



Uniform Design and Regression Analysis Methods for Optimal Operational Parameter Design of High-pressure Waterjet Machine

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Abstract: Currently, removing scales from harvested fish is a time- and labor-intensive process. To reduce labor costs and improve productivity, this study uses a uniform design and regression analysis methods to design optimal operational parameters of a high-pressure waterjet machine for removing tilapia scales. A uniform layout of $U_{10}^*(10^3)$ was used to arrange three operational parameters for experiments. The removal rate is the quality index defined by the fish scale removal area divided by full surface area covered by scales. Experimental results show a removal rate of 85.39%.

Keywords: fish scales; tilapia scales; uniform design method; regression analysis

Introduction

Removing fish scales is typically a time- and labor-intensive manual task. Attempts have been made to automate industrial scale fish descaling through machine-driven scraping, brushing and spraying with high-pressure waterjets. Such systems have been tested on fish of various weights, with results computed in terms of total area cleaned [1-5].

The present study designs a high-pressure waterjet machine (Fig. 1) to descale tilapia weighing 1 to 3 catties. Three operational parameters were found to influence the removal rate of fish scales, and the uniform design method [6] was used to identify the best combination of these three parameters. After each experiment, both sides of the cleaned fish were photographed, and the total cleaned and uncleaned areas were measured to calculate the removal rate. Regression analysis was used to build a regression model and identify the best operational parameter combination. Finally, the verified experiments were performed by using the operational

parameter combination obtained by the regression model.

Uniform Design Approach

Wang and Fang [6] proposed a uniform design approach that can effectively deal with multiple level experiments, where the number of experiments is equal to the number of levels. In addition, the uniform design approach requires fewer experiments than the Taguchi method, thus reducing development costs [7].

Table 1 shows the uniform layout of $U_{10}^*(10^3)$. The first column is the number of experiments and the other three columns are used for arranging three operational parameters of the high-pressure waterjet machine for experiments.

The steps of uniform design experiments are as follows:

- Step 1: Clearly identify system problems.
- Step 2: Identify the operational parameters that can affect the system.
- Step 3: Select the range of parameters according to expert experience.



- Step 4: Choose an adequate uniform layout, according to the number of operational parameters and levels.
- Step 5: Conduct experiments according to the uniform layout.
- Step 6: Analyze the results using the image processing method and regression analysis. The optimal operational parameter values are obtained by the regression model.
- Step 7: Conduct verification experiments to compare the results obtained by the practical experiments and the regression model.

Table 1. Uniform layout $U_{10}^*(10^3)$.

Exp. no.	1	2	3
1	1	5	7
2	2	10	3
3	3	4	10
4	4	9	6
5	5	3	2
6	6	8	9
7	7	2	5
8	8	7	1
9	9	1	8
10	10	6	4

Regression Analysis Approach

Regression analysis [8] is used to investigate the strength of correlation between two or more variables. The following introduces unary and multiple linear regressions. Unary linear regression is a simple model used to reflect the relation between a variable and an output. The following Eq. (1) is a unary linear regression model.

$$Y = \alpha + \beta X + \varepsilon \tag{1}$$

In Eq. (1), where Y is the dependent variable, X is the independent variable, α and β are regression parameters and ε is a random error. Equation (1) denotes that the relations between Y , X , α , β , and ε are usually unknown values. This study has three operational parameters. Therefore, the relation should be assessed using multiple linear regression as in Eq. (2).

$$Y = \alpha + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 + \varepsilon \tag{2}$$

The Eq. (2) is similar to Eq. (1), but the number of independent variable X and regression parameters β are increased.

Experimental Steps and Results

A. Experimental steps

The experimental steps are described as follows.

- Step 1: Use the uniform layout of $U_{10}^*(10^3)$ for the three operational parameters of the high-pressure waterjet machine and their respective resolutions (see Table 1).
- Step 2: Conduct experiments according to the uniform layout of $U_{10}^*(10^3)$ and photograph the fish on both sides.
- Step 3: Analyze the photographs using image processing software and calculate the removal rate for each experiment.
- Step 4: Build the regression model and use it to find the best combination of three operational parameters and the removal rate of fish scales.
- Step 5: Predict the maximal removal rate Y and compare against the removal rate obtained by practice experiments.

Eq. (3) was used to compute the removal rate of fish scales.

$$\text{Removal rate} = \frac{\text{Area of removed fish scales}}{\text{Area of full fish scales}} \times 100\% \tag{3}$$

Figure 1 shows the high-pressure waterjet machine to remove tilapia scales in the experiments. The red outline in Figure 2(a) shows the area of a tilapia originally covered by scales. The red outline in Figure 2(b) shows the area of the fish cleaned of scales. The cleaned area is nearly white and the color difference is used to assess the proportion of scales removed through image processing methods.



Figure 1. High-pressure waterjet machine used to remove tilapia scales.

B. Experimental results

Table 2 shows the operational parameter combinations and their removal rate results, where x_1 is



the frequency for the speed of the machine chain (27 Hz to 59.4 Hz), x_2 is the water pressure (17.5 kg/cm² to 26.95 kg/cm²), x_3 is the frequency for the speed of the nozzle (54.7 Hz to 79.9 Hz). Each operational parameter combination was tested three times. The removal rate was obtained by averaging the results from the three experimental runs. Table 2 shows that the maximal removal rate (84.47%) is obtained by the 4th operational parameter combination in $U_{10}^*(10^3)$.

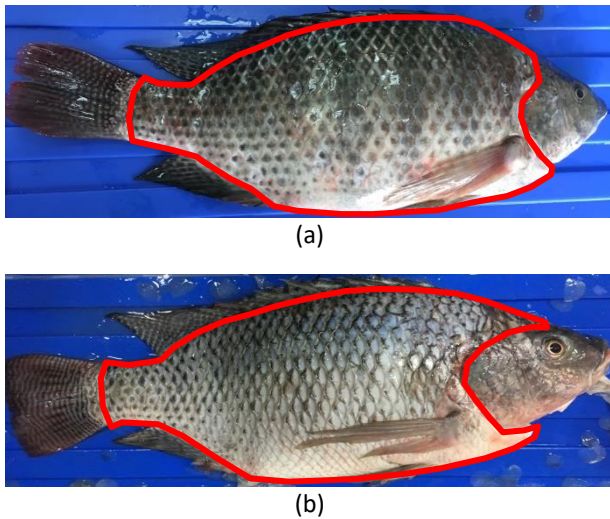


Figure 2. (a) Tilapia before cleaning and scale coverage (b) Tilapia after cleaning and scale removal coverage.

C. Regression model

The regression equation was generated by using the data of the $U_{10}^*(10^3)$ and is shown below.

$$y = -0.1294 - 0.0115x_1 + 0.0443x_2 + 0.0021x_3 \quad (4)$$

where y is the removal rate. The regression Eq. (4) shows that the items x_2 and x_3 are the more significant factors, because they have positive coefficients to obtain the maximal removal rate. The best operational parameters, obtained using the regression Eq. (4), are $x_1 = 27$, $x_2 = 26.95$, and $x_3 = 79.9$, producing a removal rate of 92.18%.

D. Verification experiment

The best operational parameters of $x_1 = 27$, $x_2 = 26.95$, and $x_3 = 79.9$, obtained using regression Eq. (4), were used to clean three different tilapia with the high-pressure waterjet machine, and achieved an average removal rate of 85.39%.

E. Discussion

The operational parameter combination obtained by regression Eq. (4) produced a theoretical scale removal rate of 92.18%, while the actual removal rate in verification experiments was 85.39%, indicating a high degree of predictive accuracy. In addition, the scaling by machine costs about one-third that for manual scaling.

Table 2. Results of the removal rate.

Exp. no.	x_1	x_2	x_3	Removal rate (%)
1	27	21.7	71.5	79.8244
2	30.6	26.95	60.3	82.6307
3	34.2	20.65	79.9	41.5756
4	37.8	25.9	68.7	84.8752
5	41.4	19.6	57.5	31.5651
6	45	24.85	77.1	53.0873
7	48.6	18.55	65.9	32.0307
8	52.2	23.8	54.7	33.4255
9	55.8	17.5	74.3	20.273
10	59.4	22.75	63.1	41.709

Conclusions

This study integrates the uniform design method and regression analysis to systematically identify operational parameters for a high-pressure waterjet machine used in removing tilapia scales. Experimental data obtained from the uniform layout of $U_{10}^*(10^3)$ were used to build a regression model for predicting the removal rate of tilapia scales. The regression model was also used to determine the optimal operational parameter combination for high-pressure waterjet scale removal. The maximal removal rate of tilapia scales obtained by the verification experiment is 85.39%. The proposed approach can be used to optimize the automation of fish de-scaling, thus significantly reducing production costs and enhancing productivity.

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