A Production Process with Precise Adjustment for Mechanical Parts Utilizing Fuzzy Control

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Abstract

Recently many production processes with assembly and adjustment are automated due to the various kinds of technological progresses. Some automated processes includes the precise adjustment with the accuracy of microns. But some other precise adjustment processes are not yet automated, that is, are still relied on skilled workers the number of which is decreasing. On the other hand, consumer products continue to move to higher functionality, the need for high-precision technology is increasing. In adjustment process, the problem is that the characteristics of product are different in each work pieces. In order to handle the dispersion of characteristics of controlled system, a new fuzzy inference method utilizing probability density functions of dispersion of measurement values defined as membership functions is proposed in this paper. Besides that, to control more precisely by consideration of qualitative knowledge of the causes of data dispersion, a method to determine the membership functions using the distributions of grade accumulation is proposed. Consequently, the application of fuzzy control, strictly fuzzy inference, to high precise control became possible using the proposed method. An experimental evaluation of magnetic head adjustment resulted in the improvement of the success rate compared with conventional adjusting devices under strict specifications. The effectiveness of this proposed method was proved from this experimental result.

1. Introduction

Many assembly and adjustment processes in production lines are automated due to various kinds of technological progresses. Some adjustment processes with the accuracy of microns are also automated. But some other adjustment processes are still relied on skilled workers and are not yet automated. In other words, automatic technologies in these production processes do not catch up with skilled workers' technologies.

Skilled workers consider many kinds of measurement data, non-linearity and mutual interference, and choose and perform multi-control inputs. In these cases, conventional linear control methods can't be applied. It is known that fuzzy inference is effective for automated control based on expert knowledge, in areas such as steam turbine or water treatment plant operation [1]-[5]. However, for precise control applications such as adjustment systems for consumer product manufacturing, how to define the membership function precisely is of much importance.
The delta rule used for back propagation in neural networks is known as a method for defining membership functions [6]-[9].

But this method can't handle dispersion of teaching data. In practical use, the characteristics of controlled system are different in each work pieces by various factors. These are unavoidable problems in practical applications. But in conventional learning schemes, vagueness of teaching data is not permitted, because the iterative calculation of the learning algorithm can't terminate. Further, there was no field study on how to handle the dispersion of teaching data for fuzzy theory and neural networks. It is stated that it is possible to take fuzzy theory as a kind of probability [10]. However, to date, there are no reports about concrete methods.

Therefore, in conventional methods it demands skill to construct teaching data that excludes vagueness from actual experimental data. To achieve precise fuzzy control in practical use, we propose a new fuzzy inference method utilizing probability density functions to cope with the dispersion of measurement values defined as membership functions. In addition, considering qualitative knowledge of the data distribution, we propose a method to determine membership functions using the distributions of grade accumulation.

By these proposed methods, the statistical quantitative information and the qualitative knowledge are processed simultaneously on fuzzy inference. And this method realizes the precise multi-inputs and non-linear adjustment algorithm.
We applied the proposed method to automatic precise adjustment device for magnetic head, and the experimental results were satisfactory.

A summary of magnetic head adjustment and the adjustment algorithm are covered within the second and third sections of this paper as concrete examples of the requirements concerning data dispersion. Then, the new inference method, in which probability-type fuzzy inference and an accumulation-grade membership function are used, are covered in the fourth section. The experimental result of this method applied to magnetic head adjustment is shown in the fifth section, which is followed by the conclusion.

2. Construction of Magnetic Head and Outlook of Adjustment

The construction of the magnetic head is shown in Fig.1. A magnetic head comprises a head base made of brass and an amorphous or ferrite head chip. The tip of the head base is divided into two projections. Each head chip is fixed on the two projections with adhesive. The gap for reading and writing is formed on the front face of the head chip. A distance between the gaps is called the gap distance as shown in Fig.2. Each height to the gap from a certain datum level is termed an absolute height. And, the longitudinal distance of two absolute heights is called the height step.

A rise in the magnetic recording density in recent years requires the above dimensional tolerances to be in the order of μm. Deviation is within the micron order when a head chip is fixed on the head base with adhesive. However, that deviation is insufficient. Therefore, readjustment must be done to satisfy specifications. So far, a worker measures, from above, each dimension by visual observation with a microscope. Then, a worker adjusts the head base by doing high precision plastic deformation using a jig, which serves as a miniature vise. In this case, it is not only inefficient to adjust large quantities of magnetic heads by hand, but the stress on the worker making the high-precision adjustment is also a troublesome problem. Therefore, automation is the desired solution.

The configuration of the adjustment mechanism of the developed automation device is shown in Fig.3. The details of the mechanism and the measuring device [11] are described in Fig.3(a) is the gap distance spreader mechanism. A wedge is pushed between the tips of the head base, and this one controls the amount of spreading by controlling depression in the vertical direction. Fig.3(b)(c) is the height step adjustment mechanism. This makes adjustments by pushing up the tip of the head base using two bar-shaped tools separately. The absolute height is lowered when a head chip is fixed with the adhesive. Therefore, pushing up the head base alone is effective for this adjustment. The adjustment mechanism to narrow the gap distance is illustrated in Fig.3(d). The gap distance is narrowed by pinching the projecting sections from both sides.

As for the movement distance (called the total deformation quantity) which is the control input for these mechanisms, control is possible. But, in the amount of spring back, some elastic deformation is returned. Therefore, the control algorithm must calculate a total deformation quantity considering the amount of spring back.

3. Problems of Adjustment Algorithm

The problems that the adjustment algorithm had to solve were as follows.

(1) Even if only parity gives it a total deformation quantity, there is dispersion in the amount of spring back.
(2) The relation between the total deformation quantity and the amount of plastic deformation is non-linear.
(3) There is mutual interference in the height direction and the gap direction.
(4) There is an effect influenced from the adjustment history.

Detailed explanations of the above issues are as follows.

3.1 Plastic Deformation Dispersion and Non-linearity

The histogram of height step plastic deformation when a head was deformed by the right-height adjustment device is shown in Fig.4. The pointed bar charts in the histogram shows the dispersion of the amount of plastic deformation when a total deformation quantity of 110μm was given. The number of samples was 59. In this way a difference in plastic deformation, even when the same total deformation quantity is used, is brought about. Though there are various causes of this dispersion, one factor is the dispersion of head base thickness. The dimensional accuracy for head base thickness is coarse because the dispersion of head base thickness doesn't finally influence the performance of the product.

A thick head with a high stiffness doesn't bend easily while a thin head with a low stiffness does bend easily. The dispersion of the data involves such qualitative trends, discussed in detail in Section 4.1. Refer to Fig.11.

And also from Fig.4, we can recognize that the relation between the average value of the height step plastic deformation and the total deformation quantity is non-linear. We must take this non-linearity into consideration as well.

3.2 Mutual Interference

A wedge is driven to adjust the width of the gap distance using the spreader adjustment mechanism. Therefore, as shown in Fig.5(a), not only is the tip of the head base spread, but also dragged downward. In other words, plastic deformation is performed in the height direction. Then, when adjustment in the height direction is

performed by the height step adjustment mechanism, the joint of the projection becomes the center of rotation, and a head base is deformed.

Therefore, the width direction is narrowed as shown in the Fig.5(b) and Fig.6. In this way, gap direction and height direction can't be adjusted independently. So, an algorithm must decide the amount of adjustment considering each amount of mutual interference.

3.3 Adjustment History Influenced Effect

A phenomenon called work hardening, the Bauschinger effect, is a plastic deformation characteristic. In the case of a head which had already been plastic deformed, an accurate total deformation quantity can't be calculated unless the former direction and quantity of deformation (adjustment history) are taken into consideration. A stress analysis of the head base made by the finite element method showed that the projection joint part of the head base is deformed by both gap direction adjustment and height direction adjustment.

An experimental result showed as follows. It is the one case that only right height is deformed. In another case, after left height is deformed, next right height is deformed. To compare with these two cases, the amount of plastic deformation is different even in the case of equal right-height total deformation. Therefore, when the amount of adjustment is decided, we must take the direction and quantity of the prior adjustment into consideration.

4. Probability-type Fuzzy Inference Adjustment Algorithm Using Accumulation-grade Membership Function

4.1 Probability-type Fuzzy Inference for Plastic Deformation Dispersion

The case of 1-input and 1-output will serve here as a simple example. Supposing that there is no mutual interference, how to calculate the total deformation quantity to adjust the height step with the right-height adjustment mechanism is explained.

What must be calculated by the algorithm is the total deformation quantity needed to get the required amount of height step plastic deformation. But, the amount of plastic deformation isn't uniquely determined even if plastic deformation is performed by the same total deformation quantity as shown in Fig.4. A probability curved surface as in Fig.7 where a vertical axis shows probability can be imagined from Fig.4. The dispersion of the total deformation quantity for a given plastic deformation quantity can be shown in the a-a' cross section of the curved surface in Fig.7. The algorithm has only to make a plausible solution for total deformation quantity in this dispersion of the total deformation quantity. In this case, because the center of gravity of the a-a' cross section is plausible, this value is made the control input of the height step adjustment.

The above operation is generalized as a fuzzy inference law that calculates control input. First, membership function is defined by using the distribution of the amount of plastic deformation for the constant total deformation quantity. The probability distribution of the dispersion of the amount of height step plastic deformation when the right-height was deformed by the total deformation quantity 110 μm is shown in Fig.8. The probability density function $f(x)$ of a normal distribution with mean α , Standard Deviation σ is Eq.(1). x is a continuous probability variable.

$$f(x) = \frac{1}{\sigma\sqrt{2\pi}} \exp\left(-\frac{1}{2}\left(\frac{x-\alpha}{\sigma} \right)^2 \right) \tag{1}$$

That probability distribution function $F(x)$ is Eq.(2).

$$F(x) = \frac{1}{\sigma\sqrt{2\pi}} \int_{-\infty}^{x} \exp\left(-\frac{1}{2}\left(\frac{v-\alpha}{\sigma} \right)^2 \right) dv \tag{2}$$

Therefore, the probability $p(a \le x \le b)$ that a continuous probability variable x is within section $[a,b]$ is calculated by Eq.(3).

$$p(a \le x \le b) = F(b) - F(a) \tag{3}$$

The integral of Eq.(1) can't be evaluated in the simple method. However, it is known that the probability that a continuous probability variable is within a small section of the width h around x can be approximated by Eq.(4).

$$f(x) \cdot h \tag{4}$$

So, probability can be calculated by Eq.(5).

$$p(x) = f(x) \cdot h = \frac{h}{\sigma\sqrt{2\pi}} \exp\left(-\frac{1}{2}\left(\frac{x-\alpha}{\sigma} \right)^2 \right) \tag{5}$$

In this case, the small section width h was defined as 1μm, the resolution of the gap measurement.

The left vertical axis of Fig.8 shows the frequency of the histogram. The right vertical axis shows the probability calculated by Eq.(5). We judged that it was possible that the dispersion of the amount of plastic deformation was approximated by the normal distribution from this result. It will be finally judged whether this approximation is correct by the quality of the adjustment experiment results. Then, the membership function is defined by using Eq.(5). Because probability is less than 1, the maximum value of the grade of this membership function becomes less than 1. In this case, probability, that is grade, doesn't take the value of 0 in any input value by the reason of the characteristics of the probability density function. In other words, the range of the membership function is infinity. Since there is no constraint that the range must be finite in the declaration of the membership function, the conditions for the membership function are satisfied. Eight kinds of membership function were defined from the distribution of plastic deformation in eight total deformation quantities. Also, the control input of then-part is a unique quantity. Therefore, the following IF-THEN rule whose then-part is singleton is derived as a fuzzy rule.

IF the targeted amount of height step plastic deformation is about 9.3μm
THEN control input of right-height deformation is 110μm
Fuzzy inference is done using these membership functions and the IF-THEN rules.
If a height step plastic deformation is x and a total deformation quantity is y, the 1-input and 1-output fuzzy inference is expressed by the following equation.

$$R^i : \text{If } x \text{ is } A_i \text{ then } y = f_i \quad (i=1,2,\ldots\ldots,8) \tag{6}$$

$$\mu_i = A_i(x) \tag{7}$$

$$y^* = \sum_i \mu_i \cdot f_i \Big/ \sum_i \mu_i \tag{8}$$

R^i : The fuzzy rule i. A_i: Fuzzy variable. f_i: Singleton. μ_i : if-part fitness value of R^i. y^*: Inference value.

The example of the inference process is shown in Fig.9. For example, an inference process to give a height step an amount of plastic deformation of 5μm is mentioned concretely. First, the fitness value of each rule is calculated in if-part. Then, this calculated fitness value is made the grade of the membership of then-part. Then the center of gravity of the total deformation quantity calculated in each rule is made an inference result as shown in the bottom right of Fig.9. In this case, the inference result that the total deformation quantity of 88.6μm should be given to the right-height is calculated.

4.2 Probability-type Multiple-input/Multiple-output Fuzzy Inference (for Mutual interference and Adjustment History)

In the case of 1-input and 1-output, even in the form of fuzzy inference, it is almost equivalent to taking the ridge of the probability curved surface in Fig.7 or the relation in Fig.4. For a problem like the magnetic head adjustment, because of mutual interference and the effect influenced from of the adjustment history, fuzzy rules become multiple-input/multiple-output. Fuzzy inference is an effective measure in such a case.

For example, it can get the following knowledge from the absolute height adjustment experiment.

The right-height is deformed plastically about 5μm when control input for right height is 103μm and control input for left height is 140μm.

Then, the left height is also deformed plastically about 15μm.

But, the gap distance is deformed plastically about 3μm as well.

In this way, the gap distance is deformed even if only the left and right heights are deformed. Plastic deformation due to mutual interference tends to be recognized as hard to manage. But, if this knowledge is taken conversely, the following fuzzy rule can be got.

IF the targeted value of right-height plastic deformation is about 5μm
and the targeted value of left-height plastic deformation is about 15μm
and the targeted value of gap distance plastic deformation is about 3μm
THEN control input of right-height deformation is 103μm
and control input of left-height deformation is 140μm
and control input of gap distance deformation is 0μm

In this case, 3-input/3-output non-linear modeling becomes necessary. However, multiple-input/multiple-output non-linear modeling can be constructed easily using the probability-type fuzzy inference discussed in this paper. Therefore, mutual interference can be taken into consideration easily.

Fuzzy inference yields the next equation in the case of 3-input x_1, x_2, x_3, output y.

R^i : If x_1 is A_{i1} and
x_2 is A_{i2} and
x_3 is A_{i3}
then $y = f_i$ $(i=1,2,\ldots\ldots,n_R)$ (9)

$$\mu_i = A_{i1}(x_1) * A_{i2}(x_2) * A_{i3}(x_3) \tag{10}$$

$$y^* = \sum_i \mu_i \cdot f_i \Big/ \sum_i \mu_i \tag{11}$$

n_R: The number of rules.

Using the probability-type fuzzy inference presented here, the fitness value of if-part in the case of 3-inputs was calculated by the multiplication of grades of three membership functions (Fig.10). This inference law achieves that inference value corresponding to the probability of the probability that 3 conditions of if-part are satisfied together. The consideration of adjustment history can be made a fuzzy rule by the same method as for consideration of mutual interference. The example of the rule of the left-height adjustment after right-height adjustment was done is shown.

IF right-height was deformed with control input of 150μm
and the targeted value of height-step plastic deformation is about -3.5μm
THEN control input of left-height deformation is 150μm

4.3 Accumulation Grade Membership Function (Consideration of Qualitative Knowledge)

The methods already mentioned can't reduce dispersion itself. In the case of Fig.8, the right-height is deformed by 110μm to adjust the height step by 9.3μm. But there is a dispersion of 7μm with 3σ by the experimental result. Therefore, adjustment can't be done one time with any further accuracy. However, if the dispersion factor can be taken into consideration, it becomes possible that an adjustment with better accuracy can be done.

Fig.4 is explained here as an example. The dispersion of the amount of height-step plastic deformation was 3σ=7.49μm when the right-height was deformed by the total deformation quantity 110μm. The number of samples was 59. The head base thickness in each work piece was measured by a capacitive sensor. The relation between the dispersion of the board thickness and the dispersion of the amount of plastic deformation are shown in Fig.11. The marks in the figure are actual measurement values, and the continuous line is the result calculated by least squares. This absolute value of the coefficient of correlation is small at 0.31. But, it is understood that the amount of plastic deformation is large when board thickness is small, and the amount of plastic deformation is small when board thickness is large. So, this distribution is divided fuzzily, based on the board thickness. The membership function of the head base thickness is shown in Fig.12. The method of fuzzy division is mentioned in detail using Fig.13. The grade of the membership function for “thin” becomes 0.51 if the board thickness of 1 sample inside the plastic deformation quantity 6μm (number of samples: 5) is 0.96mm. Grade of “average” becomes 0.49, and grade of “thick” becomes 0.0. The grade of each membership function was calculated for five samples of the total deformation quantity 110μm and plastic deformation quantity 6μm. This result is shown in Fig.13. Grade is added to every membership function.

This is called an accumulated grade. The distribution of the accumulated grade occurs as shown in Fig.14 when this operation is done for all the plastic deformations of total deformation quantity 110μm. Each accumulated grade distribution was treated as a normal distribution, and the approximation function derived from the Eq.(5) was made as the membership function. This was called the accumulation grade membership function.

In this case, the average plastic deformation for the thin board thickness becomes 10.1μm. And the rule that is shown in Section4.1 above becomes the following(Fig.15).
IF board thickness is “thin”
and the targeted value of right height-step plastic deformation is about -10.1μm
THEN control input of right height deformation is 110μm
A probability-type fuzzy inference formed by the accumulated grade membership function, which made it possible to introduce qualitative knowledge for statistical qualitative calculation, was designed as mentioned above.

5. Experimental Result of Magnetic Head Adjustment

The experimental results are shown in Table 1. Here, two times adjustments are allowed in one work piece. Because this algorithm was a stochastic inference method, accuracy was evaluated by the accumulation probability of the normal distribution.
The error of the amount of plastic deformation is taken to be a normal distribution. The mean standard deviation $\overline{\sigma}$ which is the average of the dispersion of plastic deformation in the constant total deformation quantity, and a mean computed error $\overline{d}$ are used. The distribution of the plastic deformation quantity error is expressed by the probability density function of Eq.(12) as follows.

$$f(x) = \frac{1}{\overline{\sigma}\sqrt{2\pi}} \exp\left(-\frac{1}{2}\left(\frac{x-\overline{d}}{\overline{\sigma}} \right)^2 \right) \tag{12}$$

At this time, an adjustment success rate is calculated by the accumulation probability of Eq.(12) in the "good" area ±s.

$$F(x) = \int_{-s}^{+s} f(x)dx \tag{13}$$

s is the specifications value of the quality decision. On the contrary, if we know standard deviation $\overline{\sigma}$ and a mean adjustment success rate $F(x)$, a mean computed error $\overline{d}$ can be calculated by the approximation solution. Next, performance comparison with the usual algorithm in the adjusting device developed before is performed. This algorithm only interpolates the average value of the linear dispersion. The effect of the board thickness isn't taken into consideration. Mutual interference is taken into consideration by linear simultaneous equations. Adjustment history isn't taken into consideration at a second adjustment.

For the first adjustment, the computed accuracy of the amount of adjustment improves about four times as shown in Table 1. In addition, the specifications of the height step in this experiment device are half that for usual adjustment machines. In other words, this device must perform with higher accuracy than a normal facility. Nevertheless, the adjustment success rates are improved about 25%, even when two adjustments were necessary. The success rate where specifications can be satisfied by a second adjustment is called a total success rate. Though adjustment specifications became severe, the total success rate was improved about 10%.

A very large number of work piece was required for this experiment for evaluation of the dispersion. Therefore, an experiment that didn't take head base thickness into consideration couldn't be done separately. Therefore, the effect of the consideration of board thickness was estimated. The dispersion when consideration wasn't done was 3 σ =7.49μm as in as Fig.14. However, the dispersion of the accumulation grade when head base thickness is thin decreases slightly with 3 σ =6.57μm. A success rate was calculated at 86.3% by entering a dispersion where board thickness wasn't taken into considered for Eq.(13). A success rate was calculated at 89.6% if the effect of board thickness was taken into considered. It was estimated from this result that the improvement was about 3%. This case couldn't get a remarkable effect because the coefficient of correlation was too poor at -0.31, as shown in Fig.11. However, in principle, it could be done from the viewpoint of the probability-type fuzzy inference using an accumulation grade membership function.

6. Conclusion

Application of fuzzy control to precise adjustment process in production line was studied for improving the success rate of adjustment. A probability-type fuzzy inference that catches data dispersion as fuzziness was proposed. A membership function is defined in this method as a probability density function of the dispersion. Also, an accumulation grade membership function was proposed to improve inference accuracy more. This method defines membership functions in consideration of qualitative knowledge of the causes of dispersion. The application of fuzzy inference to high precise control became possible using this proposed method.

An experimental evaluation of magnetic head adjustment resulted in a success rate of 99.5%, that was considered a sufficient success rate. The success rate was improved about 10%, as compared with conventional adjusting devices, under strict specifications. The effectiveness of this proposed method was proved from this experimental result.

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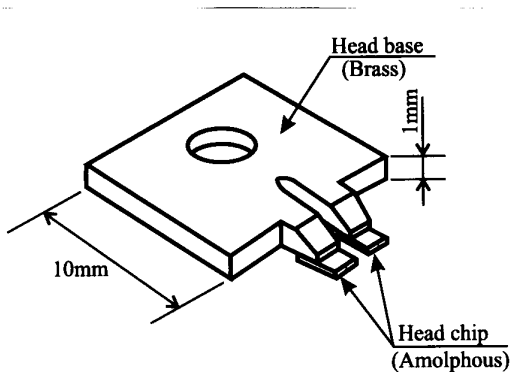


Fig.1 Construction of magnetic head

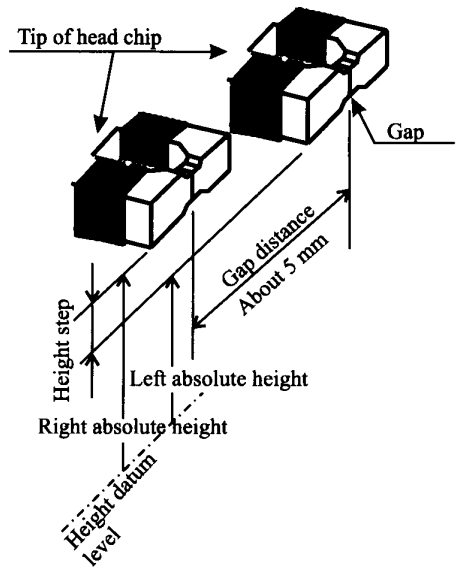


Fig.2 Adjustment items

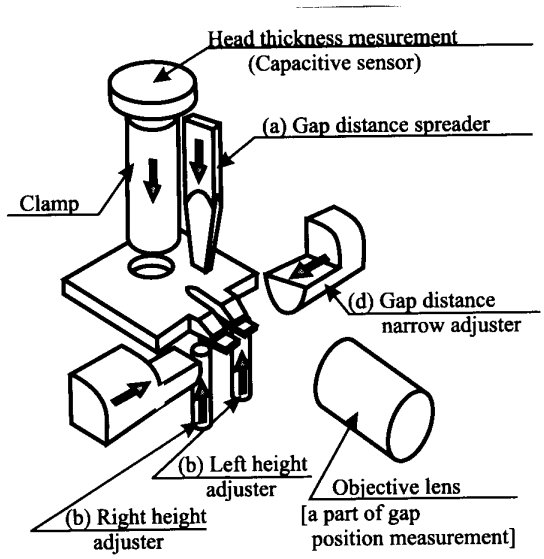


Fig.3 Configuration of adjustment mechanism

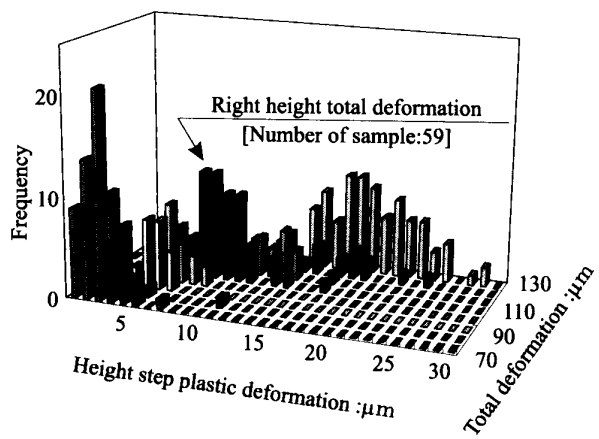


Fig.4 Histogram of dispertion and non-linearity of plastic deformation

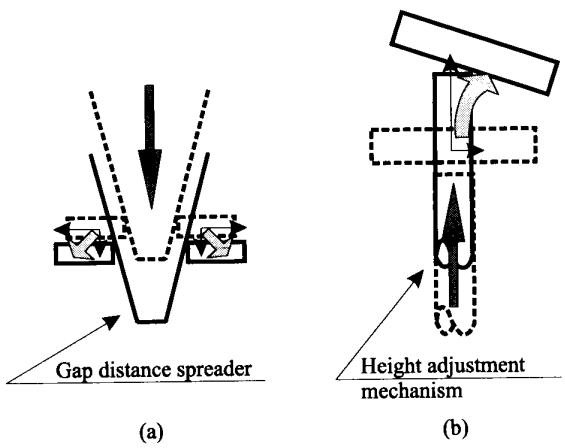


Fig.5 Gap spreader and height adjuster

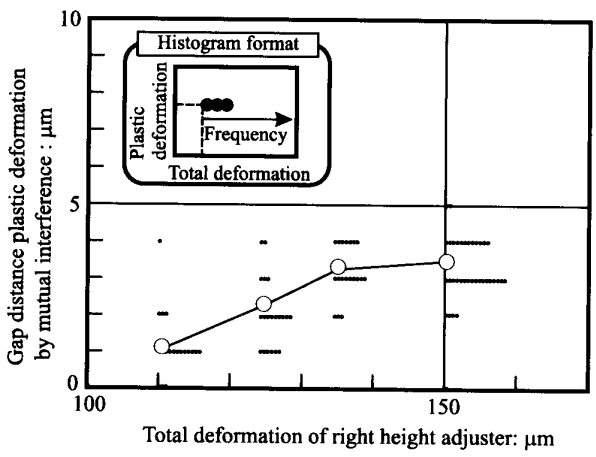
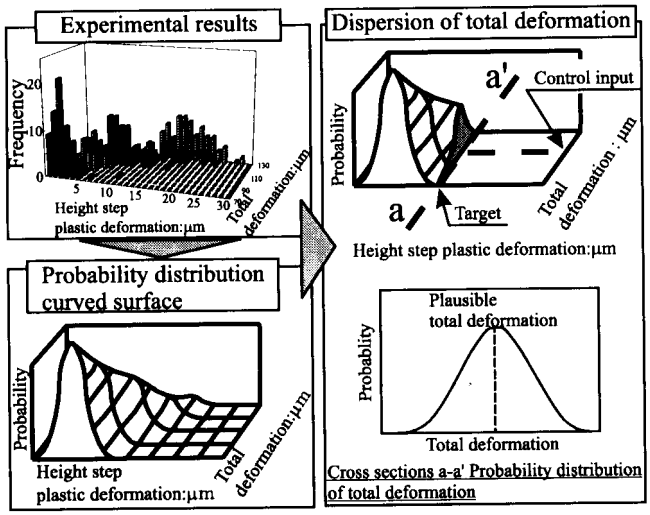


Fig.6 Total deformation and plastic deformation



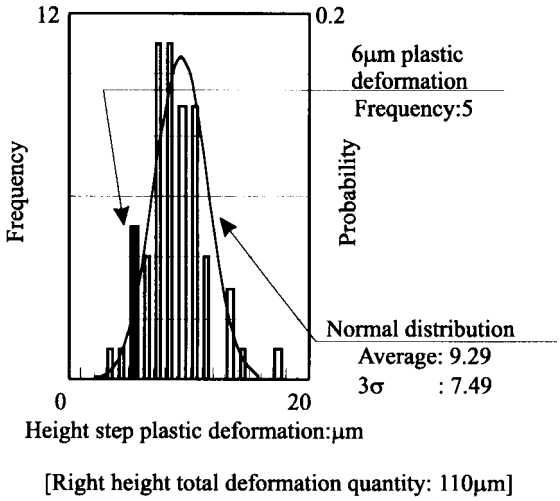
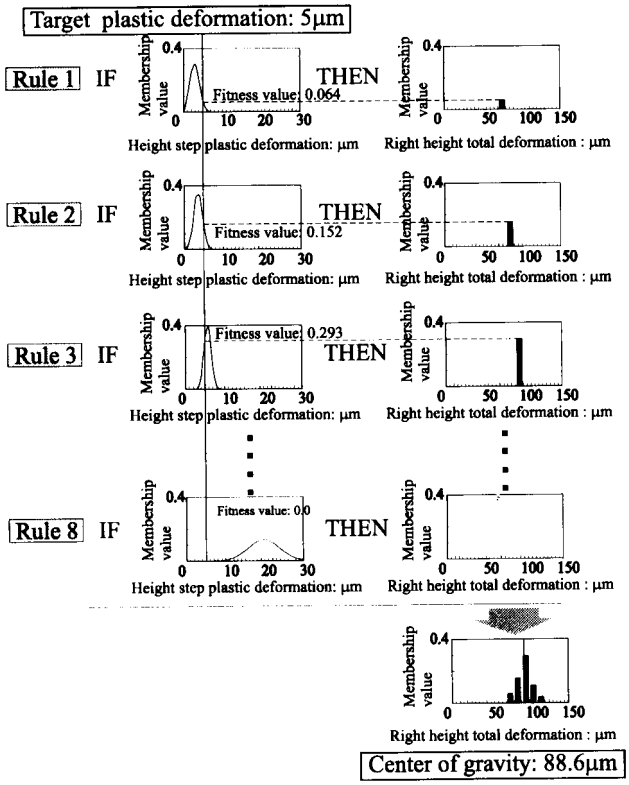


Fig.7 Cross section of probability curved surface

Fig.8 Dispersion of plastic deformation



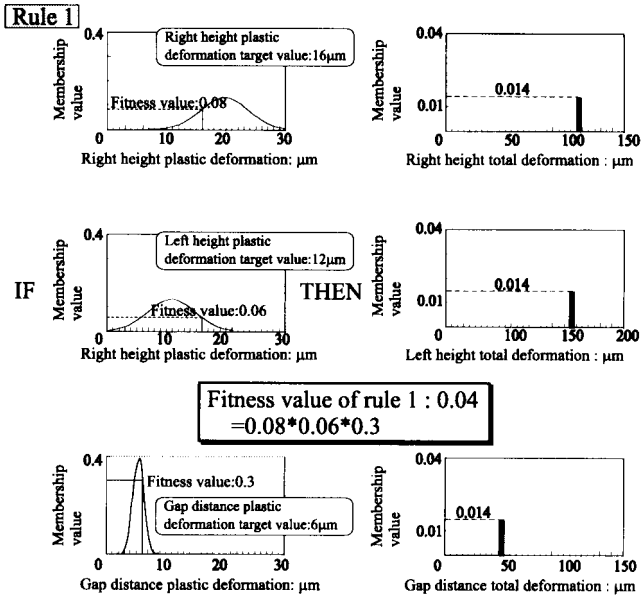


Fig.9 Fuzzy inference process (1-input、1-output)

Fig.10 Multiplication of grades of 3 membership functions

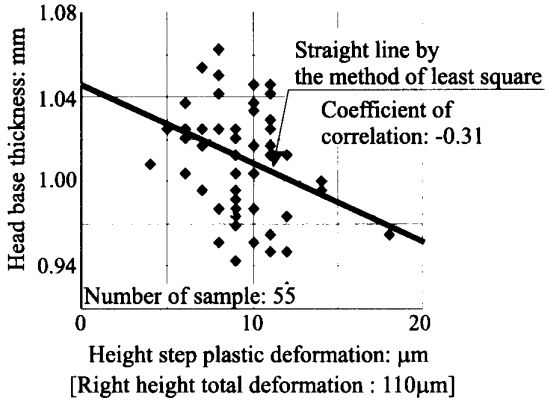


Fig.11 Correlation between plastic deformation and thickness

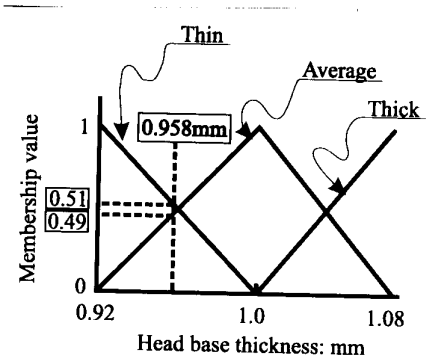


Fig.12 Membership functions for head base thickness

Right height total deformation	Height step plastic deformation	Head base thickness	Grade		
			Thin	Average	Thick
110μm	6 μm	0.96mm	0.51	0.49	0.0
		1.01mm	0.0	0.85	0.15
		1.01mm	0.0	0.90	0.10
		0.99mm	0.10	0.90	0.0
		1.02mm	0.0	0.69	0.31
Accumulated grade			0.61	3.82	0.57

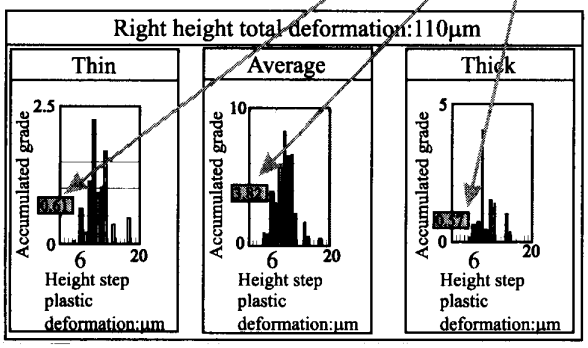


Fig.13 Calculation of accumulated grade distribution

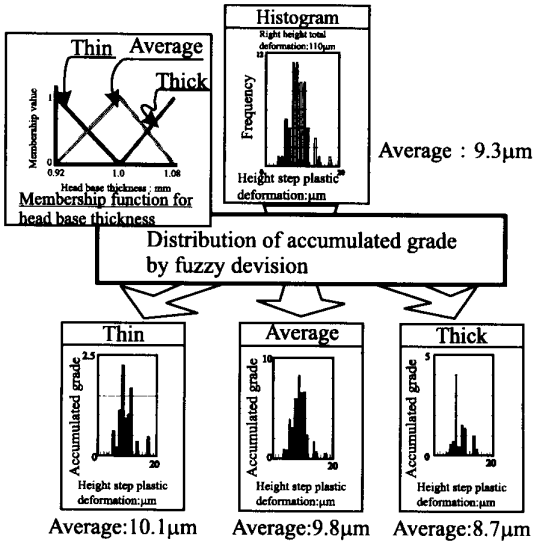


Fig.14 Distribution of accumulated grade

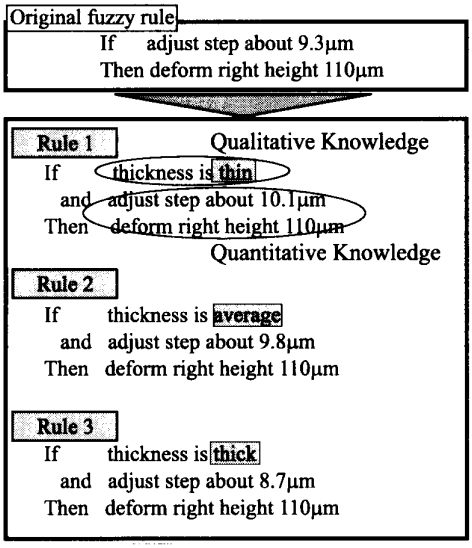


Fig.15 Fuzzy rules using accumulated grade membership function

Table 1 Experimental result

			This method	Conventional method
First time adjustment	Height step adjustment	Calculation accuracy	2.15μm	8.87μm
		Success rate	94.1%	69.3%
		Success rate 24.8% UP		
	Gap distance adjustment	Calculation accuracy	0.004μm	2.098μm
		Success rate	91.5%	67.0%
		Success rate 24.5% UP		
Retry adjustment (second time)		Success rate	92.3%	67.2%
		Success rate 25.1% UP		
Overall success rate			99. 5%	89. 9%

Fail rate decrease into about 1/20
In this case, the required precision is 1/2
in comparison with conventional specification.