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Optimization Procedure for Complete Planetary Gearboxes with Torque, Weight, Costs and Dimensional Restrictions

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Abstract. In a gear box design, it is quite difficult for a designer to quickly find an optimum solution, while the space restriction is given and the weight is to be minimized. Also the manufacturing cost, total power loss and other relevant factors have to be considered. Solving such a problem is very time-consuming, if different variants of reducers have to be evaluated carefully. A new optimization tool, based on KISSsys software, permits to layout automatically a complete gearbox using functions for the layout of gear stages, shaft dimensions and bearings, if the required torque capacity, life time, safety factors and the total ratio are given. This tool is used to generate a complete set of different variants of gear reducers. The main results are displayed in 3D graphics, showing weight, costs and efficiency of the different variants. Another graph shows the casing dimensions of the variants in three dimensions in order to check the compliance with space restriction. The use of this tool in two typical engineering applications gives very good results; the potential for weight reduction is higher than expected, going up to 30%. Manufacturing price reduction is even higher, going up to 50%.

Introduction

A gearbox design, for example a planetary gearbox design with the total reduction ratio of 60:1, is quite difficult for a designer to quickly find an optimum solution, when the maximum space restrictions are given and the weight is to be minimized, and even the manufacturing costs, total power loss and other relevant factors have to be considered. Is it better in such a case to design a two-stage reducer, with relatively high reduction per stage, or a three stage reducer?

Solving such a problem is very time-consuming, because a large number of different variants have to be evaluated carefully. A new optimization tool, based on KISSsys software, permits to layout automatically a complete gearbox using the layout functions of gear-stages, shaft dimensions and bearings from the given torque capacity, life time, safety factors and total ratio. The casing and the planet carrier is also automatically dimensioned, and the gross manufacturing price is calculated based on per kg-prices for gears, shafts, planet shafts, carrier and bearings.

In the first step, the number of gear stages is defined. If the number of stages is not clearly defined, variants with different number of stages are checked. Furthermore the distributions of the reductions i_{stage} over the individual stages can be different and should be checked with different variants. Other parameters giving big influence on size and weight of reducers are the face width to center distance (b/a) and the face width to reference diameter (b/d) ratio; therefore also these parameters are varied.
The automatic optimization procedure then generates the gearbox variants for a given output torque and total ratio, depending on the required variation range of parameters (b/a, i_{stage}) and the number of stages, each with its weight, efficiency, dimensions and costs. The main results are displayed in 3D graphics showing weight, costs and efficiency of all the variants. Another graph shows the casing dimensions of the variants in three dimensions for checking the compliance with external space restrictions. Furthermore, Excel compatible tables are produced with details for additional analysis of the results.

A ‘Gearbox-Variant-Generator’ based on KISSsys

In the calculation software KISSsoft [1], a tool for the optimization of gear stages (pairs of gears and planetary stages) called ‘Fine-Sizing-Routine’ was developed already in 1987 [2]. Now, this function became one of the most powerful features in KISSsoft. Based on a user-defined range of parameters (module, helix angle, etc.) the software presents a large number of possible solutions covering the full parameter space and presents a list with many data (geometry, safeties, characteristics as sliding, losses, price, transmission error) including a qualification of every solution based on required characteristics. So the user can investigate all the near-best solutions and then select the optimal variant, which best fits his needs. In order to assist the engineer during this task, the program offers filter and sorting functions. KISSsoft was the first professional gear software worldwide proposing such a concept [2]. When the ‘Fine-Sizing-Routine’ was first developed, it was impossible to imagine a similar feature for the layout of complete gearboxes. But with the evolution of the computing power of today, the more powerful tools have been developed. KISSsys [1, 4] is such software available since 2000 for the calculation of complete power transmissions. The KISSsys software combines kinematic analysis, lifetime calculation, 3D graphics and user defined tables / dialogues with a programming language (Fig. 1). Due to its flexibility, it is the tool of choice for strength and lifetime analysis of various kinds of drive trains and gearboxes.

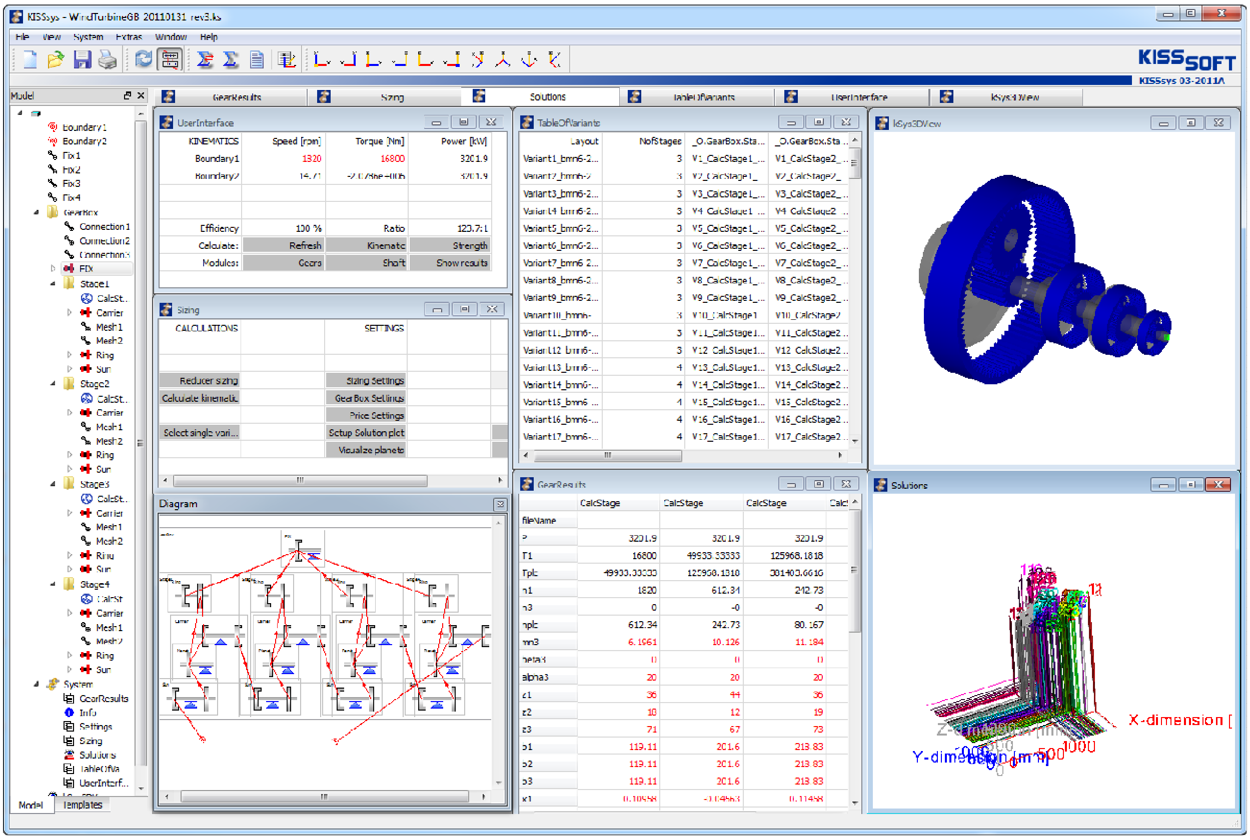

Fig. 1. KISSsys windows of the Gearbox-Variant-Generator
User Interface: Provides for input of required torque and speed
Sizing: Includes the various sizing functions and functions for user data input
Table of Variants: List of the different reducers, of which any solution can be selected
Solutions: 3D display of main results for the 90 reducer variants calculated

Optimization of a Compact Micro-Planetary-Gearbox

The tool was used in a project for a Chinese company, producing small compact gear reducers with a high speed reduction. Such reducers, having an outer diameter of 50 mm and less are called as Micro-Planetary-Gearboxes. Normally the ring gear is the housing of these reducers, and all the stages must have the same ring gear geometry to simplify the manufacturing process (cutting the inner gear

tooth form with a needle out of a steel tube). The design data for one of the required gearbox was: Output speed 31 rpm and 16 Nm torque. On the input side, a 50 W with 5000 rpm motor should be used. Therefore, the required total reduction is i = 160. Since a single planetary stage has normally a reduction between 2.5 to 7.0, the reducer can be built as a 3-, 4- or 5-stage-reducer. There are many possibilities how the total reduction is distributed over each planetary stage.
The tool proposes in the first step different possibilities for the ratio distribution over the stages (Fig.2). The proposal can be easily modified by the project engineer. The user can request a special design to share the same ring gear for all stages. Additionally other design parameters can be varied, for example the b/a ratio. Then all the different gear reducers are automatically designed for the required torque, and then the weight and manufacturing price are calculated. In this example, 42 reduction ratio variants combined with 4 different b/a ratio results in 168 different reducers. All the solution can be visualized and in 3D graphics with showing the different characteristics. As shown in Fig. 2, the 5-stage solutions are the most economic.

	A	B	C	D	E	F	G
1	Variant	Stages	iStage1	iStage2	iStage3	iStage4	iStage5
2	Variant no: 1	3	6.056458	5.697265	4.636976		
3	Variant no: 2	3	4.929321	7	4.636976		
5	Variant no: 6	3	4.01195	5.697265	7		
6	Variant no: 7	4	5.52084	3.774012	3.071649	2.5	
7	Variant no: 8	4	4.493384	4.636976	3.071649	2.5	
9	Variant no: 29	5	3.333714	3.071649	2.5	2.5	2.5
10	Variant no: 30	5	2.713293	3.774012	2.5	2.5	2.5
11	Variant no: 31	5	3.333714	2.5	3.071649	2.5	2.5
13	Variant no: 42	5	2.713293	2.5	2.5	2.5	3.774012

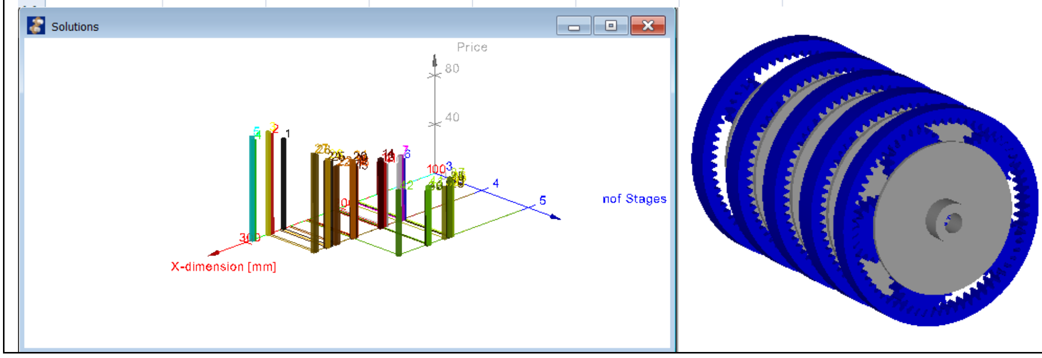

Fig. 2. Micro-Planetary-Gearbox with common outer ring (Analyzing 168 different reducer-variants)
Above: Proposed stages and ratio variants.
Below: Manufacturing prices of the different reducers (left), 3D-model of the selected variant (right)

Optimization of a 3-MW Wind Turbine Gearbox

One of the most important criteria in wind turbine design is weight reduction. Normally lower weight of the gearbox is even more important than lower manufacturing cost, because when the reducer is lighter, this reduces the cabin and tower construction costs. The wind turbine gearbox can have various configurations, and we decided to design a 3- or 4-stage planetary gearbox with no restriction on the ring gear geometry. The design data for the gearbox was: Input speed 15 rpm and output power 3.2 MW. The required total gear ratio is i = 120 (speed increaser). The number of planets of all the stages is set to 3 to simplify the design.

The tool proposes 153 different gearboxes from 51 ratio variants combined with 3 different b/a-ratio from 0.3 to 0.7 with the step of 0.2. Fig. 3 shows the minimum and the maximum priced variants for each b/a ratio. The average prices of the 3- and 4-stage gearboxes are 1.51×10^5 and 1.73×10^5, and have less than 13% of difference. However, it is surprising that the difference of the minimum and the maximum prices is over 4 times (1.05×10^5 and 4.44×10^5) with the similar level of safeties. In addition, it should be noted that the minimum price gearbox was found in 4-stage variants, not in 3-stage. Thus, the proper selection of the design is most important to reduce the gearbox price, and it’s inevitable to use the tool in order to achieve the optimal gearbox design.

	A	B	C	S	T	AG	AH	AU	AV	BI	BJ	BM	BU
2	bmn 6/20	bd1 0/1.6	ba 0.3/0.3	Stage 1		Stage 2		Stage 3		Stage 4			
3	variant	Stages	Total ratio	min SF	min SH	min SF	min SH	min SF	min SH	min SF	min SH	Total price	
6	Variant: 3	3	123.017	1.6	1	1.403	1.184	1.435	1.184			109639	
13	Variant: 10	3	120.963	1.706	1	1.413	1.228	1.417	1.234			148321	
20	Variant: 17	4	120.982	1.753	1	1.412	1.19	1.49	1.361	1.525	1.486	218527	
39	Variant: 36	4	124.076	1.754	1	1.4	1	1.4	1.044	1.447	1.228	104609	<< Min.price
55													
56	bmn 6/20	bd1 0/1.6	ba 0.5/0.5										
57	variant	Stages	Total ratio	min SF	min SH	min SF	min SH	min SF	min SH	min SF	min SH	Total price	
60	Variant: 54	3	123.017	1.645	1	1.419	1.145	1.408	1.171			120036	
69	Variant: 63	3	121.669	1.769	1	1.416	1.134	1.434	1.198			185807	
78	Variant: 72	4	120.794	1.637	1	1.407	1.17	1.405	1.203	1.466	1.048	272551	
106	Variant: 100	4	121.384	1.637	1	1.4	1	1.4	1	1.406	1.17	109495	
109													
110	bmn 6/20	bd1 0/1.6	ba 0.7/0.7										
111	variant	Stages	Total ratio	min SF	min SH	min SF	min SH	min SF	min SH	min SF	min SH	Total price	
112	Variant: 103	3	123.455	1.982	1	1.401	1.044	1.405	1.179			139920	
123	Variant: 114	3	125.04	1.801	1	1.401	1.022	1.415	1.076			229082	
125	Variant: 116	4	120.016	1.838	1	1.423	1.073	1.809	1.057	1.588	1.012	444354	<< Max. price
154	Variant: 145	4	121.886	2.044	1	1.506	1	1.426	1.132	1.426	1.188	127579	

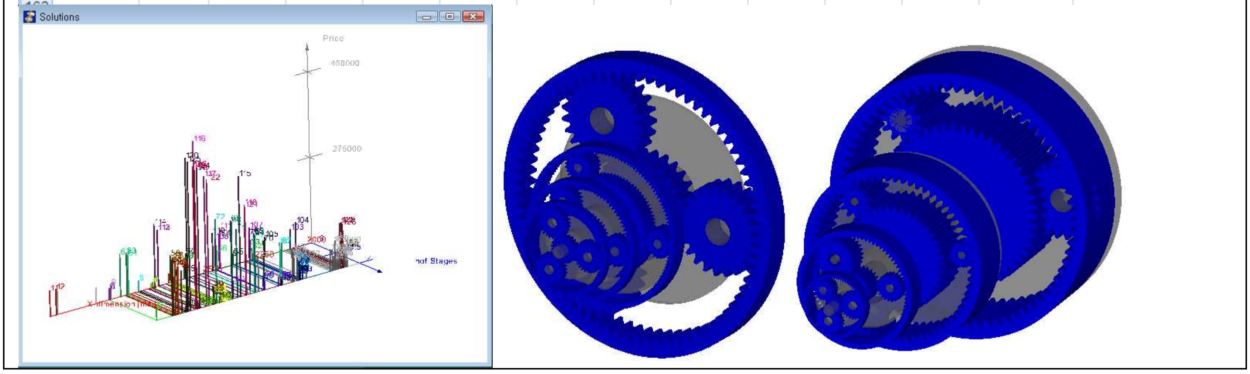

Fig. 3. Wind turbine gearbox variants
Above: Gearbox variants with minimum and maximum masses.
Below: Price of the gearboxes (left), 3D-models of the minimum(center) and maximum prices (right)

Conclusions

A new tool, a Planetary-Variant-Generator permits an arbitrary number of completely defined planetary gearbox variants to be created automatically using functions for the layout of gear-stages, shaft dimensions, bearings and planet carrier; given the required torque capacity, life requirement, safety factors and the total ratio. As specified by the user, gearbox variants with different number of stages and different distribution of the ratios over the stages are calculated. The results such as weight, power loss, manufacturing price, torque capacity can be visualized in 3D-diagrams, in which the numbered variants are displayed. Thus the user can review the best proposition, but he can also see all the near-best solutions and then select the optimal variant, the one that best fits his needs.
The use of this tool in two typical engineering applications gives very good results; the potential for weight reduction is higher than expected, going up to 30%. Manufacturing price reduction is even higher, going up to 50%. This product will be enhanced with some additional features and be available for general use.

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