Artificial neural network base on grey relational analysis estimate displacement of bridge-type amplifier

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Abstract. The power of compliant mechanisms is able for a dramatic reduction in the number of parts required to compass a specified task. It may reduce manufacturing and assembly time and cost. Reduce the number of joints can also increase mechanism precision. The output displacement must be larger than input displacement with lower stress. Thus, Optimize geometry-shape for besting parameter design of the structure was investigated in this paper. The part was designed by Autodesk Inventor and determined displacement amplifier and stress by FEM in ANSYS. We estimate the displacement of a bridge-type amplifier using Artificial Neural Network (ANN) and regression method (RM) base on Grey relational analysis (GRA). The variability of the thickness, the incline angle, the length and the width of the flexure hinges (FH) affects the variability of target displacement (DI) and stress (ST). The influence of the width and the area of the location force is very small and not clear. The result of the simulation is verified by ANOVA and also compared with the predicted value of ANN, GRA, and RM. The displacement of a bridge-type amplifier is reached 0.95 mm with displacement input 0.01 mm. The ratio amplifier is got 95 times.

1. Introduction

In recent years, many researchers have designed many types of flexure hinge to replace traditional joints. For example, Yong and Lu proposed the kinetostatic modeling for 3-RRR compliant mechanisms [1]. These joints were used as the rotation joints for a 3-DOF paralleled mechanical systems for smooth and high precision motion in Micro/ Nano scale, designed by Tian et al. [2]. Qi et al. [3] use the kinematics theory and elastic beam theory (EBT) to calculate DAR of a bridge-type FH. The equivalent formula and FEM were applied to analyze failure for Triple-LET and LET FHs by Qiu, Yin and Xie [4]. Tian et al. [5] applied closed-form compliance equation to compute deformation of filleted V-shaped FHs and was verified by FEM. Yang et al. [6] applied super elastic materials for a FH and their numerical computations were able to accurately forecast the displacement and effectively reduce the computation cost compared by FEA in ANSYS and was con-firmed by the experiments. Ling et al. [7] applied Lagrange's equation to design semi-analytical FEM for a flexure hinge in complex compliant mechanisms. Dao and Huang [8-13] designed and applied multi-objective optimization to optimize design parameters of compliant mechanisms.

The objective of this paper analyzed and optimized effects of design parameters of a bridge-type amplifier displacement employing FHs by using FEM and ANN base on GRA. The model of the mechanism and finite element method was presented in section 2. After that optimization approaches
were description in section 3. The FEM and optimization results was analyzed and discussed in section 4. The section 5 is the conclusions.

2. Modelling and methodology

2.1. Modelling

The mechanism was presented in Figure 1 with dimension of 70mm x 25mm x 10mm. Figure 1b is the solid part, Figure 1a is the drawing 2D. The mechanism has 8 FHs with variable length (L), thickness (T), width (W) include the incline angle (Ø) of 2 FHs.

![Figure 1. Active magnetic bearing control system](image)

2.2. Finite element analysis

The aluminum alloy was used for the mechanism as listed in Table 1. The first, the mechanism is drawn in Autodesk Inventor and then imported to ANSYS. The alloy was aluminum AL-7075. In Figure 2a, the meshed mechanism was created by automatic mesh with adaptive size. The mesh convergence as h-refinement function is used to reduce the element sizes at the each FHs. The mesh type is used as triangular mesh. The number of nodes and the number of elements is equal to 130524 nodes, 73352 elements, respectively.

| Alloy   | E (GPa) | v (ratio) | σY (MPa) |
|---------|---------|-----------|-----------|
| AL7075  | 72      | 0.33      | 503       |

Table 1. Material mechanical properties

In Figure 2b, the static structural function in Ansys is used to analyze the output displacement and stress of the structure. The fixed support is chosen at the surface A. Two input displacements which magnitude is 0.01mm are located at the surface B and C. The direction of movements is in the opposite direction. The output displacement and output stress are observed.

![Figure 2. (a) The grid model, (b) Location of Fixture and DI for the model](image)

3. Optimization
3.1 Selection of simulation parameter
In this study, the geometry parameters were designed by the orthogonal array table. The Taguchi method can effectuate optimally and highly operated in diverse environments with a powerful capacity. The geometry parameter are showed as the length of the flexure hinge (LOFH), the width of the flexure hinge (WOFH), the thickness of the flexure hinge (TOFH) and incline angle. The parameters for the simulation are shown in Table 2.

| Table 2. System parameters |
|-----------------------------|
| Factor | Unit | Level 1 | Level 2 | Level 3 |
| Incline angle | Ø | Degree | 0.6 | 0.75 | 0.9 |
| LOFH | L | mm | 4 | 5 | 6 |
| WOFH | W | mm | 2 | 4 | 6 |
| TOFH | T | mm | 0.3 | 0.4 | 0.5 |

3.2 Grey’s method
Normalization: Rewrite each sequence between 0 and 1 as follows [8, 11].

The larger the better formula:

$$ D_i^+ = \frac{D_i^{(0)}(k) - \min D_i^{(0)}(k)}{\max D_i^{(0)}(k) - \min D_i^{(0)}(k)} $$

(1)

The smaller the better formula:

$$ D_i^- = \frac{\max D_i^{(0)}(k) - D_i^{(0)}(k)}{\max D_i^{(0)}(k) - \min D_i^{(0)}(k)} $$

(2)

Where $D_i^+$ is the normalized S/N for the $k$th response ($k=1,2,…n$). Max $D_i^{(0)}(k)$ and min $D_i^{(0)}(k)$ are the maximum and minimum values of $D_i^{(0)}(k)$, respectively.

Grey relational coefficient (GRC) ($\gamma$) : is quantified in the Grey relational space. GRC is as requirement before solving for the Grey relational grade (GRG).

$$ \Delta_{hi} = \|D_i^+(k) - D_i^-(k)\| $$

(3)

$$ \Delta_{\max} = \max_{\forall i,\forall k} \|D_i^+(k) - D_i^-(k)\| $$

(4)

$$ \Delta_{\min} = \max_{\forall i,\forall k} \|D_i^+(k) - D_i^-(k)\| $$

(5)

Where $\Delta_{hi}$ is deviation between $D_i^+(k)$ and $D_i^-(k)$. Calculate grey relational coefficient (GRC).

$$ \gamma_i(k) = \frac{\Delta_{hi} + \zeta \Delta_{\max}}{\Delta_{hi} + \frac{\zeta}{\zeta} \Delta_{\max}} $$

(6)

Here, $\zeta \in [0,1]$ is the distinguishing coefficient. Determine the weight

$$ \omega_e(x) = xe^{(1-x)} + (1-x)e^{-x} - 1 $$

(7)

Where $\omega_e(x)$ is the mapping function in the entropy measurement. This function obtains the maximum value when $x=0.5$ and $e^{0.5} \cdot 1=0.6487$ and the mapping value in $[0,1]$ is obtained as follows:
\[
    w = \frac{1}{(e^{0.5} - 1)} \sum_{i=1}^{m} \omega_i e(x)
\]

\( \epsilon = \{\gamma_1(1), \gamma_1(2), \ldots, \gamma_1(n)\} \). Note that \( i = 1, 2, \ldots, n \). Determine the total of the grey relational coefficient:

\[
    D_j = \sum_{i=1}^{m} \gamma_i(j), \quad j = 1, 2, \ldots, n
\]

Estimate the normalized coefficient:

\[
    k = \frac{1}{(e^{0.5} - 1) \times m} = \frac{1}{0.6487 \times m}
\]

Determine the entropy:

\[
    e_j = k \sum_{i=1}^{m} \omega_i e\left(\frac{\gamma_i(j)}{D_j}\right), \quad j = 1, 2, \ldots, n
\]

Here, \( \omega e(x) \) uses Eq. (10). Compute total of entropy:

\[
    E = \sum_{j=1}^{n} e_j
\]

Determine the weight:

\[
    \omega_j = \frac{1}{n-E} \frac{[1-e_j]}{\sum_{j=1}^{n} \frac{1}{n-E}[1-e_j]},
\]

Here, \( j = 1, 2, \ldots, n \).

GRG \( \psi \) is written as follows:

\[
    \psi = \sum_{k=1}^{n} \omega_k \gamma_i(k)
\]

Predict output characteristics and GRG: output the acceleration, contact force and GRG can be estimated as:

\[
    \mu_0 = D_o + \sum_{i=1}^{q}(D_o - D_m)
\]

\[
    \mu_o = \sigma_o + \sum_{i=1}^{q}(\sigma_o - \sigma_m)
\]

\[
    \mu_g = G_o + \sum_{i=1}^{q}(G_o - G_m)
\]

Where \( \mu_0, \mu_o \) are the optimization values of the predicted mean of displacement and stress.

The (CI) value for the optimal parameter level combination was estimated at a 95% confidence level as follows:
\[ CI_{CE} = \pm \sqrt{F_{a}(1, f_{e})V_{e}\left(\frac{1}{n_{\text{eff}}} + \frac{1}{R_{e}}\right)} \]  

where \( \alpha = 0.05; F_{a}(1, f_{e})= F_{0.05}(1, f_{e}); f_{e} \) is the error of freedom degrees; \( V_{e} \) is the error of the adj MS value; \( n_{\text{eff}} = n/(1+R) \); \( n \) is the quantity testing for the orthogonal array; \( R \) is the sum of the effect parameters and \( R_{e} \) is the simulation times.

### 3.3 Artificial neural network

This study used 3 classes, the input class with five input parameters, the hidden layer with eleven neurons. The network is trained using the Levenberg-Marquardt hybrid (trainlm) [7, 14-15]. The input \( L, \phi, T, W, \) fillet radius of the FH were taken as the input factors, and displacement or stress were taken as the output factors. The simulation values in Table 3 were utilized for training.

| No. | \( \phi \) | \( L \) | \( W \) | \( T \) | Displacement (mm) | Stress (MPa) |
|-----|-----|-----|-----|-----|----------------|--------------|
| 1   | 0.6 | 4   | 2   | 0.3 | 0.9806         | 102.9614     |
| 2   | 0.6 | 4   | 4   | 0.4 | 0.6536         | 106.8779     |
| 3   | 0.6 | 4   | 6   | 0.5 | 0.4446         | 99.8693      |
| 4   | 0.6 | 5   | 2   | 0.4 | 0.7687         | 97.6351      |
| 5   | 0.6 | 5   | 4   | 0.5 | 0.5312         | 95.6649      |
| 6   | 0.6 | 5   | 6   | 0.3 | 0.9962         | 91.0395      |
| 7   | 0.6 | 6   | 2   | 0.5 | 0.6236         | 82.5444      |
| 8   | 0.6 | 6   | 4   | 0.3 | 1.0819         | 75.0702      |
| 9   | 0.6 | 6   | 6   | 0.4 | 0.7761         | 81.9193      |
| 10  | 0.75| 4   | 2   | 0.3 | 0.9519         | 93.9727      |
| 11  | 0.75| 4   | 4   | 0.4 | 0.6851         | 105.3196     |
| 12  | 0.75| 4   | 6   | 0.5 | 0.4928         | 101.1267     |
| 13  | 0.75| 5   | 2   | 0.4 | 0.7835         | 91.6975      |
| 14  | 0.75| 5   | 4   | 0.5 | 0.5744         | 93.9629      |
| 15  | 0.75| 5   | 6   | 0.3 | 0.9639         | 81.9564      |
| 16  | 0.75| 6   | 2   | 0.5 | 0.6590         | 79.8422      |
| 17  | 0.75| 6   | 4   | 0.3 | 1.0259         | 66.7393      |
| 18  | 0.75| 6   | 6   | 0.4 | 0.7906         | 76.8598      |
| 19  | 0.9 | 4   | 2   | 0.3 | 0.8967         | 92.8028      |
| 20  | 0.9 | 4   | 4   | 0.4 | 0.6870         | 95.9143      |
| 21  | 0.9 | 4   | 6   | 0.5 | 0.5182         | 89.5852      |
| 22  | 0.9 | 5   | 2   | 0.4 | 0.7676         | 84.2787      |
| 23  | 0.9 | 5   | 4   | 0.5 | 0.5920         | 90.5757      |
| 24  | 0.9 | 5   | 6   | 0.3 | 0.9059         | 73.1690      |
| 25  | 0.9 | 6   | 2   | 0.5 | 0.6646         | 75.1992      |
| 26  | 0.9 | 6   | 4   | 0.3 | 0.9507         | 58.8989      |
| 27  | 0.9 | 6   | 6   | 0.4 | 0.7733         | 71.0449      |

### 3.4 Statistical analysis

The precision model is assessed by four error standards as follows. The root mean squared error (RMSE) is the difference between forecast values and the simulation values or observed actual values:
The mean square error (MSE):
\[
MSE = \frac{1}{m} \sum_{i=1}^{m} (x_i - y_i)^2
\]  
(20)

The mean absolute percentage error (MAPE):
\[
MAPE = \frac{100}{m} \sum_{i=1}^{m} \left| \frac{x_i - y_i}{x_i} \right|
\]  
(21)

The coefficient of determination (R^2) must be at least 0.8 for forecast models to be accepted:
\[
R^2 = 1 - \frac{\sum_{i=1}^{m} (x_i - y_i)^2}{\sum_{i=1}^{m} (x_i - \bar{y})^2}
\]  
(22)

where m is number of simulation of experiments, \(x_i\) and \(y_i\) represent the simulation and predicting value, respectively, and \(\bar{y}\) is the mean simulation value.

4. Results and discussion

4.1. Influence of thickness
Figure 3 presents the response of the displacement and stress of the mechanism. It was pointed out that the displacement output is decreased by 1.058mm, 0.748mm, 0.538mm when the thickness T is changed 0.3 mm, 0.4mm, 0.5mm, respectively. The stress is relatively decreased by 76.50MPa, 74.436MPa, 74.50MPa.

4.2. Influence of width
In Figure 4, the incline angle between two FHs is 0.6 degree. The thickness of FHs is 0.3mm. The length of FHs is 4mm. When the width of the FHs is increased by 2mm, 4mm, 6mm, the output displacement is decreased by 1,084mm, 1,058mm, 1,03mm, while the output stress is increased 74.436MPa, 74.7MPa, 75.347MPa, respectively.
4.3. Influence of incline angle

Figure 5. FEM result for displacement and stress with different Incline angle (0.6-0.75-0.9 (degree))

In Figure 5, the thickness, the length and the width of FHs are kept at 0.3mm, 4mm, 2mm, respectively. When the incline angle between two FHs is increased by 0.6 degrees, 0.75 degrees, 0.9 degrees, the displacement of output is decreased by 1.088mm, 1.055mm, 0.992mm, the stress is also decreased by 74.7MPa, 67.19MPa, 60.41MPa, respectively.

4.4. Influence of incline length

In Figure 6, the width of FHs is 2mm. the thickness of FHs is 0.3mm. The incline angle between two FHs is 0.6degree. When the length L is changed by 4mm, 5mm, 6mm, the value of the displacement is increased by 0.995mm, 1.0621mm, 1.121mm and the stress is decreased by 110.68MPa, 88.317MPa, 71.93MPa, respectively.

Figure 6. FEM result for displacement and stress with different LOFH (4mm–5mm–6mm)

4.5. The Grey relation analysis
Eqs. (1)-(3) is used to calculate the deviation. Level max-min of deviation values was determined by Eqs. (4)-(5). Solve the GRG value by Eqs. (8), (16). The result is displayed in Table 4. The maximum of GRG in Figure 7 shows the optimal value of the Grey relational analysis. The combination parameter obtained for DI and ST is Ø3L2W3T1.

![Figure 7](image)

**Figure 7.** Plot GRG values for simulation (a) and response graph of GRG (b)

| No. | $D_i^*(1)$ | $D_i^*(2)$ | $\Delta_{oi}(1)$ | $\Delta_{oi}(2)$ | $\gamma(1)$ | $\gamma(2)$ | GRG | Rank |
|-----|------------|------------|------------------|------------------|--------------|--------------|------|------|
| 1   | 0.841      | 0.0816     | 0.159            | 0.9184           | 0.7587       | 0.3525       | 0.5558 | 9    |
| 2   | 0.328      | 0.672      | 1                | 0.4266           | 0.3333       | 0.3800       | 0.3025 | 25   |
| 3   | 0          | 0.1461     | 0.8539           | 0.3333           | 0.3693       | 0.3513       | 0.3758 | 27   |
| 4   | 0.5086     | 0.1926     | 0.4914           | 0.8074           | 0.5043       | 0.3824       | 0.4434 | 18   |
| 5   | 0.1359     | 0.2337     | 0.7663           | 0.3665           | 0.3949       | 0.3807       | 0.2578 | 24   |
| 6   | 0.8655     | 0.3301     | 0.6699           | 0.788            | 0.4274       | 0.6078       | 0.6078 | 6    |
| 7   | 0.2809     | 0.5072     | 0.7191           | 0.4928           | 0.4101       | 0.5036       | 0.4568 | 17   |
| 8   | 1          | 0.663      | 0                | 0.337            | 1            | 0.5974       | 0.7989 | 3    |
| 9   | 0.5202     | 0.5202     | 0.4798           | 0.4798           | 0.5103       | 0.5103       | 0.5103 | 13   |
| 10  | 0.796      | 0.269      | 0.204            | 0.7102           | 0.4062       | 0.5583       | 0.5583 | 8    |
| 11  | 0.3775     | 0.0325     | 0.6225           | 0.9675           | 0.4454       | 0.3407       | 0.3931 | 23   |
| 12  | 0.0757     | 0.1199     | 0.9243           | 0.8801           | 0.351        | 0.3623       | 0.3566 | 26   |
| 13  | 0.3519     | 0.3164     | 0.4681           | 0.6836           | 0.5165       | 0.4224       | 0.4695 | 16   |
| 14  | 0.2037     | 0.2692     | 0.7963           | 0.7308           | 0.3857       | 0.4062       | 0.3959 | 22   |
| 15  | 0.8148     | 0.5194     | 0.1852           | 0.4806           | 0.7297       | 0.5099       | 0.6199 | 5    |
| 16  | 0.3365     | 0.5635     | 0.6635           | 0.4365           | 0.4297       | 0.5339       | 0.4818 | 15   |
| 17  | 0.9121     | 0.8366     | 0.0879           | 0.1634           | 0.8505       | 0.7537       | 0.8021 | 2    |
| 18  | 0.5429     | 0.6257     | 0.4571           | 0.3743           | 0.5224       | 0.5719       | 0.5471 | 10   |
| 19  | 0.7094     | 0.2934     | 0.2906           | 0.7066           | 0.6324       | 0.4144       | 0.5235 | 11   |
| 20  | 0.3804     | 0.2285     | 0.6196           | 0.7715           | 0.4466       | 0.3932       | 0.4199 | 19   |
| 21  | 0.1156     | 0.3604     | 0.8844           | 0.6396           | 0.3612       | 0.4388       | 0.4000 | 21   |
| 22  | 0.5069     | 0.471      | 0.4931           | 0.529            | 0.5035       | 0.4859       | 0.4947 | 14   |
| 23  | 0.2314     | 0.3398     | 0.7686           | 0.6602           | 0.3941       | 0.431        | 0.4125 | 20   |
| 24  | 0.7238     | 0.7026     | 0.2762           | 0.2974           | 0.6442       | 0.627        | 0.6356 | 4    |
| 25  | 0.3453     | 0.6603     | 0.6547           | 0.3397           | 0.433        | 0.5955       | 0.5142 | 12   |
| 26  | 0.7941     | 0             | 0.2059           | 0.7083           | 1            | 0.8540       | 1      |
| 27  | 0.5158     | 0.7468     | 0.4842           | 0.2532           | 0.508        | 0.6638       | 0.5858 | 7    |

4.6. Analysis of variance (ANOVA)

The design factor have greatly impacted on GRG with P-values are less than 0.05. The width variable is 0.137. It is insignificant impact factor than another parameter. The distribution of the length
and the thickness is greatly with 30.72% and 57.88%. The R-square value is equal 91.39%. The result is as Table 5.

### Table 5. The variance of GRG

| Source      | DF | Seq SS    | Contribution (%) | Adj SS    | Adj MS    | F-Value | P-Value |
|-------------|----|-----------|------------------|-----------|-----------|---------|---------|
| Regression  | 5  | 0.196357  | 91.39%           | 0.196357  | 0.039271  | 44.56   | 0.000   |
| Ø           | 1  | 0.003534  | 1.64%            | 0.003534  | 0.003534  | 4.01    | 0.058   |
| L           | 1  | 0.066006  | 30.72%           | 0.054147  | 0.054147  | 61.44   | 0.000   |
| W           | 1  | 0.000129  | 0.06%            | 0.002106  | 0.002106  | 2.39    | 0.137   |
| T           | 1  | 0.124354  | 57.88%           | 0.023805  | 0.023805  | 27.01   | 0.000   |
| W*T         | 1  | 0.002334  | 1.09%            | 0.002334  | 0.002334  | 2.65    | 0.119   |
| Error       | 21 | 0.018508  | 8.61%            | 0.018508  | 0.000881  |         |         |
| Total       | 26 | 0.214865  | 100.00%          |           |           |         |         |

The RE of GRG was reached by Minitab as:

\[
GRG = (0.7645 + 0.0934Ø + 0.0693L - 0.0339W - 1.184T + 0.0882W*T)^2
\]

### 4.7. The ANN Models

The results of training are shown in Figure 8. The best validation performance is \(9.645 \times 10^{-12}\). The gradient is \(1.0019 \times 10^{-5}\).

![Figure 8](image.png)

(a) Performance plot for GRG (a) and Training state of ANN for GRG(b)

Table 6 shown that RE and ANN were significant for optimal design. R square = 99.77%. RMSE is less than 0.05.

### Table 6. Analysis of variance of GRG

| Criteria | ANN for GRG | RE for GRG |
|----------|-------------|------------|
|          | Training    | Testing    | Training    | Testing    |
| RMSE     | 0.01        | 0.04       | 0.04        | 0.022377   |
| MSE      | 0           | 0.0016     | 0.0016      | 0.000501   |
| MAPE     | 0.42        | 5.93       | 1.92        |            |
| R\text{ quad} (%) | 99.77 | 91.15 | 99.43 |            |

As the level of Rank, the optimal value of GRG by Eqs. (15)-(17). The predicted value of DI, ST, GRG are 0.5403mm, 75.3451MPa and 0.6578.
5. Conclusions
The target of this study is to reach the maximum response displacement achieved when optimizing the geometric design parameters of the amplifier structure. L27 orthogonal array was investigated with four levels of inline angle, length, width, and thickness of bridge-type flexure hinges. The FEA values were taken to the Grey model to approximate the best parameter geometry and determine optimal by the ANN method. The outcome obtained high displacement with the design parameter as following: Ø3L2W3T1. The displacement is 0.9507mm. In the future, compare the optimal result to other optimal methods to achieve the best value and the optimal results will be verified by measurement data on the actual model.

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