Experimental Study on the Influence of Air Conveyor System Parameters on Vibration of Glass Substrate

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Abstract. In this paper, the method of experimental research is used to minimize the micro-vibration amplitude of 0.6 mm thick glass substrates in the air conveyor system. The optimal parameter combination of the small orifice throttling glass substrate air conveyor system is obtained as follows: orifice diameter 0.25 mm, orifice spacing 60 mm and air-film thickness 50 μm. Secondly, based on the orthogonal experimental data, the influence of the main parameters of the air conveyor system at the micro vibration of the glass substrate is analyzed by variance analysis technology. The results show that the three principal parameters of the air conveyor system have significant influence on the vibration of the glass substrate. Among them, the thickness of the air-film has the greatest influence on the vibration of the glass substrate, the diameter of the orifice has the second influence, and the spacing of the orifice has the least influence. Finally, the influence of the three key parameters of orifice diameter, orifice spacing and film thickness on the micro vibration of glass substrate in the orifice throttling air flotation support system was studied and discussed, and the relationship curves between the maximum amplitude of micro-vibration of glass substrate and the main parameters of air flotation system were obtained.

Keywords: micro-vibration of glass substrate; small orifice throttling air bearing system; orifice diameter; throttling hole spacing; air-film thickness.

1. Introduction

With the continuous progress of high-definition liquid crystal display panel technology, the accuracy requirements of glass substrate surface defect detection are also getting higher and higher. As a key technology, air conveyor and transmission technology have become inevitable for optical automatic detection instrument of glass substrate surface defect. Air conveyor has the advantages of non-contact, pollution-free and high precision. Many researchers have studied the technology of transporting the glass substrate on air conveyor platform. Lee H G et al. [1] designed a simple air slit suspension conveyor, established the airflow model between the liquid crystal glass panel and the conveyor, and verified its effectiveness through experiments. Amano K et al. [2] studied the uniform supported glass plate of the porous air cushion system by numerical method, and studied the influence of the uneven design parameters and the appropriate combination of supply and exhaust pressure on the flatness. The numerical calculation results were compared with the experimental results to verify the effectiveness of the numerical prediction. Fu W S et al. [3] used Arbitrary Lagrangian Euler (ALE) method of finite element schemes to solve the moving boundary problem, and used generalized minimum residual method (GMRES) and pressure convection diffusion method to calculate the aerodynamic pressure distribution of the glass substrate. Guelpa V et al. [4] introduced the concept and design of a new modular conveyor, which can be utilized for high-speed processing of non-contact plane fragile objects. Chen X et al. [5-6] proposed a non-contact air-film system with directional porous cushion, and studied the basic characteristics of pressure distribution and viscous force of air-film. Yu X et al. [7-8] conducted theoretical and experimental studies in the pressure field of inclined airflow film, deduced the radial velocity distribution of inclined airflow film, and established the theoretical model of radial velocity dominant pressure distribution considering the inclination angle and center height of inclined airflow film. The pressure field of inclined airflow film with different inclination angles and center height was experimentally measured, and the results were in good agreement with the theoretical results. Zhong W et al. [9] carried out a series of experimental and theoretical studies on the design of the glass substrate air conveyor system with porous throttling, the pressure drop characteristics, friction characteristics and flow velocity characteristics of porous throttling. Liu H et al. [10] used the experimental fitting method and combined with the computational fluid dynamics (CFD) model to determine the permeability and inertia coefficients of three kinds of porous graphite throttling with a porosity of 16 %, 13 % and 8 %, respectively.

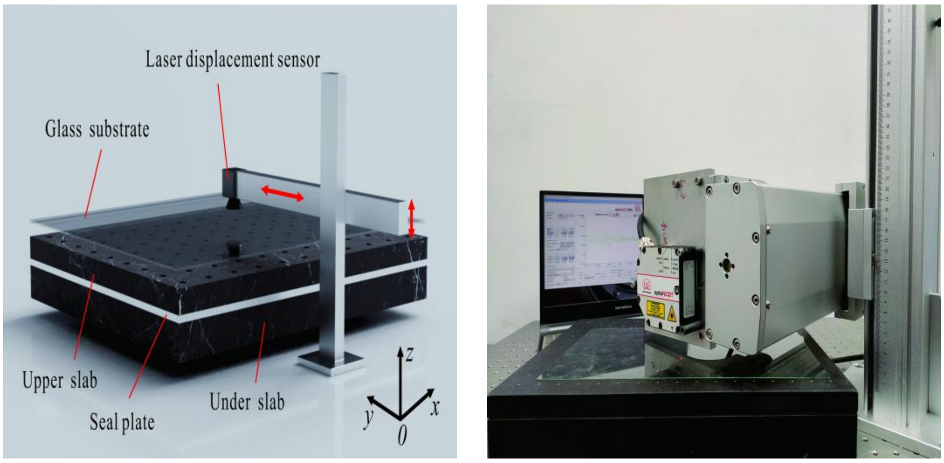
At present, porous throttling technology is primarily used in research and application of glass substrate air flotation system. The porous air flotation system has the advantages of good stability, but it has high requirements and high cost. As a widely used mature technology, orifice throttling technology has the advantages of easy manufacturing and low cost. However, from the stability of the air flotation system, orifice throttling is not as stable as porous throttling.

The huge advantages of the orifice throttling air conveyor system in terms of the usual cost to induce people to explore the orifice throttling technology for the glass substrate air conveyor system. Since the orifice throttling technology has been extensively used in various precision gas bearing systems, it can stably achieve high support accuracy. Theoretically, it is feasible to apply the orifice throttling technology to the air-bearing support and transmission system of the glass substrate. Appropriate design of the parameters of the orifice throttling system can ensure that the glass substrate meets the required stability requirements under the air bearing state. This stability is mainly measured by the maximum amplitude of the micro vibration of the glass substrate.

The principal parameters of orifice throttling air conveyor system include orifice diameter, orifice spacing and film thickness. In this paper, an experimental study on the micro-vibration of a common 0.6 mm thick glass substrate under the condition of orifice throttling air flotation support is carried out. 36 groups of glass substrate vibration tests with different levels of air flotation parameters are designed by orthogonal test method. Based on the experimental test data samples, a set of optimal parameters is obtained, which has a general reference value of the parameter design of the orifice throttling air flotation support system of 0.6 mm thick glass substrate. In addition, considering the needs of engineering to design, the influence of the parameters of the air flotation system on the maximum amplitude of the vibration of the glass substrate is studied, and the influence curve of the main parameters on the maximum amplitude of the glass substrate is obtained.

2. Organization of The Textorthogonal Design of Vibration Parameters Affecting Glass Substrate

In order to study the vibration law of glass substrate under air flotation support and obtain the optimal air flotation system parameters, an experimental system is designed, as showed in Figure 1. The experimental system includes vibration isolation platform, air flotation platform, glass substrate, laser sensor, pressure sensor, gas pressure regulating valve, etc.



(a) (b)

Figure 1. (a) An experimental device schematic and (b) actual measurement

The commonly used 0.6 mm thick glass substrate was selected as the experimental research object. The glass substrate was suspended in the air flotation platform in the air flotation support, and its vibration was measured by a laser sensor fixed on the support. The laser sensor is a laser triangular reflection sensor produced by German Iridium company, and the model is optoNCDT2300. In order to reduce the influence of environmental vibration on the experimental results, the whole experimental device is placed on the vibration isolation platform.

The whole air conveyor is regarded as a model composed of multiple elements, which are shown in Figure 2. In the air conveyor unit model shown in Figure 2, the gas supply system sends the gas with pressure p_0 into the air supply hole on the air flotation plate through the throttle valve, and p_d is the gas pressure at the outlet of the pressure chamber. p_a is atmospheric pressure, h is gas film thickness.

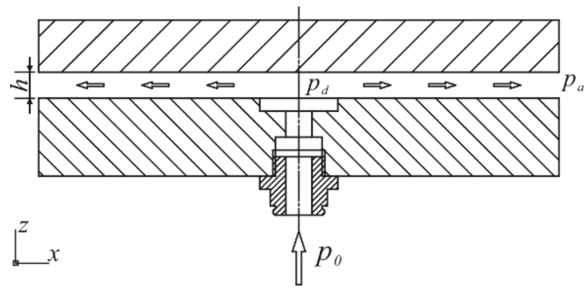


Figure 2. Air conveyor unit

The mass flow rate of gas flowing through the orifice is (Powell J W 1970) [11]

$$m_{in} = \frac{A_1 p_0}{\sqrt{gRT_0}}\left(\frac{p_d}{p_0}\right)^{\frac{1}{k}}\sqrt{\frac{2k}{k-1}\left[1-\left(\frac{p_d}{p_0}\right)^{\frac{k-1}{k}}\right]} \tag{1}$$

The gas mass flow rate in the carrier gas film is

$$m_{out} = \frac{A_2 p_d}{\sqrt{gRT_0}}\left(\frac{p_a}{p_d}\right)^{\frac{1}{k}}\sqrt{\frac{2k}{k-1}\left[1-\left(\frac{p_a}{p_d}\right)^{\frac{k-1}{k}}\right]} \tag{2}$$

Where A_1 and A_2 are the throttle area of the corresponding position, $A_1 = \frac{\pi d^2}{4}$, $A_2 = \pi Dh$

The bearing capacity of the platform is

$$W = (p_d - p_a)\frac{\pi(b^2-a^2)}{2\ln(b/a)} \tag{3}$$

According to the continuity condition of gas flow, $m_{in} = m_{out}$, the expression of gas film thickness and carrying capacity is

$$h = \frac{d^2}{4D}\left(\frac{p_0}{p_d}\right)^{\frac{k-1}{k}}\left(\frac{p_d}{p_a}\right)^{\frac{1}{k}}\frac{\sqrt{1-(p_d/p_0)^{(k-1)/k}}}{\sqrt{1-(p_a/p_d)^{(k-1)/k}}} \quad (4)$$

Since the bearing capacity of the flotation platform is always equal to the gravity of the glass substrate, the gravity of the glass is constantly under the condition of the glass substrate. It can be seen from Formula (3) that the pressure p_d of the pressure chamber is determined. From formula (4), it can be seen that the structural parameters of a specific flotation platform are determined, so there is a certain relationship between the gas film thickness and the supply pressure, and only the change of the gas film thickness is considered in the experimental design.

According to the vibration condition of defect detection of glass substrate under air flotation support, three main parameters of air flotation system, including orifice diameter, orifice spacing and film thickness, which affect the vibration of glass substrate at room temperature, were selected as variables. The experimental scheme was designed by the orthogonal test method. On the basis of previous studies, the appropriate variation range of each parameter is set. In this range, the stability of the glass substrate can be ensured, and the glass substrate will not be damaged due to the small thickness of the gas film. The factor level table is shown in Table 1. According to the principle of orthogonal design, there are 36 groups of horizontal combinations of different parameter factors, corresponding to 36 rows in the orthogonal table, that is, the number of vibration experiments of glass substrate needed to be arranged is 36 times. Each vibration experiment is set up according to the horizontal combination of a group of air flotation parameters in Table 2, and the corresponding parameters are tested to measure the maximum amplitude of the glass substrate. In order to ensure the accuracy of the amplitude data of the glass substrate under the horizontal combination of each group of air flotation parameters, each group of experiments was repeated for three times. The average amplitude measured after three experiments were taken as the final amplitude. The orthogonal experimental scheme and the obtained experimental data are shown in Table 2.

Table 1. Level table of vibration test parameters of glass substrate

level	***d***(mm)	***s***(mm)	***h***(mm)
1	0.25	20	50
2	0.35	40	60
3	0.45	60	70
4	0.60		80
5	0.75		90
6	1.00		100

Table 2. Orthogonal table of horizontal combination of air flotation parameters and maximum vibration amplitude results of glass substrate

序号	***d***(mm)	***s***(mm)	***h***(mm)	***x***(mm)	序号	***d***(mm)	***s***(mm)	***h***(mm)	***x***(mm)
1	0.25	20	50	0.4567	19	0.60	20	90	1.43
2	0.25	20	60	0.467	20	0.60	20	80	0.98167
3	0.25	40	90	0.5	21	0.60	40	50	0.645
4	0.25	40	70	0.525	22	0.60	40	60	0.76335
5	0.25	60	100	0.61	23	0.60	60	70	0.61167
6	0.25	60	80	0.77	24	0.60	60	100	0.6875
7	0.35	20	70	0.4483	25	0.75	20	90	1.73
8	0.35	20	100	0.655	26	0.75	20	100	1.805
9	0.35	40	50	0.44	27	0.75	40	60	0.50835
10	0.35	40	80	0.767	28	0.75	40	80	0.53825
11	0.35	60	90	0.60335	29	0.75	60	50	0.505
12	0.35	60	60	0.5835	30	0.75	60	70	0.567

13	0.45	20	70	1.05	31	1.00	20	50	0.6675
14	0.45	20	80	0.705	32	1.00	20	60	0.6835
15	0.45	40	90	0.6143	33	1.00	40	70	1.4115
16	0.45	40	100	0.65	34	1.00	40	100	1.93167
17	0.45	60	50	0.4567	35	1.00	60	90	0.59335
18	0.45	60	60	0.465	36	1.00	60	80	1.025

3. Analysis of Vibration Tests Results of Glass Substrate

3.1 Maximum Amplitude Range Analysis of Glass Substrate Vibration.

For range analysis, the total value T_{ij} of the specific level in each factor is calculated, which is equal to the sum of all the test results of the j level in the i factor; then calculate the average water $\overline{K_{ij}}$; finally, the range R_{ij} of each factor can be calculated. $\overline{K_{ij}}$ and R_{ij} are calculated according to Equations (5) and (6):

$$\overline{K_{ij}} = \frac{1}{n} T_{ij} \tag{5}$$

$$R_{ij} = \max\overline{K_{ij}} - \min\overline{K_{ij}} \tag{6}$$

According to the maximum vibration amplitude data of glass substrate in Table 2, the maximum vibration amplitude of the glass substrate is calculated by range analysis, and the results are shown in Table 3.

It can be seen from the range values calculated in Table 3 that the range values corresponding to the three factors of orifice diameter, orifice spacing and gas film thickness are 0.4973073, 0.30013 and 0.5280453. The range values for the three factors are in the order of a > b > c from large to small. That is to say, among the three factors that have an impact on the maximum amplitude of the basic vibration of glass in this paper, due to the maximum range value corresponding to the gas film thickness, it can be seen that the change of the gas film thickness level has the greatest impact on the maximum amplitude of the vibration of the glass substrate. The gas film thickness is the most important factor affecting the vibration of the glass substrate, followed by the orifice diameter. Orifice spacing is the smallest among the three factors, indicating that its horizontal change has the smallest influence on the vibration of the glass substrate. Therefore, the influence of various factors on the maximum vibration amplitude of the glass substrate is in the order of film thickness > orifice diameter > orifice spacing.

Table 3. Range analysis of factors affecting maximum amplitude of glass substrate vibration

	d	s	h
T_{i1}	3.3287	11.01967	3.1109
T_{i2}	3.49715	9.29442	3.4707
T_{i3}	3.941	7.4787	4.61347
T_{i4}	5.11911		4.78692
T_{i5}	5.6536		5.471
T_{i6}	6.31252		6.33917
$\overline{K_{i1}}$	0.554783	0.92330583	0.528483
$\overline{K_{i2}}$	0.5828583	0.774535	0.57845
$\overline{K_{i3}}$	0.65683	0.6231725	0.76891167
$\overline{K_{i4}}$	0.8531983		0.79782
$\overline{K_{i5}}$	0.942267		0.91183
$\overline{K_{i6}}$	1.0520867		1.0565283
R_{ij}	0.4973037	0.30013	0.5280453
order	2	3	1

By comparing the average $\overline{K_{ij}}$ of each water, it can be seen that the amplitude of the glass substrate reaches the minimum when the orifice diameter of the air flotation system is 0.25 mm, the orifice spacing is 60 mm and the film thickness is 50 mm. By the way, the amplitude value can meet the requirements of the glass substrate floating support and transmission.

3.2 Variance Analysis of Maximum Vibration Amplitude of Glass Substrate

According to the variance analysis theory of orthogonal test and the maximum vibration amplitude data of glass substrate in Table 2, the sum of squares of deviation, degree of freedom, variance estimation value and variance ratio (F value) of each factor can be calculated as shown in Table 4.

Table 4. Analysis of variance of maximum amplitude factors affecting vibration of glass substrate

source	S^2	n	σ^2	F	P
d	1.288	5	0.258	2.287	0.080
h	1.218	5	0.244	2.161	0.094
s	0.523	2	0.261	2.320	0.121
error	2.591	23	0.113		

Table 5. Results of interaction analysis of factors affecting maximum vibration amplitude of glass substrate

source	S^2	n	σ^2	F	P
$d*s$	3.314	10	0.331	12.052	0.000
$s*h$	1.549	10	0.155	1.196	0.355
$d*h$	3.140	25	0.126	400.998	0.039

It can be seen from Table 4 that among the three factors that affect the maximum amplitude of the vibration of the glass substrate, the explicitness corresponding to the orifice diameter and the film thickness is less than 0.1. Therefore, when the explicitness level is 0.1 (confidence level is 90%), the orifice diameter and the film thickness have a momentous influence on the vibration of the glass substrate. Therefore, in the actual control of the working parameters of the air flotation platform, it is necessary to strictly control the orifice diameter and orifice spacing as strategic air flotation parameters to accurately control the vibration amplitude of the glass substrate.

Interaction among throttle orifice diameter, throttle orifice spacing and film thickness can also be investigated through variance analysis. Generally, the interaction among the three factors is very small. This paper mainly studies the interaction between the two factors. Owing to the limitation of test time, variance analysis can only be carried out separately. The analysis results are summarized in Table 5.

It can be seen from Table 5 that the apparent indignity corresponding to the interaction between the orifice diameter and the orifice spacing is less than 0.01, so under the condition of the apparent indignity level of 0.01 (confidence level is 99%), the interaction between the orifice diameter and the orifice spacing has a significant influence on the vibration of the glass substrate. The visibility corresponding to the interaction between the orifice diameter and the film thickness is less than 0.05, so the interaction between the orifice diameter and the film thickness has a significant influence on the vibration of the glass substrate at the visibility level of 0.05 (confidence level is 95%). The interaction between orifice spacing and film thickness is more than 0.1, indicating that the interaction between orifice spacing and film thickness does not affect the vibration of the glass substrate.

4. Effect of Flotation Parameters on Vibration of Glass Substrate

4.1 Effect of Air-film Thickness on Vibration of Glass Substrate

According to the preceding test results, the diameter and spacing of throttle holes were determined to study the influence of a single factor of film thickness on the vibration of the glass substrate. When the orifice diameter is 0.25 mm, the orifice spacing is 60 mm, and the gas film thickness changes from 50 mm to 100 mm, the vibration of the glass substrate is shown in Figure 3.

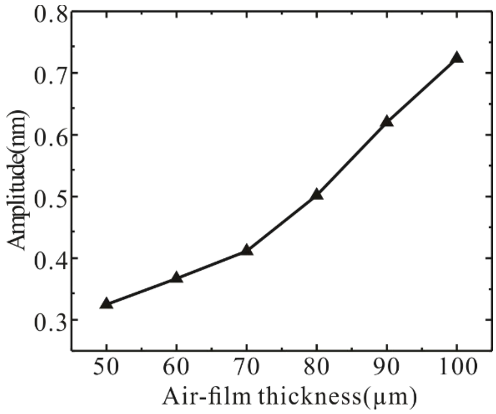


Figure 3. Relationship between film thickness and vibration of glass substrate

It can be observed in Figure 3 that when other conditions remain unchanged, the maximum amplitude of vibration of the glass substrate increases gradually with the increase of gas film thickness. It indicates that the stability of the glass substrate gradually deteriorates with the increase of gas film thickness, and the reason for this phenomenon may be linked to the gas film stiffness.

According to the gas lubrication theory, the bearing capacity of the floating platform can also be expressed as

$$W = \frac{3\mu A\varphi\Phi(b^2-a^2)p_0}{\rho h^3}\sqrt{\frac{2}{RT}} \tag{7}$$

The derivative of bearing capacity to film thickness is film stiffness

$$K = \left|\frac{dW}{dh}\right| = \frac{9\mu A\varphi\Phi(b^2-a^2)p_0}{\rho h^4}\sqrt{\frac{2}{RT}} \tag{8}$$

Depending on the formula (7) and (8), the curves of the relationship between gas supply pressure and gas film stiffness with the change of gas film thickness are drawn as showed in Figure 4.

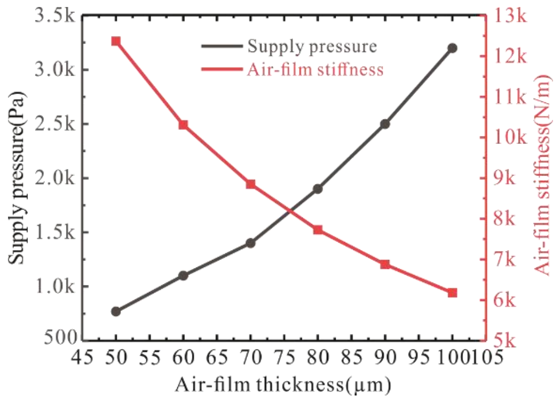


Figure 4. The relationship between gas film thickness and gas supply pressure and gas film stiffness

It can be seen from Figure 4 that with the increase of film thickness, the required gas supply pressure slightly increases, and the film stiffness gradually decreases. This is because the same glass substrate is employed in the test process, so the bearing capacity of the air flotation platform remains unchanged, equal to the gravity of the glass substrate. The increase of gas film thickness is realized by increasing the gas supply pressure. Therefore, with the increase of gas film thickness, the gas supply pressure increases and the gas film stiffness decreases. The gradual decrease of gas film stiffness leads to the decrease of gas film stability, the increase in vibration amplitude of glass substrate, and the decrease of stability of the glass substrate.

4.2 Effect of Orifice Diameter on Vibration of Glass Substrate

According to the aforementioned test results, the orifice spacing and film thickness were determined to study the influence of a single factor of orifice diameter on the vibration of the glass substrate. When the orifice spacing is 60 mm, the film thickness is 50 mm, and the orifice diameter changes from 0.25 mm to 1.00 mm, the vibration of the glass substrate is shown in Figure 5.

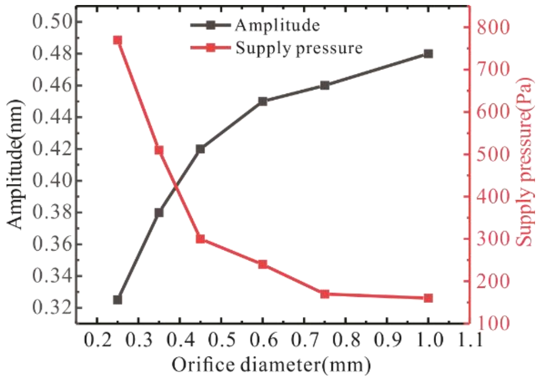


Figure 5. The relationship between orifice diameter and gas supply pressure and vibration of glass substrate

Figure 5 shows that when other conditions remain unchanged, with the increase of orifice diameter, the maximum vibration amplitude of the glass substrate increases gradually, and the gas supply pressure decreases gradually. It suggests that the stability of the glass substrate gradually deteriorates with the increase of the orifice diameter. Therefore, under the premise of no blockage, smaller orifice diameter is useful to suppress the vibration of the glass substrate.

4.3 Effect of Orifice Spacing on Vibration of Glass Substrate

According to the foregoing test results, the diameter of orifice and the thickness of the gas film were determined to study the influence of a single factor of orifice spacing on the vibration of the glass substrate. When the orifice diameter is 0.25 mm, the film thickness is 50 mm and the orifice spacing changes from 20 mm to 60 mm, the vibration of the glass substrate is shown in Figure 6.

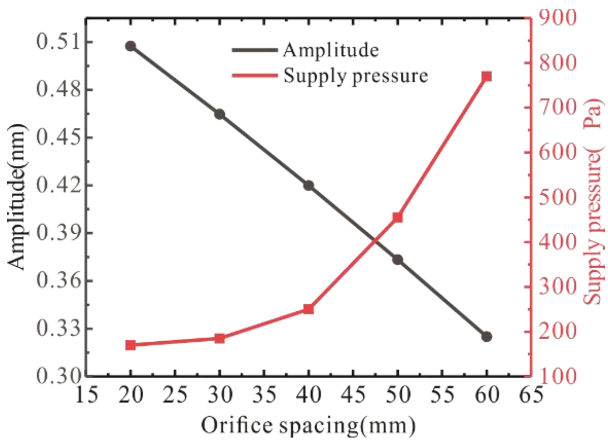


Figure 6. Relationship between orifice spacing and air supply pressure and vibration of glass substrate

It can be observed in Figure 6 that when other conditions remain unchanged, with the increase of the orifice spacing, the maximum amplitude of the vibration of the glass substrate gradually decreases, and the air supply pressure of the single orifice gradually increases. The experimental data demonstrate that the stability of the glass substrate becomes better with the increase of orifice spacing in engineering application.

This phenomenon can be explained from the pressure distribution of the gas film: the change of the orifice spacing leads to the change of the pressure distribution of the gas film, and the simulation results are presented in Figure 7.

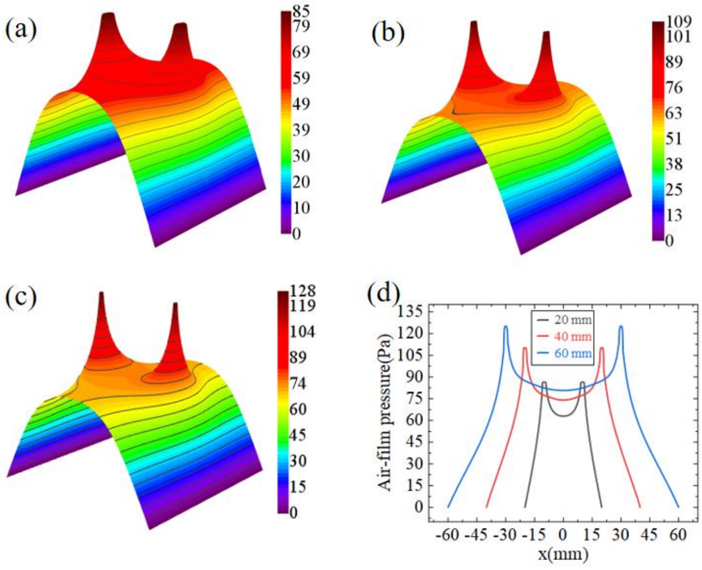


Figure 7. (a) 20 mm spacing, (b) 40 mm spacing, (c) 60 mm spacing, and (d) relationship between orifice spacing and gas film pressure distribution

From Figure 7 (a)-(c), the pressure distribution of the gas film flow field can be intuitively felt, and the pressure at the outlet of the flotation platform s the most important thing. It can be observed in Figure 7 (d) that with the increase of the orifice spacing, the interaction between the two orifices is gradually weakening, which is reflected in the widening of the ‘stationary band’ of the pressure distribution between the two orifices, and the improvement of the stability of the gas film. Therefore, with the increase of orifice spacing, the vibration stability of the glass substrate can be improved.

5. Conclusion

In this paper, 36 groups of vibration tests on a glass substrate with different combinations of air flotation parameters were carried out on 0.6 mm thick glass substrate by an orthogonal experimental design method, and the maximum amplitude values of corresponding glass substrate vibration were obtained. Built on the experimental data, the optimal parameters of orifice throttling air flotation system are obtained. Combined with statistical analysis, the influence of various factors on the vibration of the glass substrate was studied. The main conclusions are as following:

1.For 0.6 mm thick glass substrate, the optimum design parameters of orifice throttling air-floating support and transmission system are orifice diameter 0.25 mm, orifice spacing 60 mm and film thickness 50 mm.

2.The influence of air flotation parameters on the maximum vibration amplitude of the glass substrate is arranged in the order of film thickness > orifice diameter > orifice spacing; throttle hole diameter and film thickness have significant influence on the maximum amplitude of the glass substrate. The interaction between the orifice diameter and the orifice spacing and the interaction between the orifice diameter and the film thickness has a significant effect on the maximum amplitude of the glass substrate.

3.In the engineering application range, the vibration stability of glass substrate reduces with the increase of gas film thickness. Vibration stability of glass substrate decreases with the increase of orifice diameter; the vibration stability of glass substrate increases with the increase of orifice spacing.

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