Computer Aided Analysis of Animal Driven Gear Box

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Abstract

An animal driven prime mover which has a speed enhancement gear box as one of its main components was studied by IIT Delhi in 2003. Here the analysis of a gear box is provided using some software (e.g., MATLAB, Autodesk inventor). Actually design equations were programmed in MATLAB for quick calculations, whereas Autodesk inventor allowed one for quick visualization of the movement. Such tool allows one to systematically study such gearboxes to check their designs, e.g., whether they are over-designed or under-designed. In this paper, one such gear box made by Panchal Pumps Ltd, Kanpur, India was studied in detail. Some of its gears were found to be over-designed which was conveyed to the manufactures for modification.

Keywords: Animal, Gearbox, software

List of symbols:

C: dynamic load rating (N)
P: equivalent load (N)
V: rotational factor
X: radial factor
Y: thrust factor
Wr: radial load (N)
Wt: tangential load on gear tooth (N)
E: modulus of elasticity (MPa)
N_f : factor of safety in cyclic loading
Rx, Ry: reactions on the shafts
FOS: factor of safety
σ_b: bending stress in gear tooth (MPa
f: face width (mm)
m: module
y: Lewis form factor
σ_c: surface fatigue stress (MPa)
d_1: pitch diameter of gear (mm)
d_2: pitch diameter of pinion (mm)
v: Tangential velocity of gear pair (mm/sec)
σ_e : endurance strength ($0.5\sigma_{ut}$ MPa)
σ_y : yield strength (MPa)
k_f: fatigue factor in bending
k_{fs} : fatigue factor in torsion

1 Introduction

India is a predominantly an agricultural country, where about 70% of population lives in rural areas and depends on the agriculture. The use of animal source of energy (human and draught animal power) is very predominant in the country and will be continued. The draught animal power can be utilized in different fields, e.g., water pumping, electricity generation etc., by the use of animal driven prime mover. Animal driven prime mover consists of a gear box assembly directly coupled with the animal, as shown in Figure 1. Such gear boxes were made by different NGOs and research establishments of the country [1]. One such gear box comprised of two spur gear and pinion sets, and one helical gear and pinion set (Figure 2) to transmit the motion from input shaft to the output pulley. The gear box made is by Panchal Pump Ltd, Kanpur, India. This paper presents the analysis of the gear box.

2 Analysis

The gear box is analyzed to check if its components are over-designed or not. The analyses of the following components were attempted in this research:

- Gear pairs
- Shafts
- Bearings

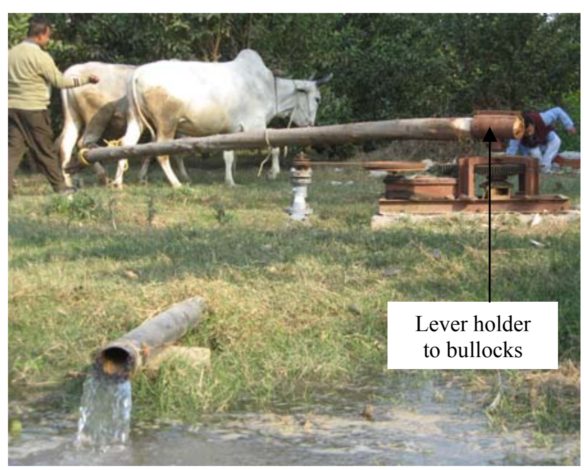

Figure 1: Bullock driven gear box

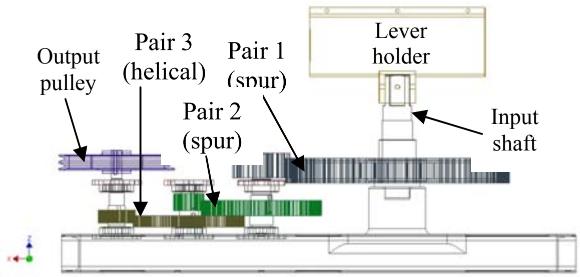

Figure 2: Gear box

Table 1: Specification of the gear box

Input power	2 hp (~1.5 kw)
Overall gear ratio	63:1
Input velocity	2 rpm
Module of gear pair 1 (spur gear)	6 mm
Face width of gear pair 1	35 mm
Module of gear pair 2 (spur gear)	7 mm
Face width of gear pair 2	70 mm
Module of gear pair 3 (helical gear)	2.5 mm
Face width of gear pair 3	35 mm

The specification of the gear box is given in Table 1.

2.1 Gear pairs

There are two spur gear pairs and one helical gear pair. The gear pairs have been analyzed using the first principle and the AGMA equations [2]. The gear pairs are subjected to bending load as well as surface fatigue. The safety factors for different gear pairs have been found using a MATLAB program. Note that the bending stress induced in the gear teeth is given by

$$\sigma_b = W_t / (f*m*y) \text{ Mpa} \quad (1)$$

The surface fatigue stress induced in the gear teeth is obtained from the following formula:

$$\sigma_c^2 = 2 *Wt*B / [\pi*f*\cos\varphi*(m_1+m_2)] \quad (2)$$

where

$$B= (1/d_1)+(1/d_2)$$

$$M_1= 1-v_1^2/ E_1 \quad (3)$$

$$M_2= 1-v_1^2/E_2$$

Using equations (1-3), factor of safety (FOS) of different gear pairs were obtained which are tabulated in Table 2. From Table 2, it is clear that gear pairs 1 and 2 are not over-design but the gear pair 3, which is a helical gear pair, is over-designed (FOS > 5) and needs to be redesigned to reduce mainly the material cost. The FOS of the helical gear pair can be reduced by changing the following properties of the gear pair:

- Material
- Face width
- Module

They are done as follows:

Table 2: FOS for different gear pairs

Pair and type	Gear or pinion	Material	FOS in bending	FOS in surface fatigue
Pair 1: Spur	Gear	CI FG-210-Gr	1.29	1.22
	Pinion	EN-8= AISI 1040	1.25	1.36
Pair 2: Spur	Gear	EN-24= AISI 4340	1.99	1.87
	Pinion	EN-24= AISI 4340	1.5	1.87
Pair 3: Helical	Gear	EN-24= AISI 4340	6.87	5.16
	Pinion	EN-24= AISI 4340	5.37	5.16

1. Effect of material: Effect of different material combinations on the FOS of the helical gear pair are shown in Figure 3. So minimum FOS (5.2) can be achieved by using the gear of AGMA class-one material and maximum FOS (7.1) can be achieve by using the gear of AISI 4340 material. In order to use the available stock it was decided to continue with the material AISI 4340. The FOS will be reduced by considering other affecting parameters like face width and module, as shown next.

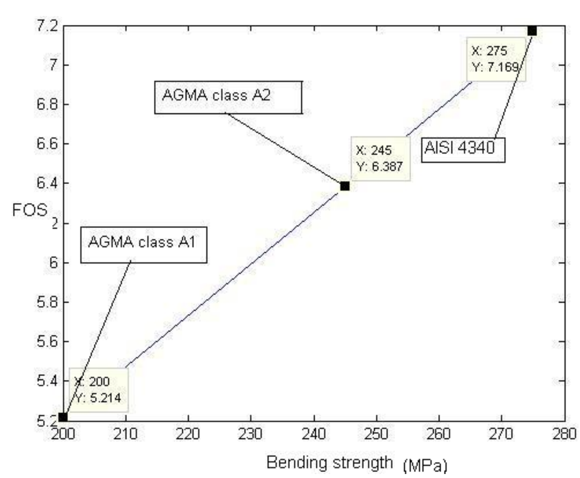

Figure 3: Variation of FOS in bending with respect to different materials.

2. Effect of face width: The face width directly affects the strength of the helical gear pair. The strengths (bending strength and surface fatigue strength) of the helical gear pair increase as the face width increases. The effect of face width on the FOS is shown in Figure 4. Corresponding to face width of 18 mm, the FOS is minimum for both bending as well as for surface fatigue strength. Hence 18 mm face width is proposed.

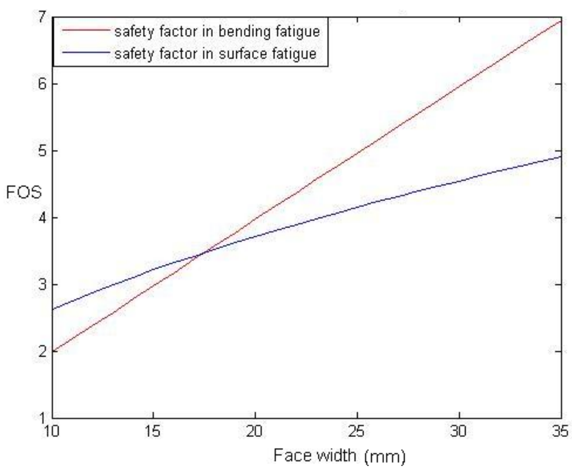

Figure4: Variation of FOS with respect to face width (material AISI 4340)

3. Effect of module: Gear pairs are generally available with standard modules. Helical gear with module of 2.5 mm is used in this gear box. The use of gear with lower module will reduce the strength. The effect of module on the FOS is shown in Figure 5. From the plot it is clear that the module 1.2 mm gives FOS 3.4 for both bending and fatigue strengths, which is acceptable. Hence module of 1.2 mm is proposed for gear pair 3 (Figure 2).

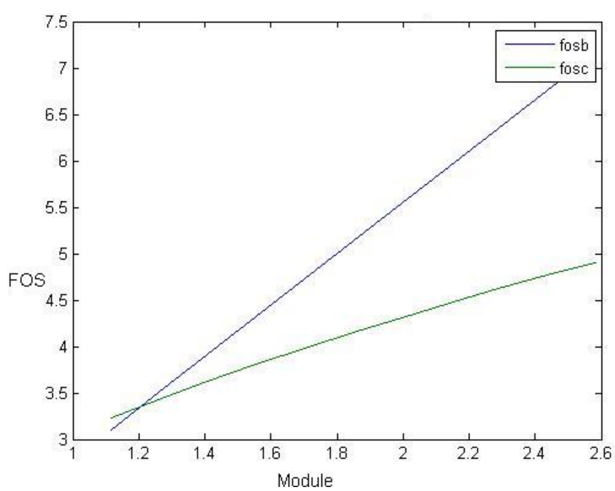

Figure.4: Variation of FOS with respect to module (material AISI 4340)

2.2 Shafts

There are four shafts used in this gear box (Figure 2). Each shaft is subjected to bending as well as torsion load. The keyways used to fix the gears and pulley reduces the strength of the shaft. So during the analysis of each shaft stress concentration factor was taken into account. The analysis of a shaft for fully reversed bending and steady torsion stress has been done by using the ASME code [2]. The formula used is given below:

$$1/ N_f^{\,2} = (\sigma_a / \sigma_e)^2 + (1.73*\tau_m / \sigma_y)^2 \tag{4}$$

where

$$\sigma_a = k_f*(32*Ma / \pi*d3) \text{ MPa} \tag{5}$$

$$\tau_m = k_{fs}*(16*Tm / \pi*d3) \text{ MPa} \tag{6}$$

$$k_f = 1+q*(k_t-1)$$
$$k_{fs} = 1+q*(k_{ts}-1) \tag{7}$$

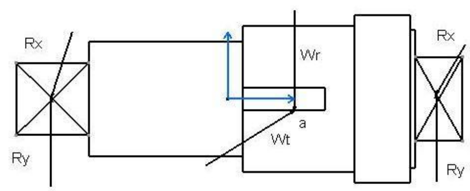

Figure 6: Free body diagram of a shaft

The most critical parts of a shaft are the point of application of load (point a in Figure 6) and the point where the step size is changing. Analyses were done to these critical locations and the FOS is coming within tolerable limit (Table 3). From Table 3, it is clear that each shaft is not over-designed.

2.3 Bearings

There are four bearings used in the gear box. Each bearing is subjected to radial as well as axial loading. The expected life of the bearings has been calculated on the basis of the service of the gear box as $1.7*10^6$ cycles (based on 4 hrs daily use for 10 years).

Table 3: FOS of each shaft

Shaft	Material	FOS
Cattle drive gear shaft	AISI 4340	1.28
Drive gear shaft	AISI 4340	1.08
Idler gear shaft	AISI 4340	1.52
Driven gear shaft	AISI 4340	1.23

Note that the equivalent load on the bearings is given by [2]

$$P = X*V*F_r + Y*F_a \quad \text{N} \tag{8}$$

Also the Life of the bearing is taken from [2] as

$$L = (C / P)^{3} * 10^{6} \text{ revolutions}$$

The actual life of the each bearing was calculated from the above formulas and the results are shown in Table 4. From the analysis it is clear that the life of each bearing is coming out very high as compared to the desired life. However, as the analysis was carried out under ideal conditions with proper lubrication in dust-free environment and no overheating which are never achieved in real life, the selected bearings are considered acceptable, i.e., not over-designed.

Table 4: Life of the different bearing

Bearing type	Desired life (revolutions)	Calculated life (revolutions)
Taper roller bearing SKF-300356	$1.7*10^{6}$	$4.2*10^{10}$
Ball bearing SKF 6215	$1.7*10^{6}$	$4.56*10^{8}$
Ball bearing large SKF 6310	$5.9*10^{6}$	$2*10^{9}$
Ball bearing small SKF 6306	$1.05*10^{8}$	$2.3*10^{9}$

3 CAD Modeling

Modern CAD (Computer Aided Design) software (like Autodesk inventor, etc.) enables engineering and design staff to create 3D solid model of components and assemblies. Some benefits of CAD are productivity improvement in design, shorter lead times in design, more logical design process and analysis, fewer sign errors, greater accuracy in design calculations, standardization of design, more understandability and improved procedures for engineering changes. The modeling of the gear box of animal driven prime mover components, e.g., gears, shafts, casing, and base frame, were modeled in Autodesk inventor. The assembly of gear box was also done in Autodesk inventor, as shown in Figure 7. The animation using the CAD model provided greater understanding to the users. If a design change is needed it can now be done easily by simply changing the parameters and re-running the simulation. Such modeling is also referred to as Virtual Prototyping (VP), where a product developer can avoid many real prototypes which is time consuming and expensive. Thus, a product developed through VP is cost competitive. It is expected that the developed VP will help the gear manufacturer to bring out new designs quickly.

4 Conclusions

In this paper, software like MATLAB, Autodesk Inventor are used to analyze a gear box meant for pumping water using animal power. Use of advanced tools will help manufacturers to check their design without having detailed knowledge of engineering. Moreover, it will help them bring new designs quickly. Such concepts are generally used in high-tech industries like automobile, aerospace, etc., which are now brought to rural industries for the benefit large rural masses of India.

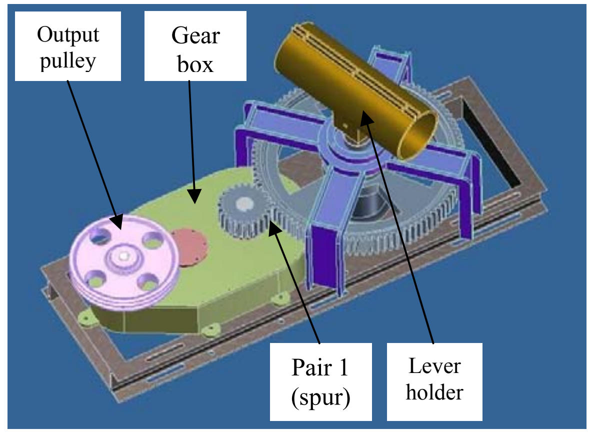

Figure 7: CAD model of gear box in Autodesk inventor

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