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MULTIFACTORIAL ORTHOGONAL DECISION ON DIFFRACTION EFFICIENCY OF FRESNEL HOLOGRAM

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The method of multifactorial orthogonal decision on diffraction efficiency (DE) of Fresnel hologram is proposed in this paper. The orthogonal table is designed for such major manufacturing parameters as beam ratio, exposure, development time and developer density. With variance analysis, the conspicuous factors on DE are obtained, and the optimal technological conditions are established. In addition, by regression analysis to the conclusion, we obtain a fit rate of about 88% to the calculated and experimental results.

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1. INTRODUCTION

Diffraction efficiency (DE) is one of the most important technological indexes of hologram. In the process of manufacturing, DE is mainly determined by comprehensive influence of both exposure parameters (including exposure and beam ratio) and development parameters (including development time and developer density). Because conclusions of influences of some single parameter are not suitable for concluding the comprehensive effect of all macro-manufacturing parameters on DE, the optimal manufacturing conditions cannot be obtained. With regard to this problem, the method of multifactorial orthogonal design (MOD) is proposed in this paper to determine the DE comprehensively. Compared with the fuzzy multifactorial decision method in Ref.[1], MOD method can not only predict the concrete value of DE by comprehensive calculation, but also indicate the conspicuous factors on DE and establish the optimal technological conditions by multifactorial analysis. In conclusion, the major advantages of MOD method are that by choosing some typical experimental conditions from practice, and with further analysis, more information about each factor is provided than that of experimental results. Both variance analysis and regression analysis can be carried out with MOD method, and calculations are very simple.[2]

We make the holographic grating as the research object in this paper. MOD method is applied with such major experimental parameters as beam ratio, exposure, development time and developer density.

II. EXPERIMENTAL

The recording pattern of holographic grating is shown in Fig. 1. The angle between the two interference beam is 50°. The recording plate used in experiments is AGFA 8E75HD. A series of holographic gratings are recorded separately according to the experimental parameters determined by the orthogonal table. The processing techniques after exposure follow the standard procedures: development, water washing, bleaching, washing and drying naturally. Also, the recording plates are processed according to the development parameters required by the orthogonal table. DE is measured under the Brag condition, using the instrument introduced in Ref. [3].

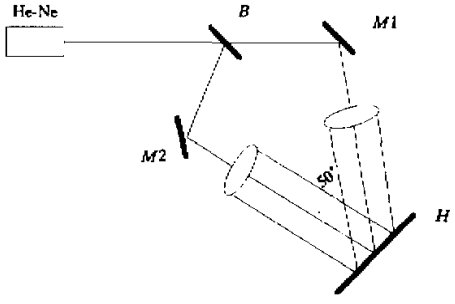

Fig.1. The recording pattern of holographic grating.

III. THE COMPREHENSIVE DECISION METHOD BASED ON ORTHOGONAL DESIGN

A. Design of orthogonal table

Specify the change ranges and levels of the experimental parameters based on practical experiences.

A. Beam ratio(times): [1, 5], (5, 10], (10, 20], (20, 30];

B. Exposure (mJ/cm^2): [3, 9], (9, 15], (15, 20], (20, 30];

C. Development Time(s): [10, 15], (15, 60], (60, 110], (110, 180];

D. Developer density (times): 0, 2, 4, 6.

Orthogonal table $L_{16}(4^5)$ shown in Table 1 is chosen according to the experiment parameters and their levels. Experimental parameters *A*, *B*, *C*, *D* are placed in the first four rows. The fifth row is the error item. We arrange the experiments according to the orthogonal table, and record the results.

B. Initial analysis of orthogonal design

M_{ij} represents the sum of the experimental results that are of the same level number i in row j. $m_{ij} = M_{ij}/4$ is the corresponding average value. M_{ij} and m_{ij} of each

factor are shown in Table 2. With regard to factor A, m_{11} is the biggest among the four values, so it can be derived initially that level A_1 is the best choice of factor A. Same analysis can be carried on to factor B, C and D. The results are B_1, C_3 and D_1, respectively.

Table 1.

	A	B	C	D	Error item	Experimental result	Decision calculation	Decision error
	1	2	3	4	5	η/%	η'/%	$\lvert\eta-\eta'\rvert:\eta$/%
1	1	1	1	1	1	59.7	57.43	3.8
2	1	2	2	2	2	48.1	51.28	6.6
3	1	3	3	3	3	52.5	54.47	3.8
4	1	4	4	4	4	47.1	44.20	6.2
5	2	1	2	3	4	50.3	47.41	5.7
6	2	2	1	4	3	17.4	19.45	11.8
7	2	3	4	1	2	34.2	37.38	9.3
8	2	4	3	2	1	38.7	36.34	6.1
9	3	1	3	4	2	44.9	48.00	6.9
10	3	2	4	3	1	43.3	41.03	5.2
11	3	3	1	2	4	35.9	33.01	8.1
12	3	4	2	1	3	43.0	45.06	4.8
13	4	1	4	2	3	36.4	38.46	5.7
14	4	2	3	1	4	35.8	32.82	8.3
15	4	3	2	4	1	24.9	22.64	9.1
16	4	4	1	3	2	17.6	20.78	18.1

Let T represent the total value of all experimental results. Here, $T=629.8$. Let $\bar{y}$ be the average value of all experimental results, $\bar{y}=T/16$. We evaluate the importance of each factor by ultra-difference R_j which is defined as the greatest difference between the maximal M_{ij} and minimal M_{ij} in column j. That is:

$$R_j = \max\{M_{ij}\} - \min\{M_{ij}\}. \tag{1}$$

The importance of the factors can be compared approximately according to R_j of A, B, C and D. The importance sequence is $A>B>C>D$.

Let S_j be the square sum of column j, that is,

$$S_j = \frac{1}{4}\sum_{i=1}^{4} M_{ij}^2 - \frac{1}{16}T^2. \tag{2}$$

The calculated S_j are listed in Table 2. S_j can also be used to evaluate the importance of each factor, and the result is in agreement with what obtained above.

C. Variance analysis of orthogonal table

Although the importance sequence is obtained by evaluating S_j, the statistic conclusion of whether a factor is conspicuous can only be decided by comparing it with the error item in the fifth row and analyzing the variance.

Define $f_j=r-1$ (r is the level number) as the freedom degree of S_j. S_j of factor A to D are recorded as S_f, and the corresponding freedom degrees are f_f. S_5 which is

not caused by the change of any factor is regarded as error square sum S_e, and the corresponding freedom degree is f_e. Calculate

$$\overline{S}_j = S_j/f_j. \tag{3}$$

The results are also shown in Table 2.

Calculate

$$F_f = \overline{S}_f/\overline{S}_e \tag{4}$$

and compare it with $F(F_f, f_f)$. If $F_f > F(F_f, f_f)$, we can decide that the factor is conspicuous, otherwise the factor is inconspicuous. Those f_j, S_j and F_j are listed in Table 2.

Table 2.

M_1	$M_{11}=207.4$	$M_{12}=191.3$	$M_{13}=130.6$	$M_{14}=172.7$	$M_{15}=166.6$
M_2	$M_{21}=140.6$	$M_{22}=144.6$	$M_{23}=166.3$	$M_{24}=159.1$	$M_{25}=144.8$
M_3	$M_{31}=167.1$	$M_{32}=147.5$	$M_{33}=171.9$	$M_{34}=163.7$	$M_{35}=149.3$
M_4	$M_{41}=114.7$	$M_{42}=146.4$	$M_{43}=161.0$	$M_{44}=134.3$	$M_{45}=169.1$
m_1	$m_{11}=51.85$	$m_{12}=47.83$	$m_{13}=32.65$	$m_{14}=43.18$	$m_{15}=41.65$
m_2	$m_{21}=35.15$	$m_{22}=36.15$	$m_{23}=41.58$	$m_{24}=39.78$	$m_{25}=36.20$
m_3	$m_{31}=41.78$	$m_{32}=36.88$	$m_{33}=42.98$	$m_{34}=40.93$	$m_{35}=37.33$
m_4	$m_{41}=28.68$	$m_{42}=36.60$	$m_{43}=40.25$	$m_{44}=33.58$	$m_{45}=42.28$
R_j	$R_1=92.7$	$R_2=46.7$	$R_3=41.3$	$R_4=38.4$	$R_5=24.3$
S_j	$S_1=1174.90$	$S_2=383.02$	$S_3=255.17$	$S_4=202.57$	$S_5=111.48$
f_j	3	3	3	3	3
S_j	391.63	127.67	85.06	67.52	37.16
F_j	10.54	3.44	2.29	1.82	

Examining F distribution table, we obtain: $F_{0.95}(3,3)=9.23$; $F_1=10.54>F_{0.95}$. This shows that factor A is more conspicuous than factor B, C and D.

D. Establishment of optimal technological condition

Define

$$a_{ij} = m_{ij} - \bar{y} \tag{5}$$

as the effect of level i in row j. The optimal technological condition and optimal engineering average are established by the effect a_{ij} of each factor level. The calculated results are listed in Table 3.

Table 3.

Effect	$a_1=12.49$	$b_1=8.47$	$c_1=-6.71$	$d_1=3.82$
	$a_2=-4.21$	$b_2=-3.21$	$c_2=2.22$	$d_2=0.42$
	$a_3=2.42$	$b_3=-2.48$	$c_3=3.53$	$d_3=1.57$
	$a_4=-10.68$	$b_4=-2.76$	$c_4=0.89$	$d_4=-5.78$

It can be derived from Table 3 that the optimal technological condition is $A_1B_1C_3D_1$. The optimal engineering average is defined as the sum of the total average value $\bar{y}$ and the effect of optimal level of each factor, i.e.

$$\mu_0 = \bar{y} + a_1 + b_1 + c_3 + d_1 = 67.67.$$

It can be found that $A_1B_1C_3D_1$ is not included in the 16 experiments in Table 1. This phenomenon demonstrates a major advantage of MOD method, with which more information can be obtained than that of experiments itself.

E. Decision calculation

Regression decision calculation under certain manufacturing condition can be carried out by calculating the sum of total average value and the effect of each factor level. The decision calculating results of the 16 experiments are listed in Table 1. Compared with the practical results, a fit rate of 88% is obtained. This shows they are in good agreement.

F. Analysis of the results of MOD decision

some conclusions are obtained by orthogonal analysis. The function of beam ratio is the key element among the four manufacturing parameters. Besides, exposure is also very important according to F_j of each factor in Table 1. During development process, the influence of development time on DE is relatively greater. To some extent, within the range of developer density in experiment, its effect on AGFA 8E75HD is not very remarkable compared with other development parameters. It is shown that there is a wider allowable range of developer density for AGFA 8E75HD. Through orthogonal analysis, the optimal technological conditions are established that the beam ratio should be 1 – 5, exposure within 3 – 9 mJ/cm^2, non-diluted developer is used, and development time should be 60 – 110 s. The highest DE will be obtained under this condition.

IV. CONCLUSIONS

Optimal technological conditions are established and the highest DE is predicted conveniently by using the MOD method to decide the DE comprehensively. The conspicuous factors on DE under certain manufacturing conditions are analyzed to provide theoretical basis to improve manufacturing techniques. In addition, regression analysis can be carried out to predict experimental results.

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