Application of Regression Analysis for Quality Control In Suspension Manufacturing

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Abstract: This paper presents the laser processing to adjust the roll and pitch directions of the flex suspension assembly for hard disk drive production. The adjustment is accomplished using a number of laser beam projections that can be approximated using the regression model of the existing measured roll and pitch directions. Information derived from the analysis can be applied to control the quality of flex suspension assembly. The performances of the proposed technique were observed using the flex suspension assembly plant in Thailand as an illustrative case study. The experimental results are given to support the improving manufacturing yields and some economic benefits of the proposed technique.

Keywords: roll and pitch directions, flex suspension assembly, regression analysis, laser processing.

1. INTRODUCTION

Among the components of the head actuator assembly for hard disk drive (HDD), a suspension or load beam is relatively thin as compared to an arm; thus, it is flexible to roll and pitch at the slider location to allow the adaptation due to the unevenness of the disk surface. The roll is an angular rotation of a slider about the axis parallel to the travel of the media. The pitch is an angular rotation of the slider about the axis parallel to the plane of the media and perpendicular to the record track. Moreover, the suspension should not bend or twist during the operation as this would misdirect the head away from the track it is following.

Recently, there has been much effort to improve the suspension performance [1-3]. The optimal mass and stiffness of the suspension for enhancing performance is one of the most significant problems to be solved [4-5]. The critical parameters a suspension has to maintain are gram load, static roll, and pitch stiffness. The gram load adjustment for improved HDD performance using laser processing has been proposed in literature [6]. This paper aims to present the similar laser processing to adjust the roll and pitch directions of the flex suspension assembly for HDD production.

The proposed adjustment can be applied to the suspension manufacturing to control the mean and standard deviation of the roll and pitch directions. The number of the laser beam projections is the important factor that impacts the roll and pitch directions. Therefore, the regression analysis [7-8] is recommended to estimate the number of the laser beam projections based on the existing measured roll and pitch directions. Information derived from the analysis can help control the quality of flex suspension assembly.

The suspension manufacturing, KR. Precision Public Company Limited, Thailand, was studied as an illustrative case study. The experimental results demonstrating the improving manufacturing yield and some benefits of the proposed technique are obtained.

2. REGRESSION ANALYSIS

Regression analysis is a commonly used method in order to obtain a prediction function that estimates the values of one dependent variable from known values of one or more independent variables. The simple linear regression analysis [9], which involves only one predictor, is used in this paper. Given a discrete sampling of N data points having coordinates

$$P_i = (x_i, y_i) \quad ; i = 1, 2, \ldots, N \tag{1}$$

It is assumed that the value of y_i can be correlated to the value of the x_i coordinate via an approximate function Y having the form:

$$Y(x) = a_n x^n + a_{n-1} x^{n-1} + \ldots + a_1 x + a_0 \tag{2}$$

which corresponds to an nth degree of polynomial expansion. If n = 1, it is called a first-order polynomial equation, which is identical to the equation for straight line. If n = 2, it is called a second-order or quadratic equation. If n = 3, it is called a third-order or cubic equation. The expansion coefficients a_n, a_{n-1}, … , a_1, a_0 are determined by least-square fitting the data points to this expansion. The resulting continuous function may then be used to estimate the value of y over the entire x region where the approximation has been applied.

The simplest classes of regression functions that are useful in economics area such as forecasting and cost-benefits analysis are straight-line function and quadratic function [10].

2.1 Straight-line regression model

The straight-line regression model can be written as

$$y_i = a_1 x_i + a_0 \tag{3}$$

The quantity a_1 is the slope and a_0 is the intercept of the regression line. The sum of squares of prediction errors E are defined by

$$E = \sum_{i=1}^{N} \left(y_i - a_1 x_i - a_0 \right)^2 \tag{4}$$

It can be mathematically proven that the values of a_1 and a_0 that minimize E in Eq. (4) are given by

$$a_1 = \frac{\sum_{i=1}^{N} (x_i - \bar{x})(y_i - \bar{y})}{\sum_{i=1}^{N} (x_i - \bar{x})^2} \tag{5}$$

and $a_0 = \overline{y} - a_1\overline{x}$ (6)

where $$\overline{x} = \frac{1}{N}\sum_{i=1}^{N} x_i \quad (7)$$

and $$\overline{y} = \frac{1}{N}\sum_{i=1}^{N} x_i \quad (8)$$

Residual variance is measure of the variation of the Y values about the regression line. Residual variance or R-squared can be given by

$$R^2 = \frac{\sum_{i=1}^{N}\left(y_i - \overline{y}\right)}{N-2} \quad (9)$$

The standard error of estimate can be calculated from the square root of the residual variance as follow:

$$\sigma = \sqrt{\frac{\sum_{i=1}^{N}\left(y_i - \overline{y}\right)}{N-2}} \quad (10)$$

2.2 Quadratic regression model

The quadratic regression model can be written as

$$y_i = a_2 x_i^2 + a_1 x_i + a_0 \quad (11)$$

The constants, a_2, a_1, and a_0 in the regression equation are called the regression coefficients. The sum of squared errors E can be written as

$$E = \sum_{i=1}^{N}\left(y_i - a_2 x_i^2 - a_1 x_i - a_0\right)^2 \quad (12)$$

Hence:

$$\frac{\partial E}{\partial a_2} = \sum_{i=1}^{N} 2\left(a_2 x_i^4 + a_1 x_i^3 + a_0 x_i^2 - y_i x_i^2\right)$$

$$\frac{\partial E}{\partial a_1} = \sum_{i=1}^{N} 2\left(a_2 x_i^3 + a_1 x_i^2 + a_0 x_i - y_i x_i\right)$$

$$\frac{\partial E}{\partial a_0} = \sum_{i=1}^{N} 2\left(a_2 x_i^2 + a_1 x_i + a_0 - y_i\right)$$

Equating these partial derivatives to zero gives:

$$a_2\sum_{i=1}^{N} x_i^4 + a_1\sum_{i=1}^{N} x_i^3 + a_0\sum_{i=1}^{N} x_i^2 - \sum_{i=1}^{N}\left(y_i x_i^2\right) = 0$$

$$a_2\sum_{i=1}^{N} x_i^3 + a_1\sum_{i=1}^{N} x_i^2 + a_0\sum_{i=1}^{N} x_i - \sum_{i=1}^{N}\left(y_i x_i\right) = 0$$

$$a_2\sum_{i=1}^{N} x_i^2 + a_1\sum_{i=1}^{N} x_i + a_0 n - \sum_{i=1}^{N} y_i = 0$$

Solve the above three simultaneous equations. The values for a_2, a_1, and a_0 are obtained as

$$a_2 = \frac{t_3 t_4 - t_2 t_5}{t_1 t_3 - t_2^2} \quad (13)$$

$$a_1 = \frac{t_2 t_4 - t_1 t_5}{t_2^2 - t_1 t_3} \quad (14)$$

$$a_0 = \frac{\sum_{i=1}^{N} y_i - a_2\sum_{i=1}^{N} x_i^2 - a_i\sum_{i=1}^{N} x_i}{N} \quad (15)$$

where

$$t_1 = N\sum_{i=1}^{N} x_i^4 - \left(\sum_{i=1}^{N} x_i^2\right)^2$$

$$t_2 = N\sum_{i=1}^{N} x_i^3 - \sum_{i=1}^{N} x_i^2 \sum_{i=1}^{N} x_i$$

$$t_3 = N\sum_{i=1}^{N} x_i^2 - \left(\sum_{i=1}^{N} x_i\right)^2$$

$$t_4 = N\sum_{i=1}^{N}\left(x_i^2 y_i\right) - \sum_{i=1}^{N} x_i^2 \sum_{i=1}^{N} y_i$$

$$t_5 = N\sum_{i=1}^{N}\left(x_i y_i\right) - \sum_{i=1}^{N} x_i \sum_{i=1}^{N} y_i$$

A formula for R^2 that demonstrates as

$$R^2 = \frac{\sum_{i=1}^{N}\left(y_i - \overline{y}\right)^2 - \sum_{i=1}^{N}\left(y_i - \hat{y}_i\right)^2}{\sum_{i=1}^{N}\left(y_i - \overline{y}\right)^2} \quad (16)$$

where $\sum_{i=1}^{N}\left(y_i - \overline{y}\right)^2$ is the total sum of squares.

$\sum_{i=1}^{N}\left(y_i - \hat{y}_i\right)^2$ is the residual sum of squares.

3. LASER ROLL AND PITCH ADJUSTMENTS

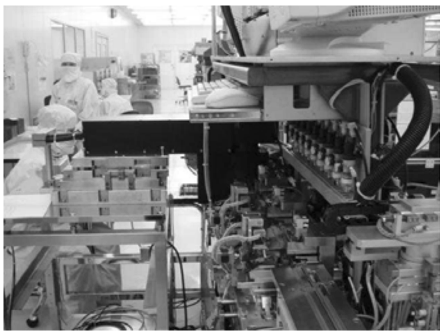


Fig. 1 Laser processing.

A laser processing as shown in Fig. 1 projects the laser beam on the target point along with measured roll and pitch directions. In order to adjust the roll and pitch directions, the radiation intensity of the laser and the number of laser beam projections must be specified. The impacts of the number of projections on the roll and pitch directions are then analyzed separately using the regression model. In the experiment, one suspension is used for each laser beam projection. If the roll and pitch directions are outside the acceptable ranges, then the suspension will be rejected. That is, the data collected for the analysis are from those suspensions that are accepted after the experiment.

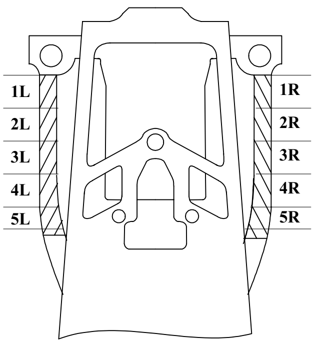


Fig. 2 Laser beam point sections on suspension.

The area of the suspension on which the laser beam is projected can be classified into 5 sections as shown in Fig. 2 when L and R represent the left and right of the suspension, respectively. The target points are then randomly selected as shown in Table 1. Note that the pitch direction is not adjusted unless the roll direction is completely adjusted.

Table 1 Sampling laser beam positions.

Beam Position	Start Point	End Point
1Lp	-1.178,0.70	-0.980,0.70
2Lp	-1.178,0.55	-0.980,0.55
3Lp	-1.178,0.40	-0.980,0.40
4Lp	-1.178,0.25	-0.980,0.25
5Lp	-1.178,0.1	-0.980,0.1
1Rp	1.178,0.70	0.980,0.70
2Rp	1.178,0.55	0.980,0.55
3Rp	1.178,0.40	0.980,0.40
4Rp	1.178,0.25	0.980,0.25
5Rp	1.178,0.1	0.980,0.1

Given that

$\Delta Roll$ is the difference of the roll directions before and after the laser beam projection.

$\Delta Pitch$ is the difference of the pitch directions before and after the laser beam projection.

n_r is the number of laser beam projections for roll adjustment.

n_p is the number of laser beam projections for pitch adjustment.

To obtain the regression models representing the relationship between predictor variables $\Delta Roll$ and n_r, the procedure starts by projecting the laser beam onto two suspensions for each specified target as shown in Table 1. The sampling $\Delta Roll$ and $\Delta Pitch$ are shown in Fig. 3, where (1) and (2) refer to the first and second projection onto the suspension, respectively. In order to determine the most appropriate area for roll adjustment, the target must have high $\Delta Roll$ and high $\Delta Pitch$. From Fig. 3, two targets, 1Rp and 2Rp, are chosen as the proper areas for the laser beam projection in order to adjust the roll's direction. Since the laser beam projection also has the impact on the specimen's pitch, re-projecting the laser beam to adjust the pitch direction further performs the compensation. The sampling experiment is further performed as given in Table 2 to evaluate the effects of the number of laser beam projections on the adjustment of roll and pitch directions. First, the projecting is aimed at the point 1Rp. Then the distance along the ordinate is decreased 10μm each time for, if any, the next projection.

Table 2 Sampling experiment to evaluate the effects of the number of laser beam projections.

Number of Projections	$\Delta Roll$	$\Delta Pitch$
1 (1^{st} Projection)	0.000	0.060
1 (2^{nd} Projection)	-0.022	0.026
1 (3^{rd} Projection)	-0.001	0.079
5 (1^{st} Projection)	-0.030	0.080
5 (2^{nd} Projection)	-0.026	0.047
5 (3^{rd} Projection)	-0.045	0.057
10 (1^{st} Projection)	-0.067	0.145
10 (2^{nd} Projection)	-0.065	0.146
10 (3^{rd} Projection)	-0.061	0.074
15 (1^{st} Projection)	-0.127	0.157
15 (2^{nd} Projection)	-0.106	0.109
15 (3^{rd} Projection)	-0.105	0.124
20 (1^{st} Projection)	-0.113	0.061
20 (2^{nd} Projection)	-0.077	0.123
20 (3^{rd} Projection)	-0.122	0.113

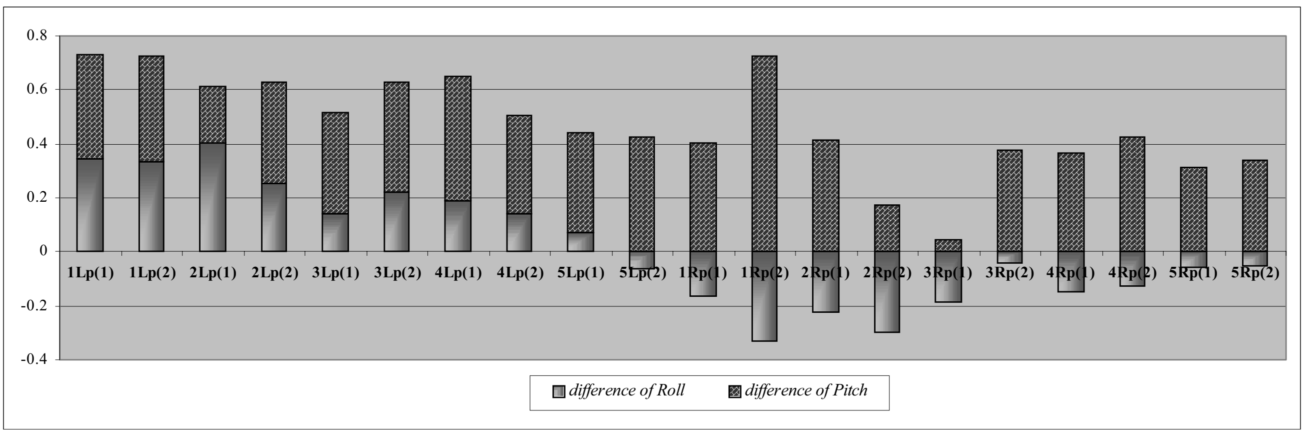


Fig. 3 Sampling $\Delta Roll$ and $\Delta Pitch$ obtained from projecting onto two suspensions for each specified target.

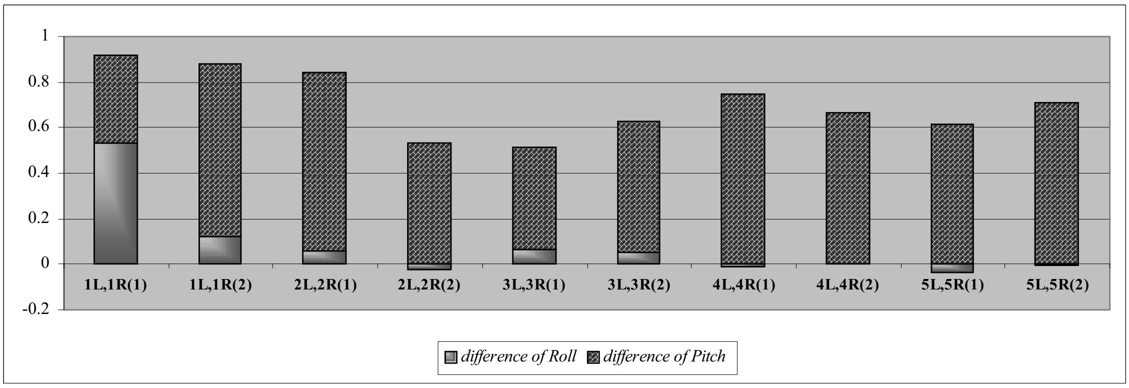


Fig. 4 Sampling $\Delta Roll$ and $\Delta Pitch$ obtained from projecting onto two suspensions for each specified target.

From Table 2, the relationship between $\Delta Roll$ and n_r can be expressed using the straight-line and quadratic regression models according to Eq. (3) and Eq. (11), respectively, given that $\Delta Roll$ is the predictor variable y and n_r is the response variable x. The regression models can be written as follows.

Straight-line regression model for roll direction:

$$\Delta Roll = -0.0056n_r - 0.0069$$

when $R^2 = 0.8419$

Quadratic regression model for roll direction:

$$\Delta Roll = 0.0002n_r^2 - 0.0101n_r + 0.0067$$

when $R^2 = 0.8782$

The relationships between $\Delta Roll$ and n_r without using regression analysis can be stated as the straight-line equation, that is,

$$\Delta Roll = a_r n_r + b_r \qquad (17)$$

where a_r and b_r are the slope and the intercept of the straight line, respectively. The values of a_r and b_r can be calculated from any two coordinates (x_{1j}, y_{1j}) and (x_{2j}, y_{2j}).
Given that
k is the collection of number of projections
$j = 1, 2, \ldots, k-1$
x_{2j} is the number of projections
y_{2j} is the average of $\Delta Roll$'s magnitudes

From Table 2, k = 5, the first straight-line equation is computed from following two coordinates,

$$x_{11} = 0, y_{11} = 0 \Rightarrow (x_{11}, y_{11}) = (0,0)$$
$$x_{21} = 1, y_{21} = \frac{0 + 0.022 + 0.001}{3} \Rightarrow (x_{21}, y_{21}) = (1, 0.008)$$

The second straight-line equation is calculated from following two coordinates,

$$x_{12} = x_{21} = 1, y_{12} = y_{21} = 0.008 \Rightarrow (x_{12}, y_{12}) = (1, 0.008)$$
$$x_{22} = 5, y_{22} = \frac{0.030 + 0.026 + 0.045}{3} \Rightarrow (x_{22}, y_{22}) = (5, 0.034)$$

Similarly, the third and fourth straight-line equations are calculated from the coordinates, (5,0.034), (10,0.079), and (10,0.079), (15,0.013), respectively. Table 3 gives the relationships between $\Delta Roll$ and n_r without using regression model.

Table 3 Relationship between $\Delta Roll$ and n_r without using regression model.

Range of $\Delta Roll$	Straight-line equation
$0 < \Delta Roll < 0.008$	$\Delta Roll = 0.008n_r$
$0.009 < \Delta Roll < 0.034$	$\Delta Roll = 0.0065n_r + 0.0015$
$0.035 < \Delta Roll < 0.079$	$\Delta Roll = 0.009n_r - 0.011$
$0.080 < \Delta Roll < 0.113$	$\Delta Roll = 0.0068n_r + 0.011$

The procedure to obtain the regression model representing the relationship between predictor variable $\Delta Pitch$ and n_p starts by simultaneously projecting the laser beam on both left and right sides (for example, projecting 1L and 1R at once) onto two suspensions for each pair of specified targets. The sampling $\Delta Roll$ and $\Delta Pitch$ are then displayed in Fig 4, where (1) and (2) refer to the first and second projection onto the suspension, respectively.

Table 4 Sampling experiment to evaluate the effects of the number of laser beam projections.

Number of Projections	$\Delta Roll$	$\Delta Pitch$
1 (1st Projection)	-0.010	-0.076
1 (2nd Projection)	0.004	-0.100
1 (3rd Projection)	-0.006	-0.089
5 (1st Projection)	0.001	-0.302
5 (2nd Projection)	0.000	-0.292
5 (3rd Projection)	-0.006	-0.290
10 (1st Projection)	-0.043	-0.501
10 (2nd Projection)	-0.008	-0.496
10 (3rd Projection)	0.074	-0.496
15 (1st Projection)	-0.033	-0.785
15 (2nd Projection)	0.072	-0.759
15 (3rd Projection)	0.050	-0.786
20 (1st Projection)	0.032	-0.998
20 (2nd Projection)	-0.007	-0.980
20 (3rd Projection)	0.036	-0.985

In order to determine the most appropriate area for pitch adjustment, the target must have low $\Delta Roll$ (since roll direction is already adjusted) and high $\Delta Pitch$. From Fig. 4, three targets, (3L, 3R), (4L, 4R), and (5L, 5R) (see Fig. 2) are chosen as the proper areas for the laser beam projection in order to adjust the pitch direction. The sampling experiment is further performed as given in Table 4 to evaluate the effects of the number of laser beam projections on the adjustment of roll and pitch directions. First, the laser beam is aimed at the target (3Lp, 3Rp). Then the distances along both ordinates is decreased 10μm each time for, if any, the next projection.

From Table 4, the relationship between $\Delta Pitch$ and n_p can be expressed using the straight-line and quadratic regression models according to Eq. (3) and Eq. (11), respectively, given that $\Delta Pitch$ is the predictor variable y and n_p is the response variable x. The regression models can be written as follows.

Straight-line regression model for pitch direction:

$$\Delta Pitch = -0.0475 n_p - 0.0445$$

when $R^2 = 0.9973$

Quadratic regression model for pitch direciton:

$$\Delta Pitch = 0.00002 n_p^2 - 0.048 n_p - 0.0429$$

when $R^2 = 0.9973$

The relationships between $\Delta Pitch$ and n_p without using regression analysis can be stated as the straight-line equation, that is,

$$\Delta Pitch = a_p n_p + b_p \quad (18)$$

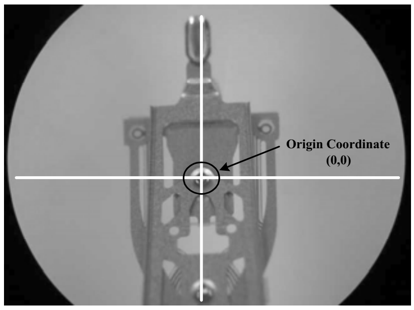
where a_p and b_p are the slope and the intercept of the straight line, respectively. The a_p and b_p calculation procedures are similar to the a_r and b_r calculations. From Table 4, the relationships between $\Delta Pitch$ and n_p without using regression model are summarized in Table 5.

Table 5 Relationship between $\Delta Pitch$ and n_p without using regression model.

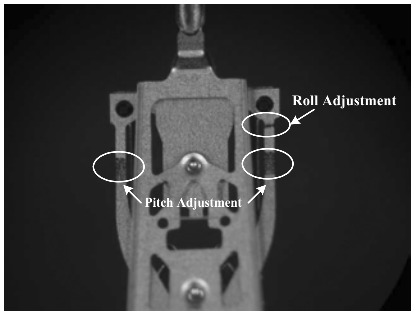
Range of $\Delta Pitch$	Straight-line equation
$0 < \Delta Pitch < 0.088$	$\Delta Pitch = 0.088 n_p$
$0.089 < \Delta Pitch < 0.294$	$\Delta Pitch = 0.0515 n_p + 0.0365$
$0.295 < \Delta Pitch < 0.497$	$\Delta Pitch = 0.0406 n_p + 0.091$
$0.498 < \Delta Pitch < 0.776$	$\Delta Pitch = 0.0558 n_p - 0.061$

Fig. 5 illustrates the roll and pitch adjustments of the suspension using the laser processing. In the experiment, the laser processing is performed automatically using the program written in Visual Basic. The procedure for each regression function (straight-line function or quadratic function) can be explained as follows (see Fig. 6)

(1) specify the parameters of the suspension which are
- Roll's mean target
- Pitch's mean target
- Roll's standard deviation
- Pitch's standard deviation
- Regression model for roll direction
- Regression model for pitch direction
- Sampling number (N_s)



(a) Before laser processing



(b) After laser processing

Fig. 5 Examples of roll and pitch adjustments.

(2) measure roll and pitch directions of the suspension before projecting and record in the database
(3) calculate $\Delta Roll$ to estimate the number of laser beam projecting (n_r) using the Roll's regression model. Also record n_r in the database
(4) project the laser beam to adjust the roll direction
(5) measure roll and pitch directions of the suspension after projecting and record in the database
(6) calculate $\Delta Pitch$ to forecast the number of laser beam projection (n_p) using the Pitch's regression model. Also record n_p into the database
(7) project the laser beam to adjust the pitch direction
(8) measure roll and pitch directions of the suspension and record in the database
(9) use data from (8) to calculate mean and standard deviation
(10) verify whether mean and standard deviation calculated in (9) is within the acceptable ranges. If yes, the regression model is unchanged. Otherwise, find the new regression model

4. RESULTS

At KR. Precision Public Company Limited, Thailand, the experiment was implemented using the following parameters
- Roll's mean target = 0.5 ± 0.05
- Pitch's mean target = 0.2 ± 0.075
- Roll's standard deviation = 0.08
- Pitch's standard deviation = 0.1
- Straight-line regression models for roll and pitch directions

$\Delta Roll = -0.0056 n_r - 0.0069$

$\Delta Pitch = -0.0475 n_p - 0.0445$

- Quadratic regression model for roll and pitch directions

$\Delta Roll = 0.0002 n_r^2 - 0.0101 n_r + 0.0067$

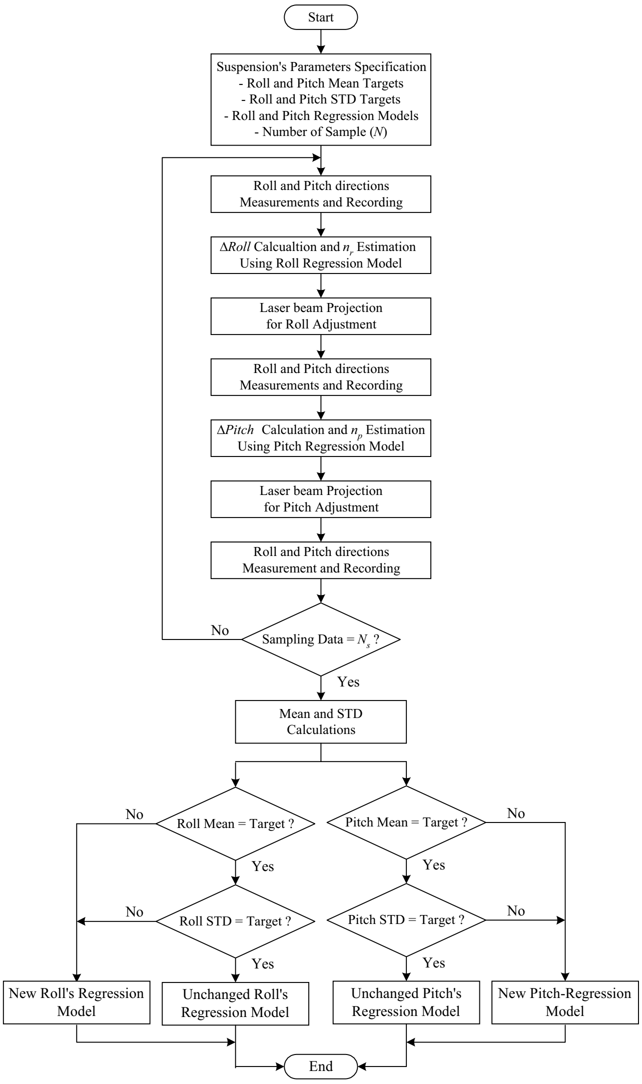


Fig. 6 Flowchart of laser processing.

$$\Delta Pitch = (-0.000021)n_p^2 + 0.026776n_p + 0.058799$$

- Sampling number = 90

The experiment was conducted in 3 approaches, with straight-line regression model, quadratic regression model, and without using regression model. The efficiency of each approach was measured using the manufacturing yield as the criteria. When randomly selecting the area for laser beam projection, the manufacturing yields are summarized in Table 6. The percent increases in the manufacturing yield are 5.64% and 17.68% based on the use of straight-line regression model and quadratic regression model, respectively.

Table 6 Experimental Results.

Experimental approach	Manufacturing yield
Using straight-line regression model	87.64%
Using quadratic regression model	96.5%
Without using regression model	82%

The experimental results show that using the regression model to help estimate the number of laser beam projections can significantly increase the manufacturing yield. The information derived from the quadratic function can help improve manufacturing yield compared with those obtained from the straight-line function.

5. CONCLUSION

This paper has described the use of laser process to adjust the roll and pitch directions of the flex suspension assembly in a disk drive production. The number of the laser beam projections is the important factor that has the impact on the roll and pitch directions. Therefore, the application of regression analysis is recommended to estimate the number of the laser beam projections. The experimental results demonstrating the improving manufacturing yield is obtained. Not only can this proposed technique significantly improve the manufacturing yield, it can also increase some economic benefits.

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