SOLVING MULTI-OBJECTIVE OPTIMIZATION OF A TWO-STAGE HELICAL GEARBOX WITH DOUBLE GEARS IN FIRST STAGE USING EAMR TECHNIQUE

GIẢI BÀI TOÁN TỐI ƯU ĐA MỤC TIÊU CHO HỘP GIẢM TỐC BÁNH RĂNG CẤP NHANH PHÂN ĐÔI SỬ DỤNG PHƯƠNG PHÁP EAMR

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ABSTRACT

In this study, the Multi-Objective Optimization Problem (MOOP) for a two-stage helical gearbox having two gears in the first stage is solved using the Multi-Criteria Decision Making (MCDM) technique. The objective is to identify the optimal design elements that would reduce the gearbox's length and boost its efficiency. The study also focused on three important design parameters: the coefficients of wheel face width (CWFW) for the first and second stages, as well as the gear ratio of the first stage. Additionally, the EAMR technique was chosen to address the MCDM problem, and the MEREC technique was employed to establish the weight requirements for resolving the MOOP. According to the study's outcomes, it's crucial to determine the optimal values for three vital design factors when creating a two-stage helical gearbox with double gears in the first stage.

Keywords: *MCDM; EAMR; MEREC; Gear ratio; Gearbox efficiency; Gearbox lengths.*

TÓM TẮT

Trong nghiên cứu này, bài toán tối ưu hóa đa mục tiêu (MOOP) cho hộp giảm tốc hai cấp bánh răng xoắn có hai bánh răng ở cấp đầu tiên được giải quyết bằng kỹ thuật ra quyết định đa tiêu chí (MCDM). Mục tiêu là xác định các yếu tố thiết kế tối ưu nhằm giảm chiều dài và tăng hiệu suất của hộp. Nghiên cứu tập trung vào ba thông số thiết kế quan trọng: Hệ số chiều rộng mặt bánh xe (CWFW) cho cấp đầu tiên và cấp thứ hai, cũng như tỷ số truyền của cấp đầu tiên. Ngoài ra, kỹ thuật EAMR đã được chọn để giải quyết vấn đề MCDM và kỹ thuật MEREC đã được sử dụng để thiết lập các yêu cầu về khối lượng để giải quyết MOOP. Theo kết quả của nghiên cứu, điều quan trọng là phải xác định được các giá trị tối ưu cho ba yếu tố thiết kế khi chế tạo hộp giảm tốc hai cấp bánh răng xoắn với bánh răng đôi ở cấp đầu tiên.

Từ khóa: *MCDM; EAMR; MEREC; Tỉ số truyền; Hiệu suất của hộp; Chiều dài của hộp.*

1. INTRODUCTION

These days, gearboxes are widely used in many different areas of mechanical engineering. As a result, many academics are working hard to create the perfect gearbox design.

A customized adaptive random search method was used by Zarefar H. and Muthukrishnan S. [1] to maximize the helical gear pair's weight. Contact stress and tooth-bending strength were the limitations, whereas the gear module, helix angle, pinion teeth, and face width were the design variables. To maximize the volume of a two-stage helical gear train, Gologlu and Zeyveli [2] used a Genetic Algorithm (GA). Static and dynamic penalty functions were added to the objective function to handle design constraints such contact stress, bending stress, gear and pinion tooth count, module, and gear face width. A study on identifying the most effective gear ratios for mechanically driven systems was conducted by Nguyen K.T. et al. [3]. In order to reduce the system's cross-sectional area, the first stage of the study used twin gear sets in conjunction with a chain drive and a two-step helical gearbox. A study on optimizing the prediction of ideal partial ratios for three-step helical gearboxes with second-step double gear-sets was carried out by Tran T.P.T. et al. [4]. The study sought to accomplish a number of goals, including reducing the mass of the gears, the gearbox length, and the gearbox cross section dimension. An investigation into the most effective technique for figuring out gear ratios in a two-stage helical reducer was conducted by Nguyen K.T. et al. [5]. Reducing the area of the reducer's cross section is the aim of the study. Two models were proposed to identify the most effective gear ratios for a two-stage reducer based on the study's findings.

In order to identify the optimal set of design parameters that would provide the shortest weight of a spur gear train, Savsani et al. [6] proposed two advanced optimization techniques: particle swarm optimization (PSO) and simulated annealing (SA). A multi-objective optimization issue involving two-stage helical gear sets in a helical hydraulic rotary actuator is presented by Liu S. et al. [7]. To solve this issue, the NSGA-II method is used. Three main goals were examined in this study: maximal contact stress, transmission efficiency, and volume.

In order to minimize gear weight, reduce contact stress across the whole contact path, and achieve the proper film thickness at the contact site, Jawaz Alam and Su-manta Panda [8] developed a technique for optimizing the design of spur gear sets. The results of the study show that, in comparison to conventional designs, the use of appropriate addendum coefficient values inside the authorized design space significantly improves gear design. In order to address the multi-objective optimization problem of a two-stage helical gearbox, V.T. Dinh et al. [9] employed the TOPSIS technique. The project's goal is to increase the gearbox's efficiency by decreasing its cross-sectional area. A three-stage bevel helical gearbox and a chain drive were used in a study by Tran T.P.T. [10] to find the ideal gear ratios for mechanical drive systems. The goal of the research is to reduce the system's cross-sectional area. The study's findings made it possible to estimate how input factors affected the ideal ratios. Equations were also put forth to make it easier to calculate the ideal gear ratios.

Several aspects of MCDM have been ☞

the subject of numerous investigations. Do D.T. [11] evaluating the impact of criterion weights on the ranking of the top 10 universities in Vietnam. Tran H.D. et al. [12] used the TOPSIS technique to determine the optimal primary design elements for a two-stage helical gearbox. The PIV Method was used by Nguyen H.S. [13] to select the crankshaft material.

The purpose of this study is to shorten the gearbox's length and increase its efficiency. The EAMR approach was used to solve the MCDM problem, and the MEREC method was used to calculate the criteria weights in order to solve the MOOP for a two-stage helical gearbox with double gear-sets in the first stage. The results of the investigation allowed for the identification of the key components of the gear-box's design.

2. OPTIMIZATION PROBLEM

2.1. Determining gearbox length

The gearbox length L_{gb} can be found by (Figure 1):

$$L = d_{w11} + d_{w21}/2 + d_{w12}/2 + d_{w22} + 2 \cdot \delta \quad (1)$$

In which, δ = 7÷10 (mm); d_{w1i}, d_{w2i} (i = 1÷2) are the pitch diameter of the pinion and the gear of step 1 and 2 which are calculated by [14]:

$$d_{w1i} = 2 \cdot a_{wi}/(u_i + 1) \quad (2)$$

$$d_{w2i} = 2 \cdot a_{wi} \cdot u_i/(u_i + 1) \quad (3)$$

Where a_{wi} (i=1÷2) denotes the gearbox center distance of i[th] stage which is calculated by [14]:

$$a_{wi} = k_a \cdot (u_i + 1) \cdot \sqrt[3]{T_{1i} \cdot k_{H\beta}/([AS_i]^2 \cdot u_i \cdot X_{bai})} \quad (4)$$

Where T_{1i} (i=1÷2) represents the torque on the pinion of i[th] stage which can be computed by:

$$T_{11} = T_{out}/(2 \cdot u_{gb} \cdot \eta_{hg}^2 \cdot \eta_b^3) \quad (5)$$

$$T_{12} = T_{out}/(u_2 \cdot \eta_{hg} \cdot \eta_{be}^2) \quad (6)$$

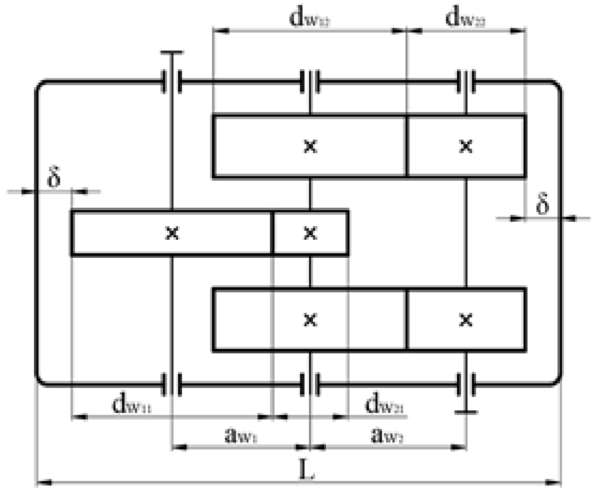

Figure 1. Schema for finding gearbox length

2.2. Determining gearbox efficiency

The gearbox efficiency can be determined by:

$$\eta_{gb} = 100 - \frac{100 \cdot P_l}{P_{in}} \quad (7)$$

Where P_l is the total power loss in the gearbox; P_l can be found by [15]:

$$P_l = P_{lg} + P_{lb} + P_{Z0} + P_{ls} \quad (8)$$

In which, P_{lg}, P_{lb}, P_{Z0}, and P_{ls} represent the power loss in the gears, in bearings, in the idle motion, and in seals; These elements are calculated as noted in [16].

2.3. Objective Functions and Constraints

2.3.1. Objectives functions

In this work, the MOOP has two targets:

- Minimizing gearbox length:

$$\min f_1(X) = L_{gb} \quad (9)$$

- Maximizing gearbox efficiency:

$$\min f_2(X) = \eta_{gb} \quad (10)$$

Assume that X is the vector that describes the design's variables. AS_1, AS_2, u_1, X_{ba1}, and X_{ba2} are the five primary design components of a two-stage helical gearbox [17]. According to additional research, AS_1 and AS_2's highest values are the most noteworthy [17]. Consequently, the three main design elements that will be employed as variables in this investigation are u_1, X_{ba1}, and X_{ba2}. As a result, our current display looks like this:

$$X=\{u_1, Xba_1, Xba_2\} \quad (11)$$

2.3.2. Constrains

For a helical gearbox:

$u_i = 1÷9$; $X_{bai} = 0.25÷0.4$ (i=1÷2) [19].

Therefore, the MOOP has two following constraints:

$$1 \le u_i \le 9 \quad (12)$$

$$0.25 \le Xba_i \le 0.4 \quad (13)$$

3. METHODOLOGY

3.1. Method for solving MOOP

Its efforts are intended to achieve two goals: either reducing the gearbox's length or increasing its efficiency. Three essential design elements that serve as inputs for our analysis are listed in Table 1. Additionally, the MOOP had been addressed using the approach outlined in reference [16]. Figure 2 shows the methodology for implementing this technique. There are two distinct steps to the approach. As shown in Table 1, the main goal of the first phase is to address the problem of single-objective optimization by minimizing the differences between the input variables. Our main objective in the next stage will be to resolve the MOOP problem by determining the crucial design components that yield the best results. The EAMR issue will be changed to account for a smaller difference between the two levels of the input elements if the variable levels in the second stage do not differ by at least 0.02.

Table 1. Input factors

Factors	Minimal value	Maximal value
Gear ratio of stage 1	1	9
CWFW of stage 1	0.25	0.4
CWFW of stage 2	0.25	0.4

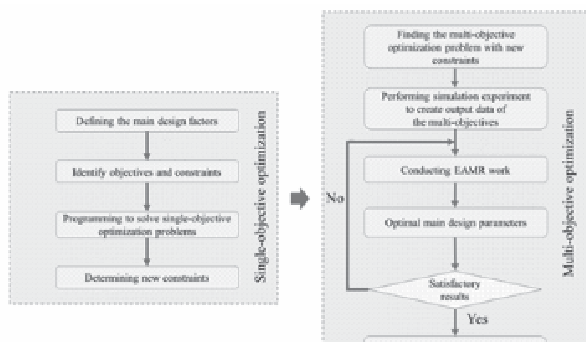

Figure 2. Workflow chart to solve MOOP

3.2. Method for solving MCDM work

3.2.1. EAMR method

The EAMR method is performed in the following steps [18]:

- Step 1: Creating the decision-making matrix:

$$X_d = \begin{bmatrix} x_{11}^d & \cdots & x_{1n}^d \\ x_{21}^d & \cdots & x_{21}^d \\ \vdots & \cdots & \vdots \\ x_{m1}^d & \cdots & x_{mn}^d \end{bmatrix} \quad (14)$$

In which, $1 \leq d \leq k$, k is the decision maker's number; d is the decision maker's indication.

- Step 2: Calculating the mean value of each alternative by:

$$\bar{x}_{ij} = \frac{1}{k}\left(x_{ij}^1 + x_{ij}^2 + \cdots + x_{ij}^k\right) \quad (15)$$

- Step 3: Computing the creation weights.

- Step 4: Determining each criterion's weighted average:

$$\bar{w}_j = \frac{1}{k}\left(w_j^1 + w_j^2 + \cdots + w_j^k\right) \quad (16)$$

- Step 5: Finding n_{ij} by:

$$n_{ij} = \frac{\bar{x}_{ij}}{e_j} \quad (17)$$

Where e_j can be found by:

$$e_j = \max_{i \in \{1,\dots,m\}}\left(\bar{x}_{ij}\right) \quad (18)$$

- Step 6: Computing the normalized weight by:

$$v_{ij} = n_{ij} \cdot \bar{w}_j \quad (19)$$

- Step 7: Finding the criteria's normalized score.

+) For the gearbox efficiency objective:

$$G_i^+ = v_{i1}^+ + v_{i2}^+ + \cdots + v_{im}^+ \quad (20)$$

+) For the gearbox length objective:

$$G_i^- = v_{i1}^- + v_{i2}^- + \cdots + v_{im}^- \quad (21)$$

- Step 8: Calculating the ranking's (RV) values from Gi^+ and Gi^-:

- Step 9: Computing the alternatives' evaluation score by:

$$S_i = \frac{RV(G_i^+)}{RV(G_i^-)} \quad (22)$$

The optimal option has the highest S_i value.

3.2.2. MEREC method

To perform the MEREC method, the following stages must be done [19]:

+) Build the first matrix as in the first stage of the MAIRCOS method.

+) Compute the value of the normalized matrix by:

- For the gearbox efficiency target:

$$h_{ij} = \frac{\min x_{ij}}{x_{ij}} \quad (23)$$

- For the gearbox length target:

$$h_{ij} = \frac{x_{ij}}{\max x_{ij}} \tag{24}$$

+) Find the effectiveness of the options S_i by:

$$S_i = \ln\left[1 + \left(\frac{1}{n}\sum_j \left|\ln(h_{ij})\right|\right)\right] \tag{25}$$

+) Calculate the efficiency of the i[th] option S_{ij}' by:

$$S_{ij}' = \mathrm{Ln}\left[1 + \left(\frac{1}{n}\sum_{k,k\neq j} \left|\ln(h_{ij})\right|\right)\right] \tag{26}$$

+) Find the removal effect of the j[th] criterion E_j:

$$E_j = \sum_i \left|S_{ij}' - S_i\right| \tag{27}$$

+) Determine the criteria's weight by:

$$w_j = \frac{E_j}{\sum_k E_k} \tag{28}$$

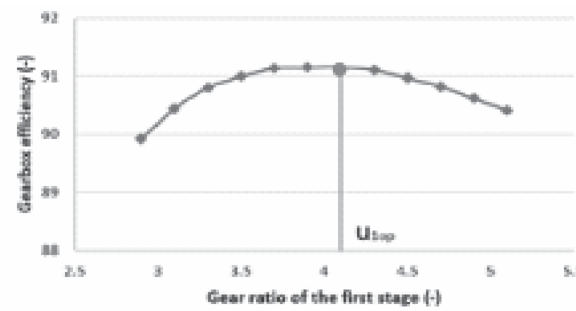

Figure 3. Relationship between u_1 and η_{gb}

4. SINGLE-OBJECTIVE OPTIMIZATION

As mentioned in Section 3.1, solving the single objective optimization problem (SOOP) is the first step in the approach to the MOOP. Two SOOPs are used in this study: maximizing η_{gb} and decreasing L_{gb}. To solve the SOOP, a Matlab application using the direct search technique was created. The results of the program are summarized in the following results. The relationship between η_{gb} and u_1 is depicted in Figure 3. The figure shows the optimal value of u_1, which is the value at which η_{gb} reaches its maximum. The relationship between the variables u_1 and L_{gb} is shown in Figure 4. As shown in Figure 4, the optimal value of u_1 is the one that yields the lowest value of L_{gb}. Additionally, the relationship between the ideal values for u_1 and u_{gb} is depicted in Figure 5. As shown in Table 2, the updated constraints for the variable u_1 were created based on the ideal values of u_1.

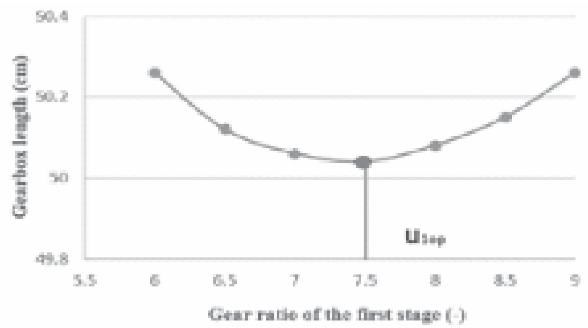

Figure 4. Relationship between u_1 and L_{gb}

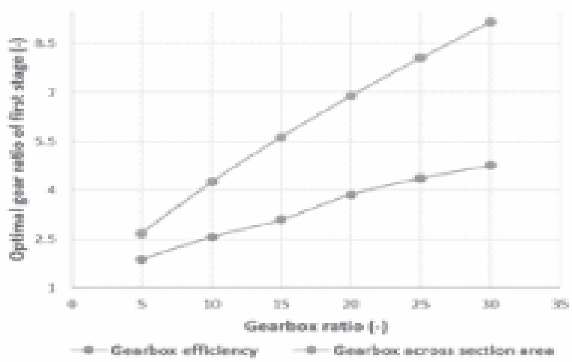

Figure 5. Relationship between u_{gb} and optimum u_1

Table 2. New limitations of u_1

u_{gb}	u_1	
	Minimal value	**Maximal value**
5	1.78	2.76
10	2.47	4.35
15	3.00	5.73
20	3.77	6.99
25	4.27	8.16
30	4.67	9.27

5. MULTI-OBJECTIVE OPTIMIZATION

To conduct simulation experiments, a computer program has been developed. The investigation examined u_{gb} values, which ranged from 5 to 30 at 5-point intervals. These are the answers to the variable u_{gb} = 20 problem. As indicated in Section 3, 125 initial testing iterations have been conducted using the gearbox ratio previously described. In order to address the MOOP, EAMR will receive the output data from the experiment about the efficiency of the gearbox length as input parameters. This approach will continue until there is less than a 0.02 difference between the two levels of each variable. The output answers and major design parameters for the fifth and final iteration of the EAMR experiment, with an u_{gb} value of 20, are shown in Table 3. As described in Section 3.2.2, the MEREC approach was used to determine the weights of the criterion in the manner shown below: Equations (22) and (23) were used to standardize the values h_j. Equations (25) and (26) were used to determine the values of S_i and S_{ij}'. Equation (27) was used to calculate the impact of removing the condition. Using Equation (28), the weights for the criteria, w_j, were determined. Suggestions on how to best use the EAMR technique to the MCDM problems are provided in Section 3.2.1. First, Formula (14) is used to create the decision matrix. Using Equation (15), find the mean of the choices for each condition. With Formula (16), the average weighted values may be calculated. Using equation (17), find the value of n_{ij} while keeping in mind that equation (18) determines e_j. Next, determine the value of v_{ij} using Formula (19). Utilize Equation (20) to determine the gearbox's efficiency and Equation (21) to determine the gearbox's length in order to determine the values of G_i. Finally, use Formula (22) to determine the S_i value. Table 4 (for the final iteration of EAMR analysis) displays the results of the option ranking and parameter computation using the EAMR approach. Out of all the options available, option 105 is the most advantageous choice, following the table. According to Table 5, u_1 = 4.48, X_{ba1} = 0.25, and X_{ba2} = 0.4 are the ideal values for the key design elements.

From the results, the following regression equation (with R^2 = 0.9984) was determined to find the optimal values of u_1:

$$u_1 = 0.1542 \cdot u_{gb} + 1.265 \quad (29)$$

Table 3. Input parameters and output results for u_{gb} = 20

Trial.	u_1	X_{ba1}	X_{ba2}	L_{gb} (dm)	η_{gb} (%)
1	4.44	0.25	0.25	50.87	91.50
2	4.44	0.25	0.29	49.19	91.78
3	4.44	0.25	0.33	47.77	92.57
4	4.44	0.25	0.36	46.56	92.47
5	4.44	0.25	0.40	45.51	92.35
…					
50	4.45	0.40	0.40	43.77	85.72
51	4.46	0.25	0.25	50.85	91.48
52	4.46	0.25	0.29	49.17	91.75
…					
104	4.48	0.25	0.36	46.53	92.41
105	4.48	0.25	0.40	45.48	92.29
106	4.48	0.29	0.25	50.28	90.19
…					
123	4.48	0.40	0.33	46.01	85.59
124	4.48	0.40	0.36	44.80	85.63
125	4.48	0.40	0.40	43.75	85.65

Table 4. Calculated results and rankings of options using EAMR when u_{gb} = 20

Trial.	η_{ij}		V_{ij}		G_i		S_i	Rank
	L_{gb}	η_{gb}	L_{gb}	η_{gb}	L_{gb}	η_{gb}		
1	1.0000	0.9884	0.6559	0.3402	0.6559	0.34	0.5187	105
2	0.9670	0.9915	0.6342	0.3412	0.6342	0.341	0.5380	75
3	0.9391	1.0000	0.6159	0.3441	0.6159	0.344	0.5588	41
4	0.9153	0.9989	0.6003	0.3438	0.6003	0.344	0.5727	16
5	0.8946	0.9976	0.5867	0.3433	0.5867	0.343	0.5851	3
…								
50	0.8604	0.9260	0.5643	0.3187	0.5643	0.319	0.5647	32
51	0.9996	0.9882	0.6556	0.3401	0.6556	0.34	0.5188	103
52	0.9666	0.9911	0.6339	0.3411	0.6339	0.341	0.5381	74
…								
104	0.9147	0.9983	0.5999	0.3436	0.5999	0.344	0.5727	17
105	0.8940	0.9970	0.5864	0.3431	0.5864	0.343	0.5851	1
106	0.9884	0.9743	0.6482	0.3353	0.6482	0.335	0.5172	106
…								
123	0.9045	0.9246	0.5932	0.3182	0.5932	0.318	0.5364	85
124	0.8807	0.9250	0.5776	0.3183	0.5776	0.318	0.5512	60
125	0.8600	0.9252	0.5641	0.3184	0.5641	0.318	0.5645	35

Table 5. Optimal main design parameters

No.	u_{gb}					
	5	10	15	20	25	30
u_1	1.83	2.92	3.66	4.48	5.20	5.70
X_{ba1}	0.4	0.325	0.288	0.25	0.25	0.25
X_{ba2}	0.4	0.4	0.4	0.4	0.4	0.4

6. CONCLUSIONS

The design of a two-stage helical gearbox with two gears in the first stage was a multi-objective optimization problem that was addressed in the study using the EAMR technique. Finding the optimal design parameters that increase gearbox efficiency while decreasing gearbox length is the goal of this study. Three essential design elements (u_1, X_{ba1}, and X_{ba2}) were determined in order to do this. There were two distinct stages to the MOOP solution approach. Managing the single-objective optimization issue with the aim of reducing the variance among variable values was the main focus of Step 1. Finding the ideal primary design factors was the main goal of step 2. This inquiry yielded the following results:

- Three main design factors (u_1, X_{ba1}, and X_{ba2}) were examined for their effects. Both ☞

gearbox efficiency and gearbox length reach their ideal levels at a certain value of u_1.

- The table and regression formula list the key design considerations for a two-stage helical gearbox with two gears in the first stage. The suggested model for demonstrating u_1 shows a high degree of agreement with verified data.

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