Effect of Main Design Factors on Two-Stage Helical Gearbox Length

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Abstract. This paper reports the results of an optimization study on the effect of major design factors on the length of a two-stage helical gearbox. Five major design factors were investigated in the study including the first stage gear ratio, the coefficient of wheel face width of stages 1 and 2, and the allowable contact stress of stages 1 and 2. A simulation experiment was also designed and accomplished by a computer program. Furthermore, Minitab R19 software was applied to analyze the experimental results. The impact of key design factors on gearbox length was investigated. The optimum values of the parameters to obtain the smallest gearbox length were also proposed.

Keywords: Helical gearbox · Main design factor · Optimum gearbox design · Gearbox length

1 Introduction

Mechanical drive systems are the most common type among many types of drive systems such as electric drive, pneumatic drive, hydraulic drive, and so on. This is due to its straightforward structure, dependable operation, and low cost. A typical mechanical drive system includes a motor, a gearbox, and two couplings, or a coupling and a V-belt or chain drive (Fig. 1). Of the mechanical drive system elements, the gearbox is undeniably the most important because it is the main component to reduce speed and torque from the motor shaft to the working shaft. Therefore, optimal design of gearboxes is an urgent research topic.

There have been numerous studies on the optimal design of gearboxes up to this point. In [1] gearbox geometric design parameters were optimized to reduce rattle noise in an automotive transmission using a torsional vibration model approach. The authors of [2] presented a study on multi-objective optimization for the drivetrain design and gear shifting control of internal combustion engine vehicles, with the goal of minimizing fuel consumption, exhaust emissions, and gearbox power losses. The optimum partial gear

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ratios to minimize the cost of a three-stage helical gearbox were determined in [3]. The problem of constrained multi-objective non-linear optimization of planetary gearboxes using a hybrid metaheuristic algorithm was reported in [4]. In [5] a modal-based design optimization of a gearbox housing using Finite Element Analysis was reported. In [6] a multi-objective optimization of a two-stage helical gearbox with a variety of constraints was described. The optimum gear ratios of different types of gearboxes have been found such as helical gearboxes [6–9], bevel gearboxes [10–12] and worm gearboxes [13–17]. According to the results of the above analysis, despite the fact that many studies on the optimization of gearbox parameters have been conducted, no optimization study has determined key design parameters (Fig. 1).

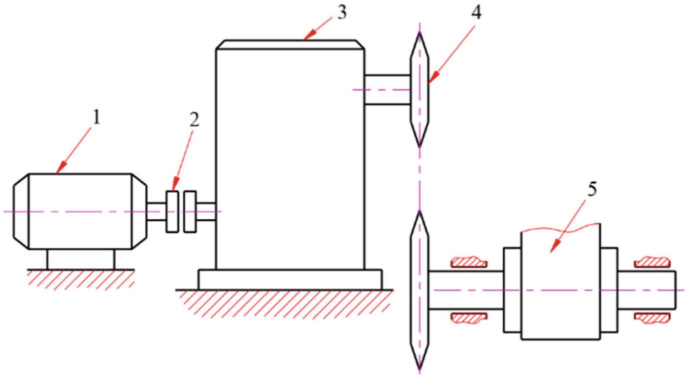

Fig. 1. Schema of a mechanical drive system: (1) Motor; (2) Coupling; (3) Gearbox; (4) Chain drive; (5) Belt conveyor

This paper presented an optimization study to determine the optimum main design parameters for a two-stage helical gearbox to obtain the shortest gearbox length. A simulation experiment was carried out using the Taguchi method and the Minitab R19 software. The effect of the main design parameters on gearbox mass was investigated. The best values for the five most important design factors have been assigned.

2 Methodology

2.1 Calculation of Gearbox Length

The length of a two-stage helical gearbox L_{gb} can be detemined by (see Fig. 2):

$$L_{gb} = \frac{d_{w11}}{2} + a_{w1} + a_{w2} + \frac{d_{w22}}{2} + 20 \tag{1}$$

In Eq. (1), d_{w11} is the diameter of the drive gear of stage 1; d_{w22} is the diameter of the driven gear of stage 2; These diameters are found by [18]:

$$d_{w11} = 2 \cdot a_{w1}/(u_1 + 1) \tag{2}$$

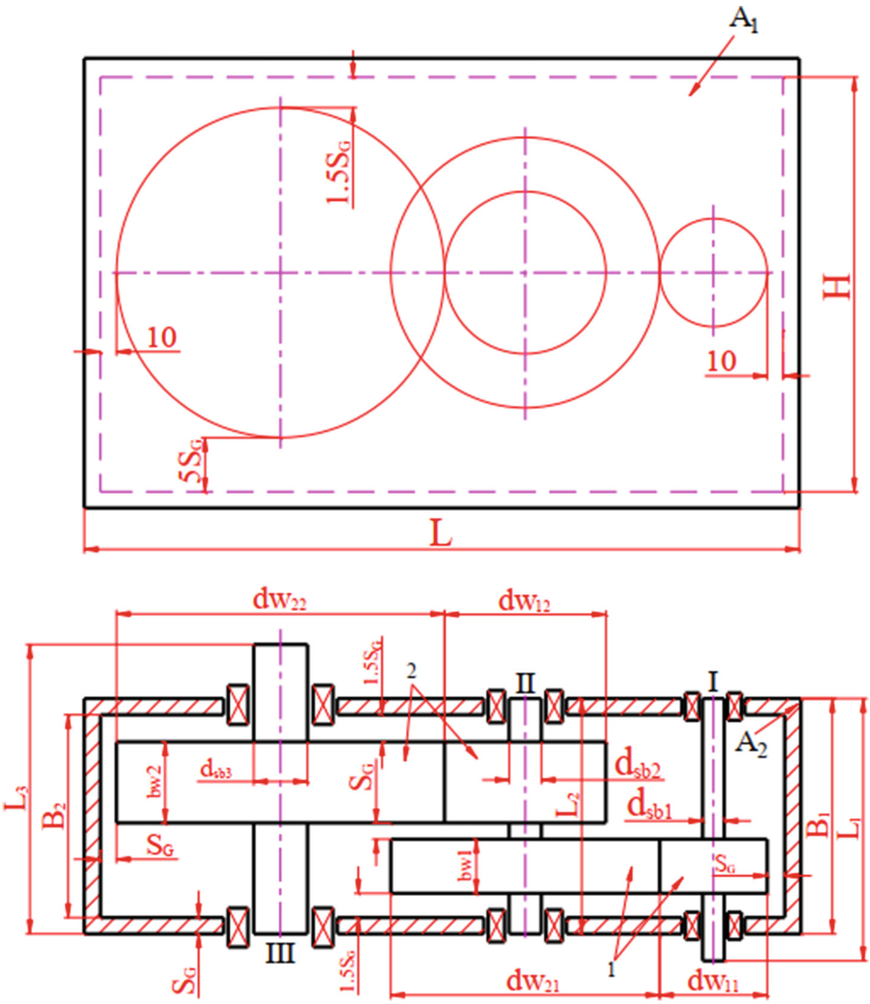

Fig. 2. Calculating schema

$$d_{w22} = 2 \cdot a_{w2} \cdot u_2/(u_2 + 1) \tag{3}$$

In Eqs. (2) to (3), u_1 and u_2 are the gear ratios of stage 1 and stage 2; $u_2 = u_g/u_1$; with u_g as the gearbox ratio; a_{w1} and a_{w2} are the center distances of stage 1 and stage 2 which are determined by [18]:

$$a_{w1} = k_a \cdot (u_1 + 1) \cdot \sqrt[3]{T_{11} \cdot k_{H\beta}/(\mathrm{AS}_1^2 \cdot u_1 \cdot X_{ba})} \tag{4}$$

$$a_{w2} = k_a \cdot (u_2 + 1) \cdot \sqrt[3]{T_{12} \cdot k_{H\beta 2}/(\mathrm{AS}_2^2 \cdot u_2 \cdot X_{ba2})} \tag{5}$$

where, $k_{H\beta}$ is the contacting load ratio for the pitting resistance; $k_{H\beta} = 1.05 \div 1.27$ [18] and it was chosen as $k_{H\beta} = 1.16$; AS_1 and AS_2 is the allowable contact stress of the first and the second stages (MPa); ka = 43 is material coefficient (for steel gear) [18]; X_{ba1} and X_{ba2} are the wheel face width coefficients of stage 1 and stage 2; T_{11} and T_{12} are the torques on the drive gear of stage 1 and stage 2 (Nmm):

$$T_{11} = T_{out}/\left(u_g \cdot \eta_{hg}^2 \cdot \eta_b^3\right) \tag{6}$$

$$T_{12} = T_{out}/\left(u_2 \cdot \eta_{hg} \cdot \eta_{be}^2\right) \tag{7}$$

In which, T_{out} is the output torque (N.mm); $\eta_{hg=}0.96 \div 0.98$ is the efficiency of a helical gear unit [18]; $\eta_{be} = 0.99 \div 0.995$ is the rolling bearing efficiency [18].

2.2 Optimization Problem

From the above analysis, the optimization problem is describes as:

$$\text{Minimize} L_{gb} \tag{8}$$

With

$$m_{gb} = f(u_1; X_{ba1}; X_{ba2}; AS_1; AS_2) \tag{9}$$

And with the following constraints:

$$1 \leq u_1 \leq 9; 1 \leq u_2 \leq 9 \tag{10}$$

3 Simulation Experiment

To investigate the impact of main design factors on gearbox length, a simulation experiment was carried out. The following design parameters were investigated in this experiment: u_1, X_{ba1}, X_{ba2}, AS_1, and AS_2. Table 1 defines these parameters and their levels. For the experimental design and data analysis, the Minitab R19 software and the Taguchi method were exploited.

To reduce computer programming workload, the impact of the main design parameters on the length of the gearbox was investigated using gear ratio values of 5, 10, 15, 20, 25, and 30. Furthermore, for this experiment, a 5-level for 5 factors Taguchi design (L25) was chosen, so the simulation experiment was conducted based on 25 test runs with each of the above values of gear ratios. Table 2 shows the test plan and the output results (the gearbox length) for the gear ratio of 5.

4 Results Discussion

To evaluate the effect of the main design factors on L_{gb} for $u_{gb} = 20$, the Analysis of Variance (ANOVA) method is used in accordance with Minitab R19 software. The signal-to-noise ratio, or S/N number, is calculated for each experiment to find the impact

Table 1. Main design parameters and their levels

Factor	Level				
	1	2	3	4	5
Total gearbox ratio u_1	1	3	5	7	9
Coefficient of wheel face width of stage 1 X_{ba1}	0.25	0.27	0.29	0.31	0.33
Coefficient of wheel face width of stage 2 X_{ba2}	0.32	0.34	0.36	0.38	0.4
Allowable contact stress of stage 1 AS_1 (Mpa)	350	368	386	404	420
Allowable contact stress of stage 2 AS_2 (Mpa)	350	368	386	404	420

Table 2. Experimental plan and output results (L_{gb}) for $u_{gb} = 5$

Trial	u_1	X_{ba1}	X_{ba2}	AS_1	AS_2	L_{gb} (kg)
1	1.78	0.25	0.32	350	350	348.93
2	1.78	0.27	0.34	368	368	331.11
3	1.78	0.29	0.36	386	386	315.14
4	1.78	0.31	0.38	404	404	300.74
5	1.78	0.33	0.4	420	420	288.55
6	1.89	0.25	0.34	386	404	317.84
…						
24	2.22	0.31	0.36	368	350	325.67
25	2.22	0.33	0.38	386	368	310.21

of each main design factor on the output results. The S/N ratios are calculated to minimize gearbox length by:

$$S/N = -10\log_{10}\left(\frac{1}{n}\sum_{i=1}^{n} y_i^2\right) \tag{11}$$

The average SN ratio for each parameter and level is calculated after calculating the SN ratio for each experiment. Table 3 and Fig. 2 show how the main design factors affect L_{gb}. Figure 2 shows that L_{gb} is inversely proportional to all five major design parameters. Furthermore, Table 1 displays that AS_2 has the greatest influence on L_{gb} (49.09%), followed by AS_1 (20.2%), X_{ba2} (18.22%), and X_{ba1} (17.22%). (11.59%). Additionally, u_1 has almost no effect on L_{gb} (0.89%). The influence order of the main design factors on the gearbox length is shown in Table 4.

Using the objective function in Equation, the S/N value is maximized for each major design factor to obtain the shortest gearbox length (8). The best main design factors are discovered after analyzing the effect of each factor on the S/N ratio in the plot in Fig. 3: $u_1 = 2.2$; $X_{ba1} = 0.33$; $X_{ba2} = 0.4$; $AS_1 = 420$ (MPa); $AS_2 = 420$ (MPa) (Fig. 4).

Table 3. Analysis of variance for means

Analysis of variance for means							
Source	DF	Seq SS	Adj SS	Adj MS	F	P	C(%)
u1	4	27.72	27.72	6.929	94.75	0	0.89
Xba1	4	360.78	360.78	90.196	1233.36	0	11.59
Xba2	4	566.91	566.91	141.726	1938	0	18.22
AS1	4	628.55	628.55	157.137	2148.73	0	20.20
AS2	4	1527.57	1527.57	381.892	5222.1	0	49.09
Residual error	4	0.29	0.29	0.073			0.01
Total	24	3111.81					
Model summary							

S	R-Sq	R-Sq(adj)
0.2704	99.99%	99.94%

Table 4. The order of impact of main design parameters on gearbox length

Response table for means					
Level	u1	Xba1	Xba2	AS1	AS2
1	316.9	320.8	322.0	322.5	326.7
2	315.4	317.4	318.4	318.5	320.2
3	314.8	314.9	314.6	314.5	314.5
4	314.3	312.1	311.7	311.4	309.0
5	313.8	310.1	308.6	308.4	304.8
Delta	3.1	10.7	13.5	14.1	22.0
Rank	5	4	3	2	1

Continue as before for the remaining u_{gb} values of 10, 15, 20, 25, and 30. The best values for the main design parameters are shown in Table 5. The following findings were obtained from Table 5 and Fig. 5:

- The optimal X_{ba1} and X_{ba2} values are their maximum values: $X_{ba1} = 0.33$ and $X_{ba2} = 0.4$. In order to obtain a minimum gearbox length, the coefficients X_{ba1} and X_{ba2} must be as large as possible to minimize the center distances of stage 1 and stage 2 (Eqs. (4) and (5)).
- The optimal AS_1 and AS_2 values are also their maximum values. The reason for this is that in order to have the shortest possible gearbox length, the AS_1 and AS_2 values must be as large as possible to minimize the center distance of the gear stage 1 and stage 2 (Eqs. (4) and (5)).

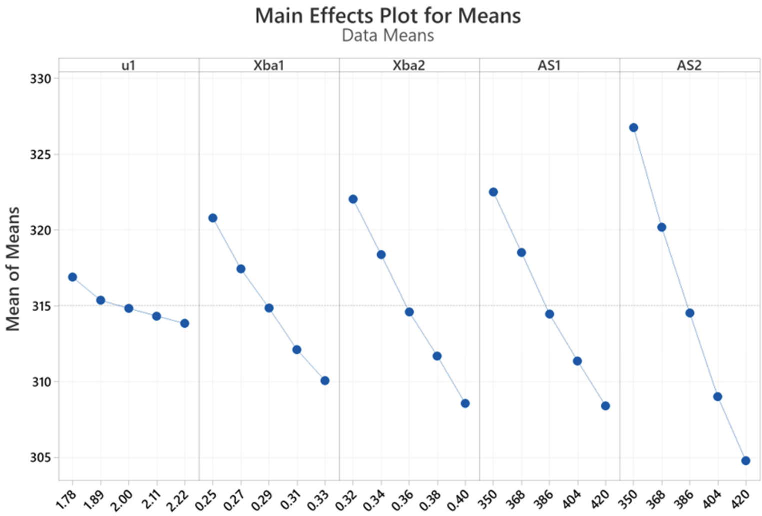

Fig. 3. Influence of main design parameters on gearbox length

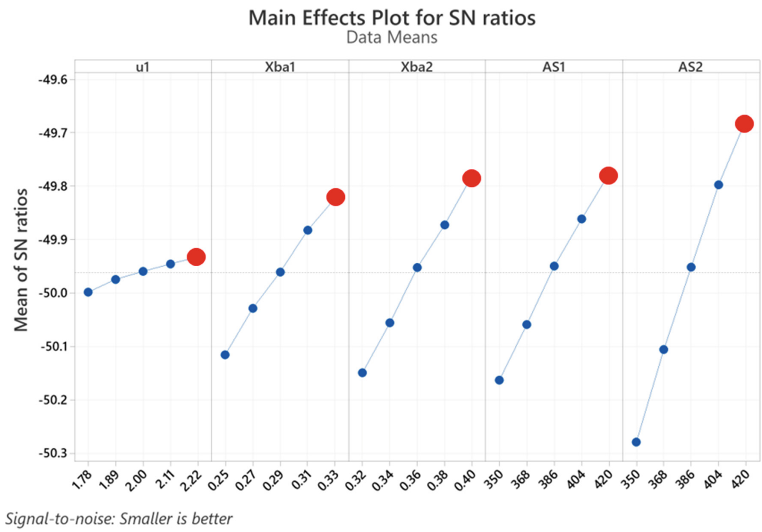

Fig. 4. Main effects plot for S/N ratios

- The optimal values of the gear ratio of stage 1 (u_1) have a first-order relationship with u_{gb} (Fig. 4). Also, the following regression equation (with $R^2 = 0.9967$) is for determining the optimum values of u_1:

$$u_1 = 0.2559 \cdot u_{gb} + 1.0453 \tag{12}$$

After obtaining u_1, the optimum values of u_2 is calculated by $u_2 = u_{gb}/u_1$.

Table 5. Optimum values of main design parameters

No	u_{gb}					
	5	10	15	20	25	30
u_1	2.2	3.72	4.78	6.28	7.58	8.56
X_{ba1}	0.33	0.33	0.33	0.33	0.33	0.33
X_{ba2}	0.4	0.4	0.4	0.4	0.4	0.4
AS_1	420	420	420	420	420	420
AS_2	420	420	420	420	420	420

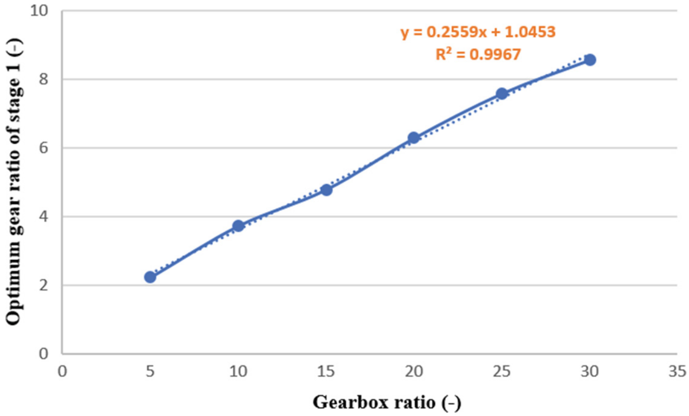

Fig. 5. Optimum gear ratio of stage 1 versus gearbox ratio

5 Conclusions

The findings of a study on optimizing a two-stage helical gearbox to obtain the smallest gearbox length are introduced in this paper. The gear ratio of the first stage, the coefficient of wheel face width of stages 1 and 2, and the allowable contact stress of stages 1 and 2 were investigated in this study. In addition, a simulation experiment with a Taguchi L25 type of design was carried out to solve the optimization problem. The effect of main design factors on gearbox length was also investigated. Furthermore, the following optimum values of the main design factors were proposed, as well as a regression model for calculating the optimum values of u1: $X_{ba1} = 0.33$; $X_{ba2} = 0.4$; $AS_1 = 420$ (MPa); $AS_2 = 420$ (MPa); u_1 is calculated by Eq. (12).

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