MEMS and semiconductor packaging. Wire bonding is one method of the pro-process of semiconductor packaging, which has the function of establishing the effective connection of the internal chip and external electrical parts [1]. As one of the most widely used methods of wire bonding, the gold ball bonding enhances the bonding strengthen and reduces the bonding time by means of the introduction of heat, ultrasonic energy and pressure.

Ultrasonic vibration system is one of the most important components of the bonding device. It consists of the piezoelectric ceramic converter, the horn and USG (ultrasonic source generator). Among them, the horn (shown in Fig. 1) is the vital part of the vibration system whose function is to amplify the mechanical vibration displacement and gather energy.

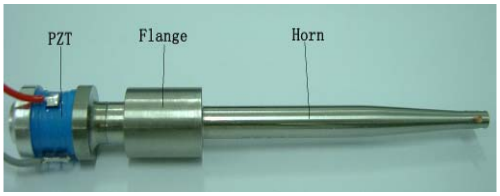


Figure 1 The ultrasonic vibration system (without USG)

Considering the ultrasonic energy transmission, both the frequency and the amplitude can be controlled to adjust the ultrasonic energy density so that it can adjust the bonding time. Nowadays, to improve the bonding efficiency, raising the ultrasonic frequency is the mainly way used to shorten the bonding time [2]. Japanese expert TSUJINO has made a long-term research on composite ultrasonic vibration for metal welding and proved that complex ultrasonic vibration technique could shorten the bonding time effectively[3,4] with the frequency unchanged. Later, Li Junhui from Central South University [5, 6] also presented that composite vibration is an optimal energy enhancement mode, which can increase the energy density in the welding area. By properly distribution locus of ultrasonic energy, brittle oxides in the welding area can be removed and pure metal interface for welding is exposed so that it can increase the atomic transmission rate and lattice mobility density, and widen the welding bonding window. All of these help improve the bonding efficiency.

This paper presents a composite two-dimension ultrasonic vibration system with parallel structure for the ultrasonic vibration system. Compared with other conventional structures, this one uses the structure of the clamping beam, weakening the horizontal deflection stiffness, instead of the clamping ring, which weakens the coupling effects existing in most parallel structures. By the right control of the amplitudes in the two directions we can get an optimized locus of the vibration, enlarge the bonding area, take fully advantage of ultrasonic energy and shorten the bonding time, increase the intensity of the bonding.

II. THE STRUCTURE OF THE COMPOSITE TWO-DIMENSION VIBRATION HORN

Serial Structure

Considering traditional serial structure for mechanism, such a serial structure is designed (shown in Fig. 2). The vibration in Y direction is transferred to the flange of X Horn, so the whole X Horn will vibrate in the Y direction through its own flange. And this motion will be superposed with its own X vibration and obtain the composite vibration result.

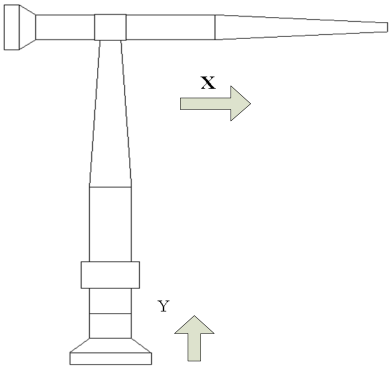


Figure 2 Conceptional design of serial structure

Assumptions:

1. The free amplitude of a single horn is *A*.

2. The end of Y Horn is fixed to the node of the longitudinal vibration of X Horn. This means the vibration in X direction of the X Horn will not be transferred to Y Horn through the flange.

3. The output amplitude of X Horn is approximate to *A*. (ignoring the possible coupling effect created by Y Horn in X Horn)

First, in the condition that the output amplitude of Y Horn is *A*, X Horn has a vibration with amplitude *A* by the base of the flange in the Y direction. However, due to the isotropic characteristics of elastic material, the two ends of the X Horn will have more displacement than the flange: $A_Y^{"} > A$. Meanwhile, in the X direction, the amplitude of X Horn is $A_X^{"} \approx A$. So the composite amplitude is:

$$S_{\mathrm{serial}} = \sqrt{(A_x'')^2 + (A_y'')^2} > \sqrt{(A)^2 + (A)^2} = \sqrt{2}A$$

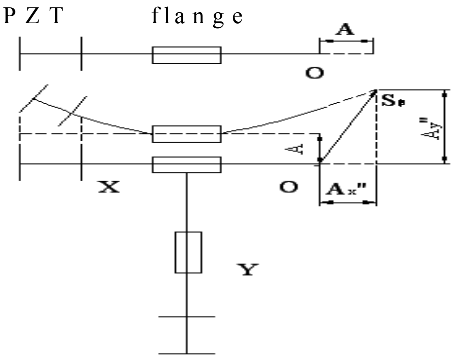


Figure 3 Diagram of serial structure

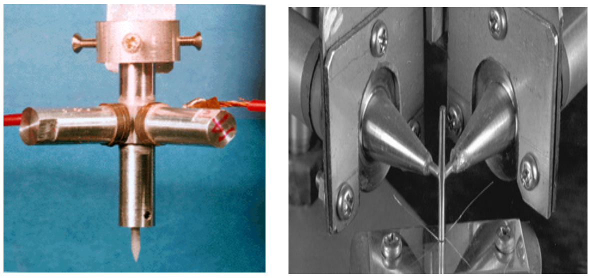
The composite vibration system with serial structure has advantages in reduction of coupling effects. But the X horn becomes the load of the Y horn, this requires the piezoelectric ceramic converter has a very high power. Because the ultrasonic energy transmission mechanism is going to be settled in the head of the encapsulation with a high speed move, the quality and volume of the structure should be small, therefore the serial structure can't be used here in the field of high speed bonding area.

Parallel structure

TSUJINO began the research of composite ultrasonic vibration in the early 1990s. He proposed various kinds of vibration structures (shown in Fig. 4). The principle is to make the superposition of two or more machinery vibration waves by means of ultrasonic oscillator, which can be used to accomplish the bonding.

However, the analysis indicates that this parallel structure has coupling affects which are common in the ordinary parallel structure. In the structure of ordinary clamping ring (shown in Fig.5), the horns have a great stiffness in the transverse direction respectively. At this point, due to the rigid connect to X Horn, there is a great force generated by Y Horn, pressing in the direction of longitudinal vibration of X Horn(shown in Fig.6), and preventing the vibration of X Horn, that's to say, increasing the force resistance. Therefore, this kind of structure needs much more powerful piezoelectric ceramic converter to activate to overcome the disturbance of the transverse resistance. In order to solve this problem, we needed design a new clamping structure which can weak the horizontal deflection stiffness effectively.

As shown in the Fig.7 this new composite structure uses the structure of the clamping beam, instead of the clamping ring. In the plane of the horns, the horns can have a small deflection around the centre axes of its clamping beam respectively, so it can weak the coupling effects which exist in most parallel structures.



a. 160-515 kHz vibration system b. 90-90 kHz vibration system

Figure 4Tsujino's ultrasonic horn with the parallel structure

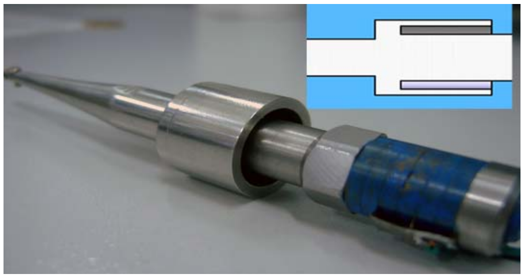


Figure.5 Structure of ordinary clamping ring

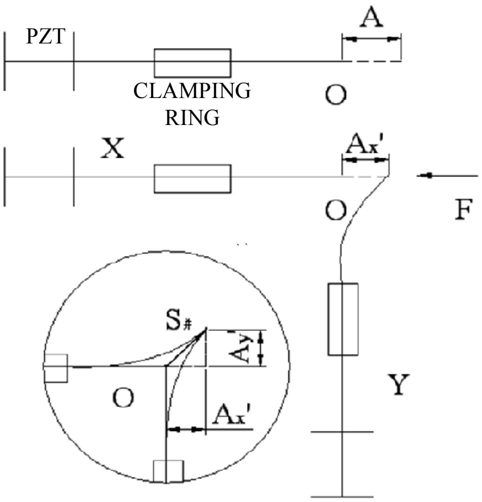


Figure.6 Diagram of the coupling effect

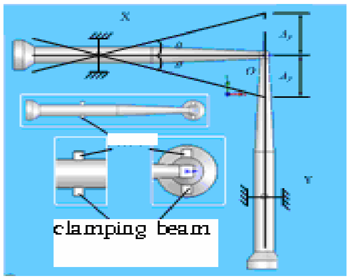


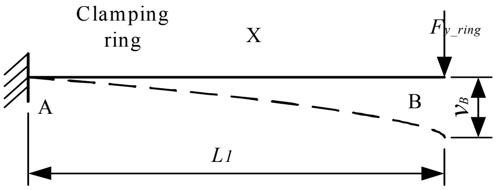
Figure 7 Improved composite ultrasonic horn with parallel

The clamping form analysis and modeling of composite structure

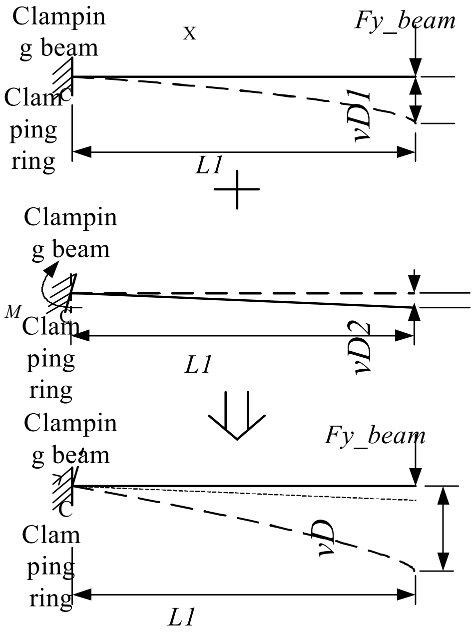
We model the two clamping form structure to analyze. The structure (shown in the Fig.5) can be equivalent as a load beam whose one end is fixed and the other end has a small extent bend at the press in the vertical direction. According to vector superposition principle, this can be seen as the combination of the following two states:

State one: a load beam whose one end is fixed, the other end has a small extent bend at the press in the vertical direction.

State two: a load beam with a distortion at the function of the moment generated by the vertical horn.



a. Deformation picture of horn with clamping ring



b. Deformation picture of horn with improved clamping beam

Figure.8 Force and deformation analysis of horns with different clamping methods

According to the material force principle, we can get the expression of the displacement of the working end B and D, and the equation of the force between each other:

$$v_B = \frac{F_{y\_ring} L_1^3}{3EI} \qquad (1)$$

$$v_D = v_{D1} + v_{D2} = \frac{F_{y\_beam} L_1^3}{3EI} + \frac{F_{y\_beam} L_1}{k} L_1 \qquad (2)$$

Where: v_B, v_D, v_{D1}, v_{D2}——the displacement of B,D;

F_{y_ring}, F_{y_beam}——the force given to the X horn by the Y horn in the two different clamping structures;

L_1 ——the distance between the work end and the clamping place;

EI——bending strength;

k——transverse torsional strength of the clamping beam;

According the equation (1) and (2), when the displacements of B and D are equal, $F_{y\_ring} > F_{y\_beam}$, this means that clamping beam can weak the horizontal deflection stiffness, so as to weak the coupling effects and get bigger amplitude.

III. STRUCTURE DESIGN OF THE COMPOSITE ULTRASONIC ENERGY TRANSMISSION SYSTEM WITH PARALLEL STRUCTURE

Considering the conclusion in the last chapter according to the request for the ultrasonic energy transmission system, we design the structure as showed in the Fig.9.

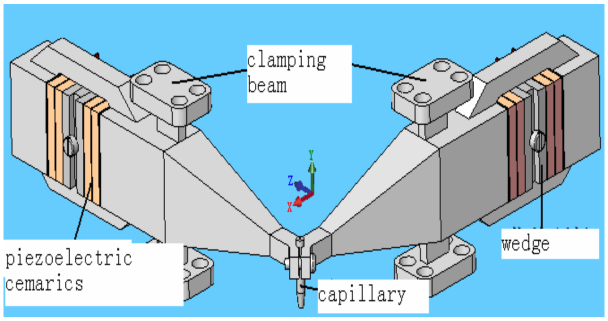


Figure 9 Model of the improved ultrasonic energy transmission system with parallel structure

The characteristic of this design is as followed:

A. *Incorporate and vertical structure*

The horn of this improved ultrasonic energy transmission system with parallel structure is made in incorporate way, so that it increases the consistency of the two direction vibration. This vertical and bidirectional horn can get different work locus (detail is told in the chapter 4.1) through adjusting the vibration parameter: frequency, amplitude and phase. In the designing process, according to the four ends' network principle, about the structure in the Fig.10 we can get the transmitted matrix and the frequency equation of the horn:

$$\tan kl_3 = \frac{-(\sin kl_1 + \frac{\alpha}{k}\cos kl_1)(\cos kl_2 + \frac{\alpha}{k}N\sin kl_2) + \cos kl_1(\frac{\alpha}{k}N\cos kl_2 - \sin kl_2)}{-(\sin kl_1 + \frac{\alpha}{k}\cos kl_1)\sin kl_2 + \cos kl_1 \cos kl_2} \qquad (3)$$

$$M_p = \left|\frac{v_e}{v_f}\right| = \frac{\left|N\left[-\left(\sin kl_1 + \frac{\alpha}{k}\cos kl_1\right)\sin kl_2 + \cos kl_1 \cos kl_2\right]\right|}{|\cos kl_3|} \qquad (4)$$

where: k is the number of the wave, $k = \omega / c$, ω is the angle frequency, c is the vibration speed;l_1, l_2, l_3,is the distance of the horn; α is the taper coefficient, $\alpha = (N-1)/(Nl)$;N is the acreage coefficient, $N = \sqrt{\frac{S_1}{S_2}}$, S_1, S_2 are the acreage of the different segments of the horn.

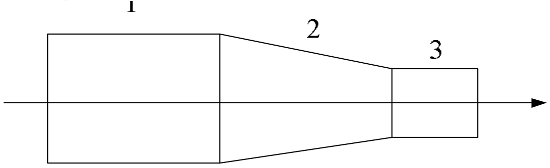


Figure 10 Three-segment horn with changeable cross-section

According to the triangle identical equation:

$$|\cos\theta| = \left(1 + \tan^2\theta\right)^{-\frac{1}{2}} \qquad (5)$$

we can get the expression of the length of the horn:

$$M_p = f(l_1, l_2) \qquad (6)$$

Assuming the length ratio t=l_2/l_1,we can get the magnifying curve with the different acreage coefficient, as shown in the Fig.11:

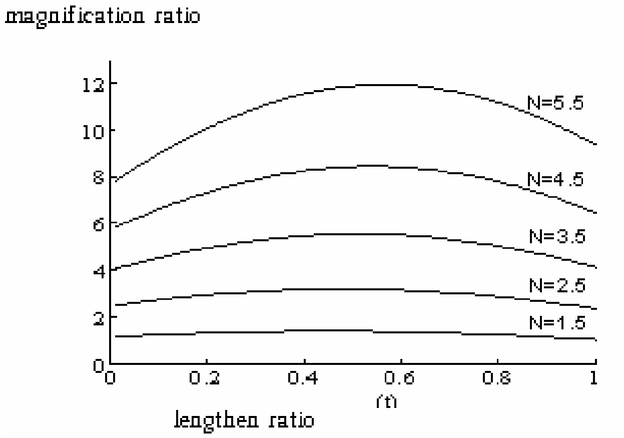


Figure 11 Relationship of magnification ratio and lengthen ratio

From the curve we can get the conclusion:

The magnifying coefficient M_p increases when the acreage coefficient increases. There is a best length ratio which makes the magnifying coefficient biggest to every acreage coefficient.

Therefore, according to the acreage coefficient, we can get a best length ratio and a biggest magnifying coefficient.

B. *Improved structure with clamping beam*

In order to reduce the couple problem, this structure uses a different clamping organ. First make sure the cut intensity is big enough, at the same time that we can reduce the couple problem which is mainly caused by the rigidity connection by weakening the horizontal deflection stiffness of the clamping beam. We design the cross-section is a rectangle whose long side's length is the three times of the short side's, and we will test the torsional strength is 0.3282N·m/rad.

C. *Horns with the rectangle cross-section*

Using the rectangle cross-section can make the structure more compact, and can restrain the free swing in the working vertical plane effectively.

D. *Wedge preload structure*

Considering the Incorporate and vertical structure, we design the wedge preload structure (shown in Fig.12). This structure can reach the preload and can prevent the piezoelectric ceramic from the high frequency impact. The principium is as followed:

When we screw down the preload bolt, the wedge piece 2 has a locomotion comparing to the wedge piece 3 and wedge 3, then the wedge angle makes the wedge piece 1 and piece 2 move to the profiles, so the piezoelectric ceramic can be preloaded , and the preload can be adjusted though the preload bolt. When the piezoelectric ceramic is imposed AC, the impact force can't affect the preload bolt for protection.

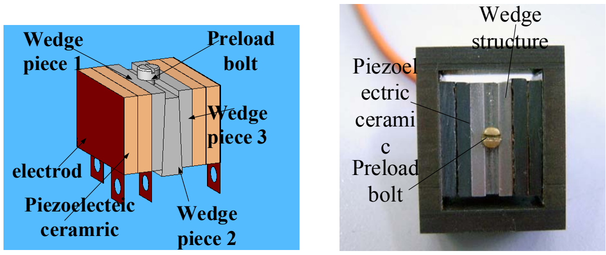


Figure 12 Wedge preload structure

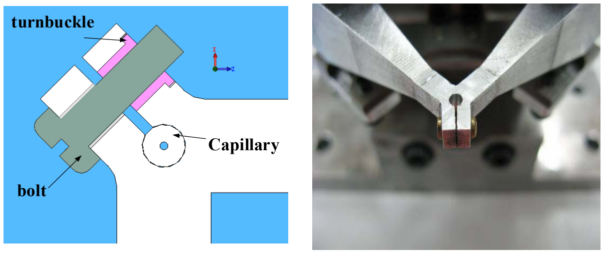


Figure 13 Symmetric clamping head

E. *Symmetric clamping head, and fast changing screw bushing (shown in the Fig.13)*

In order to keep the consistency of the composite vibration, the length and the quality of the screw and the screw bushing are all calculated to make sure the horn's centroid is in the symmetric plane.

IV. ENERGY DENSITY CALCULATION OF THE COMPOSITE STRUCTURE

According to vector superposition principle, when there is a particle involved in the vibrations from two different directions, the superposed motion is the vector sum of these two single motions.

The two vertical harmonic waves with different frequencies are:

$$x = A_1 \cos(\omega_1 t + \varphi_1) \tag{7}$$

$$y = A_2 \cos(\omega_2 + \varphi_2) \tag{8}$$

Where: A_1, A_2 are the amplitudes; ω_1, ω_2 are the vibration angular frequencies; φ_1, φ_2 are the initial phases.

When the particle vibrates at the same frequency ($\omega_1 = \omega_2$), the vibration equation of the intersection is:

$$\frac{x^2}{A_1^2} + \frac{y^2}{A_2^2} - 2\frac{xy}{A_1 A_2}\cos(\varphi_2 - \varphi_1) = \sin^2(\varphi_2 - \varphi_1) \tag{9}$$

The calculation equations of average ultrasonic energy density for single purely longitudinal vibration (assuming the energy is transmitted without reduction from the horn to the capillary)is shown as followed:

$$W = \frac{1}{2}\rho\omega^2 A^2 \tag{10}$$

Where: ρ is the density of the horn; ω is the vibration angular frequency; A is the amplitude.

As to the particle which is at the end of the horn, when the composite two-dimensional vibration frequencies are the same, the average energy density in a cycle is as followed:

$$W = W_X + W_Y = \frac{1}{2}\rho\omega^2 A_x^2 + \frac{1}{2}\rho\omega^2 A_y^2 = \frac{1}{2}\rho\omega^2 (A_x^2 + A_y^2) \tag{11}$$

We can see the ultrasonic energy density depends on the amplitude and frequency of the vibration. For improving the ultrasonic energy density, as it is said in the introduction, raising the frequency is difficult to realize. But the composite two-dimensional vibration improves the ultrasonic energy density by raising the amplitude and optimizing the focus of composite vibration.

V. FEA SIMULATION

A. *Locus of capillary in the composite vibration*

We can simulate the locus of the end particle of the composite vibration by the software Matlab. The locus of the calculation equation (9) is an ellipse. We can get different loci by adjusting the vibration parameter, the phase difference and frequency. In the

Fig.14 the respective phase difference is 0、π/6、π/3、2π/3、π and 3π/2.

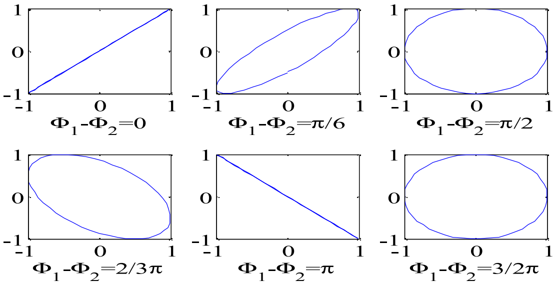


Figure 14 Loci for different phase difference

In general, if the vibration frequencies are different and phase keep changing differently, the composite locus will constantly change in the rectangle working area. Because of differential relationship, the loci of velocity and displacement have the same changing trend.

We can get different loci by controlling the frequency, phase and amplitude,so that it can wipe off the oxide on the welding face, can make the atom pervasion and crystal lattice dislocation take place in a larger area, then make the bonding more well-proportioned, shorten the bonding time and improve the bonding efficiency.

B. *Structure Vibration Simulation for different horns*

In order to verify the vibration characteristics of different structures, we simulate the structures by ANSYS. Model is shown in the Fig.16. Simulation condition: the material is aluminumalloy,, $\rho = 2.69\times10^3 kg/m^3$, $E = 69MPa$, $\delta = 0.33$. Use solid 95 as the element type and Smart Mesh 4 to mesh the volume. The simulation date is shown in the table1

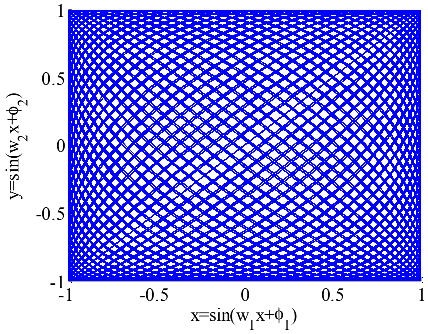
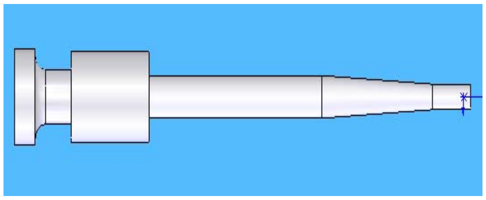
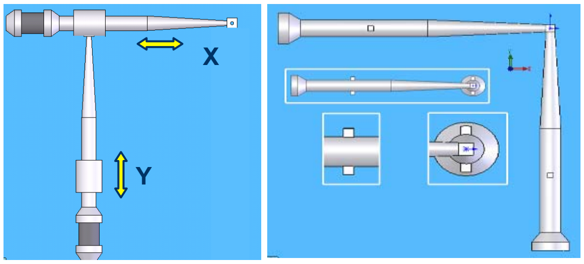


Figure 15 Locus of composite vibration



a single structure



b . serial structure c. parallel structure

Figure.16 model of the Analysis for ANSYS

Table.1 Simulation Data Unit: μm

	Type	Stimulation	*Dof*	*Dofx*	*Dofy*	*Dofz*
1	Single	Dx=0.7	1.1707	1.1707	0.0118	0.0031
2	Parallel	Dx=Dy =0.7	2.9500	0.3069	1.9260	0.0089
3	Serial		3.2897	2.3033	2.3488	0.0042

Note: Dx, Dy are the stimulation in the direction of X and Y. DOF is the superposed amplitude of the horn; DOFx, DOFy is the amplitude in the direction of X and Y respectively. The frequency is the harmonic frequency.

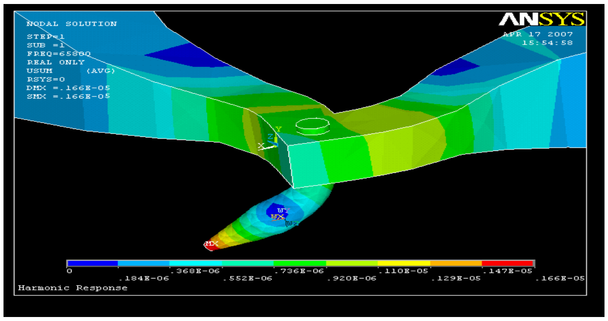
From the result we can get the conclusion:

- The amplitude of the composite structure is bigger than the single one.
- The composite structure has the coupling problem.

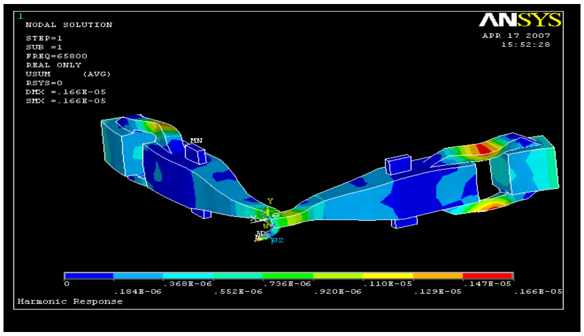
Comparing to the parallel and serial structure, the improved parallel structure will get bigger amplitude.

C. *Simulation of the improved horn*

We simulate the improved parallel structure (shown in fig.9). Simulation condition: the material is aluminum alloy, $\rho = 2.69\times10^3 kg/m^3$, $E = 69MPa$, $\sigma = 0.33$. Use solid 95 as the element type and Smart Mesh 4 to mesh the volume. The mode frequency is 65.8 kHz .The result is as followed:



a Results of the harmonic response(65.8kHz)



b Magnified graph

Figure 17 Harmonic response of the point where clamping the capillary (65.8 kHz)

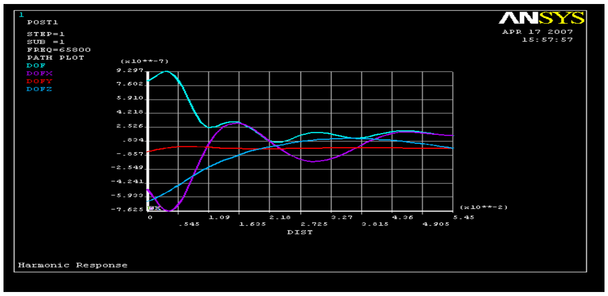


Figure 18 Amplitude of the horn

Note: the stimulation is a sine wave supplied by the piezoelectricity ceramic，and the frequency is 65.8kHz, the amplitude is $7.52\times10^{-9}m$; *DOF* is the superposed amplitude of the horn; DOF_x, DOF_y, DOF_z is the amplitude in the direction of X and Y respectively; DOF_z is the main vibration for the purely longitudinal vibration.

Table 2 Simulation data Unit: µm

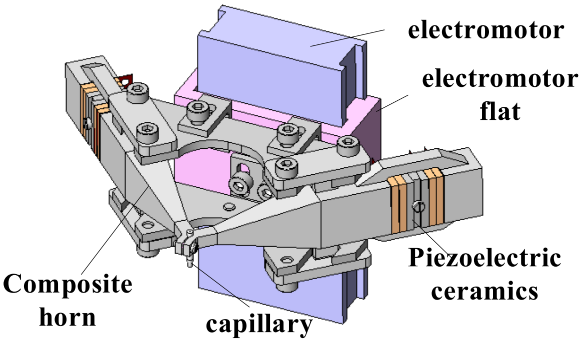
TABLE I. T YPE	TABLE II *OF*	TABLE III. *OFX*	TABLE IV. *OFY*	TABLE V *OFZ*
TABLE VI. INGLE	TABLE V .25767	TABLE VIII.	TABLE IX.	TABLE X .25767
TABLE XI. ARALL EL	TABLE X .81730	TABLE XIII. .49982	TABLE XIV. .044166	TABLE X .64515

After analyzing the result of the simulation, we can get the followings:

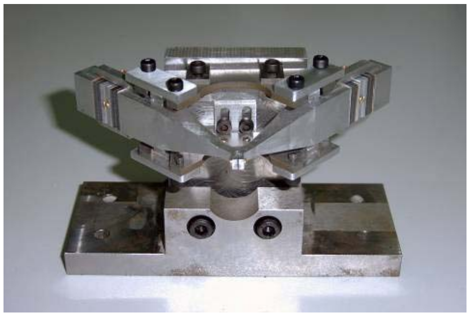
- The improved parallel structure can get bigger amplitude than the single structure.
- Weakening the horizontal deflection stiffness of the clamping beam can reduce the coupling problem

VI. Experiment

Basis at the analysis above, we design and produce the composite ultrasonic energy transmission mechanism with parallel structure (shown in the Fig.19). We have done the vibration test.



a. Model of the mechanism



b. Picture of the mechanism

Figure 19 Picture of composite ultrasonic energy transmission mechanism with parallel structure

Experiment device: Polytec Laser Doppler Vibrometer-OFV-3001(shown in the Fig.20); a flat preventing the vibration; a tripod; two ultrasonic producers, an oscillograph.

Experiment object: composite ultrasonic horn with parallel structure (shown in Fig.20)

The experiment plat is shown in the Fig.21.The result is shown in the Fig.22 and table 3.

Figure 20 Laser Doppler Vibrometer

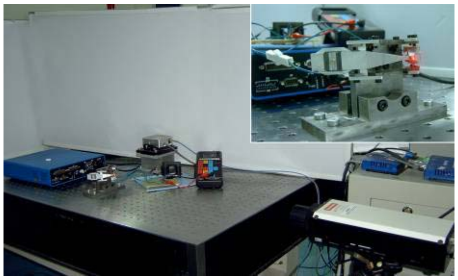


Figure 21 Experiment environment for composite ultrasonic horn with parallel structure

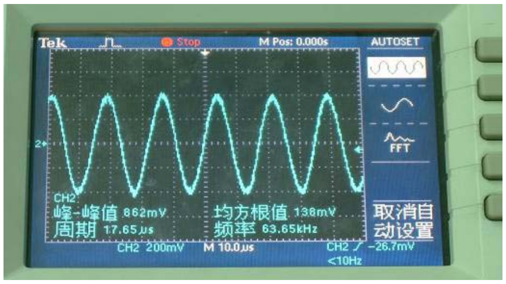


Figure 22 Output of composite ultrasonic horn with parallel structure

Table3 Data of one Dimension VibrationTest

sequence	Output pressure V_{p-p} (mV)	Frequency f (kHz)	Speed of vibration v (m/s)	Amplitude A (μm)
1	862	63.65	0.431	1.08
2	820	62.81	0.410	1.04
3	769	62.9	0.385	0.97
4	826	64.4	0.413	1.03
5	806	62.1	0.403	1.03
3σdisposal		63.17±2.67		1.13±0.12

Note: Every group of date is tested after preloading the piezoelectricity ceramic.

From the date of the impedance test and vibration test, it is known that the output amplitude of the composite ultrasonic energy transmission mechanism with parallel structure we designed is 1.13μm±0.12μm@3σ，and harmonic frequency is 63.17 kHz±2.67 kHz@3σ.

VII. CONCLUSION

The composite ultrasonic energy transmission mechanism with parallel structure we designed has been analyzed in theory, simulated by ANSYS, verified by experiment. It is obtained that the following conclution：1.Weakening the horizontal deflection stiffness of the clamping beam can reduce the coupling problem.2. We can get different loci by controlling the frequency, phase and amplitude, so that it can wipe off the oxide on the welding face, can make the atom pervasion and crystal lattice dislocation take place in a larger area, then make the bonding more well-proportioned, shorten the bonding time and improve the bonding efficiency. This provides a new direction for the research on the control and utilization of the ultrasonic energy for wire bonding

VIII. FUND ITEM

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