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Favorable gear ratio to shaping helical gear box

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KEYWORDS

Helicalgearbox,Gearratio,Gearboxcost,Simulationexperiment,SystemsEngineering.

ABSTRACT

Finding the most cost-effective configuration of a two-stage gearbox's primary design characteristics, including the second stage's double gear sets, is the goal of this article. The optimisation process takes ten parameters into account, including the total gearbox ratio, the width coefficient of the first gear stage, the width coefficient of the second gear stage, the allowable contact stress of stage 1, the allowable contact stress of stage 2, the output torque, the cost of the gearbox housing, the cost of helical gears, the cost of straight gears, and the cost of shafts. Furthermore, in order to discover the best answer, a simulation experiment is run. It turns out that the responsiveness is primarily affected by the overall gear ratio. The suggested approach has shown its dependability and is suitable for use in future research.

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I. INTRODUCTION

As contemporary industry progresses, so are the demands placed on machine designers, especially when it comes to optimising the characteristics of mechanical system components. Partial and total gear ratios significantly impact mechanical system dimensions, mass, gearbox accuracy, and cost [1–7]. So far, researchers have examined optimising the gear ratios as part of the design process of gearboxes or reducers [8–13]. The three primary methods—the graph technique [14], the practical method [15], and the model method [10-13, 16]—have been used to optimise the partial gear ratios. Research communities primarily use the latter in the aforementioned technique. A two-stage helical reducer using first-stage double gearsets is optimised for dividing overall gear ratio by Vu et al. [17]. Included in the study's seven primary design parameters are the following: total gear ratio, first-step gear face ratio, second-step wheel face ratio, allowable contact stress, output torque, gearbox housing cost, gear cost, and shaft cost. These parameters are used as inputs to the optimisation process.In addition, finding the shortest possible gearbox length is the goal function of this article. The findings validate the suggested technique and demonstrate its dependability, making it applicable to future research. Additional research has also shown the best combination of primary factors [1-3, 5, 6, 12, 16, 18, 19]. In their study, Tran et al. [20] examined a two-stage helical gearbox that had two sets of gears in the second stage. The best gear ratios may be predicted using a regression model. A significant relationship between the response and the overall gearbox ratio is seen. Prior research has shown that academics have a limited grasp of the optimal partial gear ratio optimisation problem while attempting to minimise gearbox cost. Finding the best partial gear ratio for a two-stage gearbox with a second-stage double gear set is the main objective of this research. Minimising the cost of the gearbox is the goal function. Minitab@19 allows us to execute the test plan using the Taguchi technique. Also, to forecast how much a gearbox will cost, a regression model is recommended.

METHODOLOGY

A study of gearbox contents As contemporary industry progresses, so are the demands placed on machine designers, especially when it comes to optimising the characteristics of mechanical system components. There is a significant relationship between the dimensions and the total and partial gear ratios, the Bearing, gear, shaft, and casing prices are major factors in determining the final price of a gearbox. Bearing costs will not be included in this research due to the complexity of determining these costs. Thus, the price of a two-stage helical gearbox, denoted as Cgb, is as follows:

$$C_{gb}=C_{hg}+C_{sg}+C_{gh}+C_{s} \quad (1$$

Itshouldbenoticedthatthecostofagearcontainsthecost ofused materials, machiningprocess,heattreatment, operators, etc. These costs construct the final price of a gear. In term of commerce, the price of a gear can be usuallydeterminedbyunitpriceperkilogramwhichregularlychangesaccordingtomarkets.Inthecurrentstudy, the cost of gears will be considered as variables and calculated by below equation (2).

Thecostofthehelicalgearsandthestraightgearsaredeterminedby:

$$C_{hg}=c_{hg,m}\cdot m_{hg} \quad (2)$$

$$C_{sg}=c_{sg,m}\cdot m_{sg} \quad (3)$$

Where,Chm,g,Csm,garethecostperakilogramofhelicalandstraightgears(USD/kg);

mhg,msgarerepresentativeforthemassofthehelicalandthestraightgearsinthegearbox(kg).In addition, the gearbox housing cost and the shaft cost can be determined by:

$$C_{gh}=c_{gh,m}\cdot m_{gh} \quad (4)$$

$$C_{s}=c_{s,m}\cdot m_{s} \quad (5)$$

Inwhich,$c_{g,m}$,$c_{s,m}$(USD/kg) arethecostperkilogramofgearboxhousingandshaft(USD/kg)respectively,and m_{gh},m_s(kg)aredenotedorderlytothemassofgearboxhousing,andallshafts.

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According to early analysis, it is realized that the cost of gearbox (C_{gb}) powerfully depends on the component mass,e.g.themassofgears,thegearboxhousing,andshafts.Thisisduetothecalculationofthecostperkilogram of gear, gearbox housing and shaft is far compared to the objective of this study.

Thedeterminationofgearboxhousingmass

Thegearboxhousingmass(m_{gh})canbesimplycalculatedasfollowing:

$$m_{gh}=\rho_{gh}\cdot V_{gh} \quad (6)$$

Where:ρ_{gh}istheweightdensityofgearboxhousingmaterial(kg/m^3);withgearboxhousingmaterialiscastiron, ρ_{gh}=7.2[21];$V_{gh}$is the volume of the gearbox housing (m^3). It isobserved that the form of gearbox housing is constituted by various component volumes. It means that:

$$V_{gh}=2\cdot V_b+2\cdot V_{A1}+2\cdot V_{A2} \quad (7)$$

Where, V_b is the volume of bottom housing (kg); V_{A1} and $V_{A2}$are the volume of side A1 and side V_{A2} (kg) (Figure 1):

$$V_b=L\cdot B\cdot S_G \quad (8)$$

$$V_{A1}=L\cdot\left(H-2\cdot S_G\right)\cdot S_G \quad (9)$$

$$V_{A2}=\left(H-2\cdot S_G\right)\cdot B_1\cdot S_G \quad (10)$$

EXPERIMENTALDESIGN

Table 1 lists the ten input factors and the degrees of investigation for each one. A simulation experiment is then developed to assess the influence of these parameters on the partial gear ratio u1 and, by extension, the minimal gearbox cost. Examples of possible studies that will have their scope narrowed while maintaining their quality include investigating the impact of input factors on the response and determining the minimal gearbox cost. That being said, we will be using an orthogonal array of (2k-p) 210-3= 128. This implies that a total of 128 tests are carried out. There are no major elements or interactions that correspond with others in this design, which is at configuration 5. The testing matrix with design of 210-3 will be developed using Minitab@18, as indicated before. Table 2 displays the testing matrices.

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Table1. Inputparametersandtheirinvestigatinglevels

No.	Parameters	Symbol	Unit	Level	
				Low	High
1	Totalgearboxratio	u_g	-	7	35
2	Coefficientofthefacewidthofthe first gear stage	X_{ba1}	-	0.3	0.35
3	Coefficientofwheelfacewidthofthe second gear stage	X_{ba2}	-	0.3	0.35
4	Allowablecontactstressofstage1	AS_1	MPa	350	420
5	Allowablecontactstressofstage2	AS_2	MPa	350	420
6	Outputtorque	T_{out}	Nm	1000	10000
7	Costofgearboxhousing	C_{gh}	USD/kg	1	5
8	Costofhelicalgears	C_{hg}	USD/kg	3	7
9	Costofstraightgears	C_{sg}	USD/kg	5	9
10	Costofshafts	C_s	USD/kg	1.5	5

RESULTSANDANALYSIS

You can see the effects of all the input parameters in Figure 2. Among the variables that affect u1's reaction, total gearbox ratio (ug) stands out as the most important. When ug is increased, u1 is also increased. Another factor that has a significant impact on u1 is the cost of straight gear (Csg), which is directly related to the allowable contact stress of stage 1 (AS1). On the other side, u1 becomes smaller as AS2, Chg, and Cs (shaft cost), which are all variables that increase. At the same time, u1 is unaffected by Cgh, Xba1, Xba2, and Output torque, although it is affected by first and second gear stage face width coefficients and output torque, respectively.

Table2. Testingmatrixesandthevalueofresponseu_1

Std Order	Run Order	CenterPt	Blocks	ug	Xba1	Xba2	AS1	AS2	Tout	Cgh	Chg	Csg	Cs	u1
1	1	1	1	7	0.30	0.30	350	350	1000	1	7	9	5.0	2.09
8	2	1	1	35	0.35	0.35	350	350	1000	1	3	9	5.0	8.46
70	3	1	1	35	0.30	0.35	350	350	1000	5	3	5	5.0	7.54
115	4	1	1	7	0.35	0.30	350	420	10000	5	7	9	1.5	2.19
108	5	1	1	35	0.35	0.30	420	350	10000	5	3	9	1.5	9.00
99	6	1	1	7	0.35	0.30	350	350	10000	5	7	5	1.5	2.09
…	…	…	…	…	…	…	…	…	…	…	…	…	…	…
18	127	1	1	35	0.30	0.30	350	420	1000	1	3	5	1.5	7.42
82	128	1	1	35	0.30	0.30	350	420	1000	5	7	5	1.5	6.32

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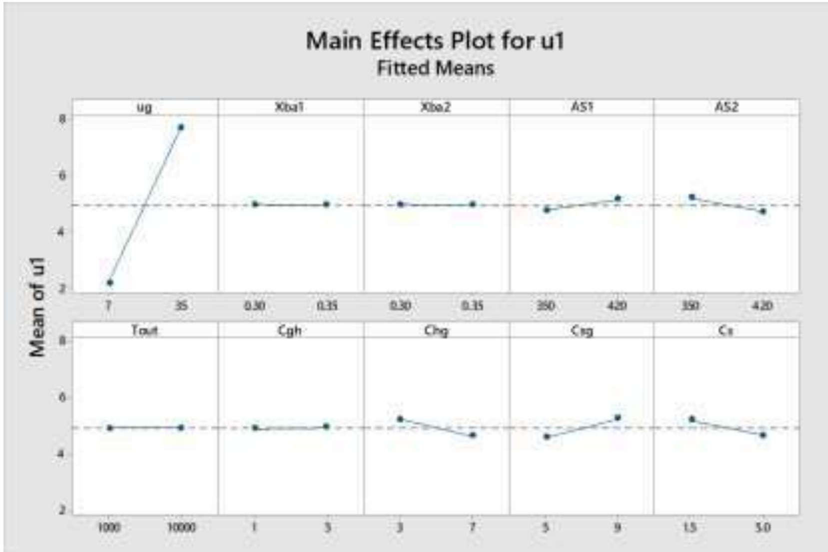

Figure2. Influencesofmainfactorsonthefirstpartialgearratio,u_1.

The influences of input parameters can be also displayed in Figure 3. It is observed that Total gearbox ratio mostsignificantly affects on u_1, shown by the first horizontal line assigned by A. Furthermore, the interactions betweeninput parameters are exhibited. The length of each horizontal line presents the influential degree. The factors having the length over red reference line are ones that critically affect u_1 with significant level of 0.05. Specifically,othershavingsignificanteffectsare D(AS_1), E(AS_2), H(C_{hg}), J(C_{sg}), K (C_s)and the interactions,
e.g. AD (u_g*AS_1), AE (u_g*AS_2), AH (u_g*C_{hg}), AJ (u_g*C_{sg}), AK (u_g*C_s), BC (X_{ba1}*X_{ba2}), GJ (C_{gh}*C_{sg}), HJ (C_{hg}*C_{sg}), HK (C_{hg}*C_s). The interactions of input parameters are also visualized in Figure 4 where one more timewecanclearlyobserve thedominantlyinfluence of $u_g$when thisparameter is combined with theremaining

ones.

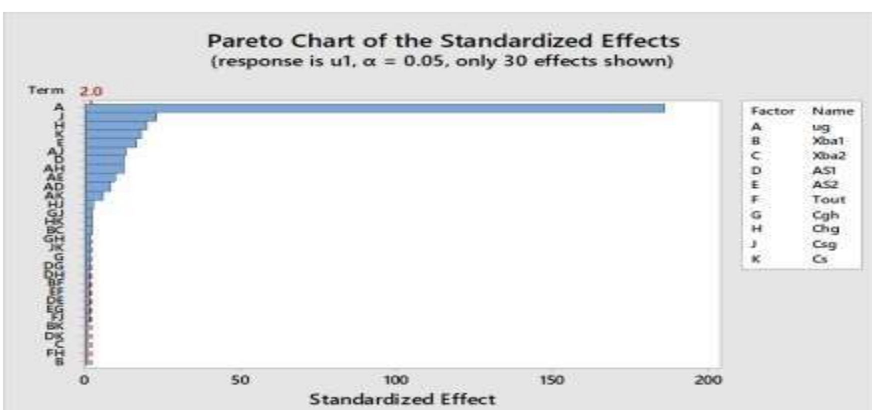

Figure3. Paretochartofthestandardizedeffectson u_1.

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In order to more clearlyidentifythe tendency and influential degree of input parameters and interactions, it can be based on the normal plot of the standardized effects as displayed in Figure 5. It is observed that the factors denoted by red are the parameters having significant impacts on u_1. These parameters are far away from the reference line. The factors of A (u_g), D (AS_1), J (C_{sg}), and the interactions of AD (u_g*AS_1), AJ (u_g*C_{sg}), BC (X_{ba1}*X_{ba2}), HJ (C_{hg}*C_{sg}), HK (C_{hg}*C_s) in the right of reference line have positive influences on u_1, while the factor of E (AS_2), H (C_{hg}), K (C_s) and the interactions of AE (u_g*AS_2), AH (u_g*C_{hg}), AK (u_g*C_s), GJ (C_{gh}*C_{sg}) inthe left of reference line have negative impacts on u_1. A regression model is proposed to predict the partial gear

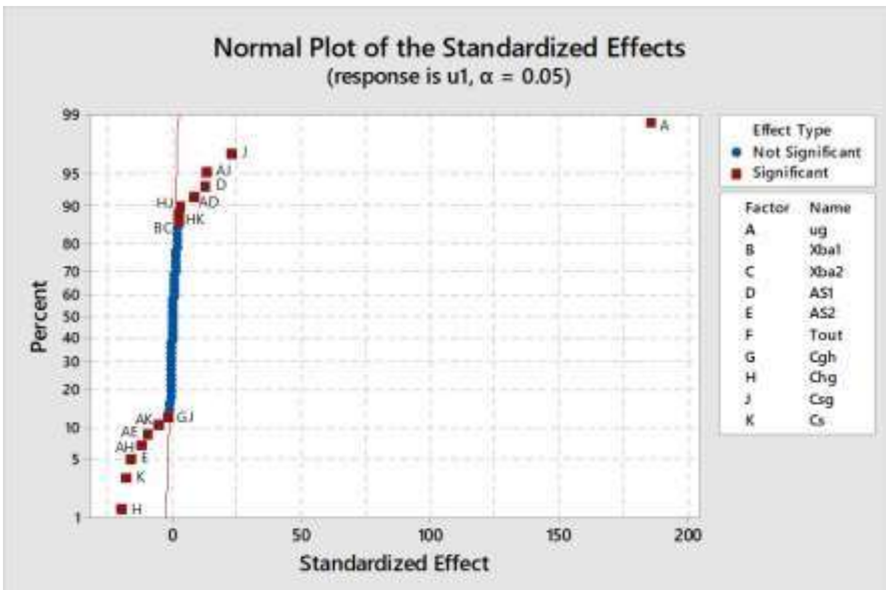

Figure4. Interactionsofinputparametersontheresponseofu1.

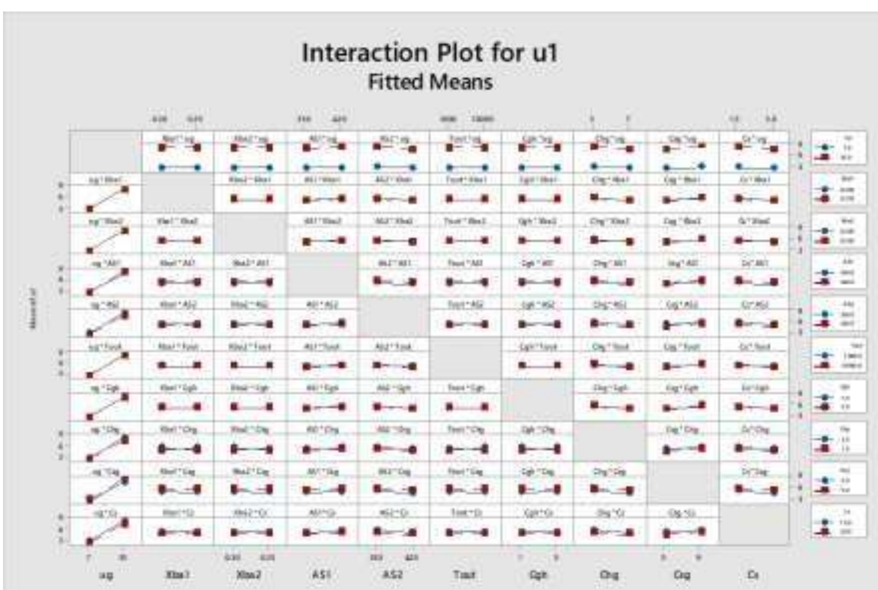

Figure5. Normalplotofthestandardizedeffectsofinputparametersandinteractionsonu1.

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Table3. Estimatedcoefficientsoftheregression modelCoded Coefficients

Term	Effect	Coef	SECoef	T-Value	P-Value	VIF
Constant		4.9305	0.0139	355.98	0.000	
ug	5.4938	2.7469	0.0139	198.32	0.000	1.00
Xba1	-0.0244	-0.0122	0.0139	-0.88	0.381	1.00
Xba2	-0.0250	-0.0125	0.0139	-0.90	0.369	1.00
AS1	0.3716	0.1858	0.0139	13.41	0.000	1.00
AS2	-0.4844	-0.2422	0.0139	-17.49	0.000	1.00
Cgh	0.0459	0.0230	0.0139	1.66	0.100	1.00
Chg	-0.5856	-0.2928	0.0139	-21.14	0.000	1.00
Csg	0.6788	0.3394	0.0139	24.50	0.000	1.00
Cs	-0.5359	-0.2680	0.0139	-19.35	0.000	1.00
ug*AS1	0.2456	0.1228	0.0139	8.87	0.000	1.00
ug*AS2	-0.2884	-0.1442	0.0139	-10.41	0.000	1.00
ug*Chg	-0.3672	-0.1836	0.0139	-13.26	0.000	1.00
ug*Csg	0.3803	0.1902	0.0139	13.73	0.000	1.00
ug*Cs	-0.1687	-0.0844	0.0139	-6.09	0.000	1.00
Xba1*Xba2	0.0616	0.0308	0.0139	2.22	0.028	1.00
Cgh*Csg	-0.0631	-0.0316	0.0139	-2.28	0.025	1.00
Chg*Csg	0.0847	0.0423	0.0139	3.06	0.003	1.00
Chg*Cs	0.0631	0.0316	0.0139	2.28	0.025	1.00

The residual assessment distribution chart, which shows the discrepancy between experimental results and predictions (see Figure 6), is used to assess the appropriateness of the suggested model. Figure 6 shows the findings. The blue dots represent the error distribution, and the solid line represents the normal distribution. With the exception of two locations quite distant from the reference line, most of the errors are near to the normal distribution. Also, when looking at how often mistakes show up on the charts, the values close to zero seem to be the most common, while the points representing strength two appear the least often. Looking at the graphs depicting the error relation and the values of the regression model (versus fit), it is clear that the points are distributed at random. With the exception of the input parameters already indicated, this finding demonstrates that u1 is independent of all other factors. Similarly, the data points in the chart of observation order are dispersed randomly. Consequently, the passage of time has no effect on u1. Previous research on chart estimating mistakes and an R-squared value of almost 99% (see Table 3) suggest that the suggested model is reliable and suitable for use in both academic and practical settings.

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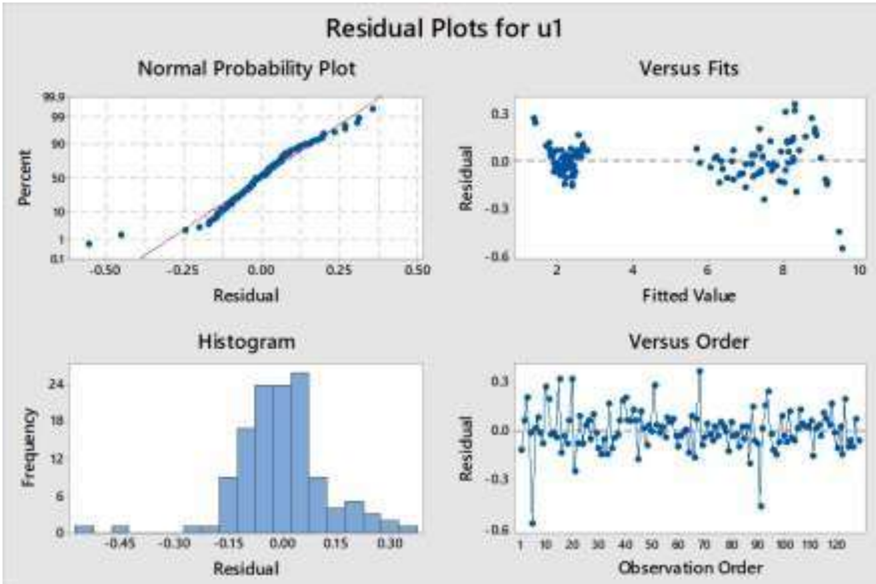

Figure6. Thechartsofresidualevaluationdistribution

CONCLUSION

A two-stage gearbox with second-stage double gear sets is optimised for cost minimization in this research. Our optimisation process takes into account the following design parameters: total gearbox ratio, coefficient of face width of the first gear stage, coefficient of wheel face width of the second gear stage, allowable contact stress of stage 1, allowable contact stress of stage 2, output torque, cost of gearbox housing, cost of helical gears, cost of straight gears, cost of shafts. It is possible to draw the following conclusions:

The following are some of the key findings:

-The response is most affected by the total gear ratio;

- The response of u1 is also strongly impacted by the interactions of the input parameters; - The proposed method, with an R-squared value of 99%, is extremely reliable and can be used in other studies.

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