ASSIGNMENT 1

MCEN6020 Advanced Machine Design

ASSIGNMENT TITTLE: ANALYSIS AND DESIGN OF A GEARBOX

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Executive Summary

This report investigates the planning, designing, and evaluation of a gearbox where in the output shaft, power has to be maintained at 2.1 KW, the speed of input and output shafts are given and the input & the output shaft have to be inline. The gearbox has to operate in uniformly loaded conditions and be capable of operating for 10 years.

This study concentrates on the optimization of the reduction ratio to have an effective power transmission. Detailed calculations have been conducted to determine the shaft size & number of teeth to select appropriate gears for the shafts. Torques have been calculated for all shafts to check the tolerable limits for structural analysis. The shaft materials and the bearings should be considered carefully to ensure the machine's durability as well as reduce wearing and losses.

This investigation emphasizes CAD tools such as SOLIDWORKS to create the design model using mathematical calculations and assumptions, ensuring the dimensions of all parts and components are correct.
In short, this study offers an extensive analysis of gearbox design, including mathematical calculations and an FEA arrangement to fulfil the design's requirements.

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Introduction

The gearbox design is an intricate and crucial part of Mechanical Engineering. It directly impacts the durability of the machine and transmits power to the different components of the shaft for better performance. This report concentrates on designing the gearbox according to the requirement of the output performance of 2.1 KW as well as having the steady state input and output speed of 1960 rpm & 560$\pm$3 rpm, have to be mounted with 4 bolts and lastly, the input shaft & the output shaft have to be collinear, will be operated by maintaining uniform load conditions.

The main objective is to calculate the enhanced reduction ratio to fill up the requirements of the torque and speed on all shafts by minimizing their size. A perfect reduction ratio will help to get enhanced transmission of power, reducing losses and maintaining the durability of mechanical components. Material selections, the configuration of gear tooth and the selection of module play an important role in getting an optimized reduction ratio. This report focuses on the design constraints for the assembly and disassembly of the gearbox for regular maintenance as it is designed to work for 10 years at 7.5 hours per day and 6 days a week.

This report investigates the complex steps to measure the torque in the input shaft, output shaft, and countershaft. The bearing section is also an important part as it determines the precision fits with the casing to maintain machine durability by reducing wearing, tearing & vibrations. Shaft materials should be carefully considered as it has to meet the tolerable limits for structural integrity.

Moreover, the design of the shaft is crucial for precision fit with the spur gear, bearing. It will be designed according to the gear and bearing’s diameter and partial assuming to maintain a good balance between weight & strength. Lastly, it will be designed to SOLIDWORKS according to the calculation to ensure that the dimensions of all components and parts are accurate, turning the manual theory calculations into the practical design.

Literature review on environmental protection and assessment

Before the implementation of applications, environmental protection has become the top priority in all sectors of Engineering. Life cycle assessment (LCA) refers to the evaluation of the environmental impacts of a product throughout its lifecycle which comprises raw material selection, production process, and ends at disposal. LCA focuses on environmental performance assessment by improving environmental sustainability through the reduction of harmful materials usage in the production process (European Commission, 2010).

Finnveden et al. (2009) emphasize on few terms for the latest development to improve the environmental conditions in product design as follows:

Eco-efficiency: It refers to the combination of environmental performance with the efficiency of economics, also offers to use fewer resources to protect the environment which minimizes costs.

Social Life Cycle Assessment (SLCA): SLCA examines the social impacts of the products, and measures the human well-being during the production process and utilization of the product in the society. It primarily focuses on diminishing the bad effects from the initial stage such that it can enhance social benefits throughout its lifecycle.

Life-cycle costing (LCC): It emphasizes an economic balance of the product, and concentrates on the selection of materials that are not only cost-effective but also environmentally sustainable. LCC should be applied through the considerations of the environmental impacts.

Triple Bottom Line (TBL): TBL measures the social, economic, and environmental evaluation of the product design stage. This framework includes LCA, SLCA, and LCC together for the basic understanding of TBL.

According to Gaha, Benamara, and Yannou (2013) state the CAD tool is advanced to implement the LCA method during the product design stage. Simapro is an LCA tool that measures environmental performance according to the dataset and alerts for environmental complications during the design process, ensuring environmental sustainability from the initial stage. Gabi offers Life cycle inventory analysis, which aids designers in knowing about the environmental impacts of the product throughout its lifecycle.

In short, the combination of LCA, SLCA, LCC, eco-efficiency, and TBL presents an extensive structure for analyzing the social, economic, and environmental impacts throughout its life cycle. Mainly, these processes concentrate on the selection of the least resources, selection of eco-friendly material, and beneficial to social well-being. More advanced tools like SimaPro and Gabi emphasize the protection of the environment, and production objectives from the design stage, which enables for environmental and social sustainable materials.

Literature Review on Gearbox Design and Analysis

The gearbox is a vital element in industrial applications and transmits power to the mechanical component for greater efficiency, enhanced output, reducing losses. The last decades witnessed technological advancement in design, and gear analysis for the introduction of upgraded Finite Element Analysis (FEA) software. This study will emphasize gearbox design, maintenance, analysis, types of gear, and gear applications.

S45C material is selected as spur gears from KHK Gear catalogue as it has a moderate level of tensile and fatigue strength. It is a medium carbon steel and is famous for good balanced mechanical properties. It'll meet the requirements of the gears as it offers durability & cost-effectiveness. (Prayogo, Arsyad & Auzani, 2023). To achieve a sustainable gearbox, the selection of gear & bearing materials, the arrangement of gear and bearing, and shaft length play a crucial role. According to Kim et al. (2022), the wrong arrangement of the bearing arrangement, and shaft length causes the shaft to deflect, causing a loss of the uniform load balance that gradually hampers the fatigue strength, and target durability of the gearbox. The shaft length has been increased the bearing arrangement has been changed and gears have been aligned precisely to get the sustainable gearbox, also micro-geometry modification has been applied to balance the uniform load distribution to reduce the losses.

Several gearboxes are used for different purposes, arrangements, and goals.

Spur Gearbox: It's a simple design and is widely used in agricultural machinery. It offers medium torque, and low to medium speed, and is better for simple machine design. However, the spur gearbox produces more vibration and noise due to the direct teeth connection (Jiri et al. 2021).

Worm Wheel: It offers a more complex design and is frequently used for heavy machinery. It produces high torque and low-speed applications and is capable of transmitting power at 90 degrees. The gearbox shows smooth operation but due to friction between the worm wheel and worm, loses efficiency. Moreover, it includes scratches on the bearing surface or on the gear that can lead to gearbox failure if it is not detected in the early stage (Barshikar 2024).

Helical Gearbox: It features less vibration and noise compared to others and offers more durability, can operate in high-speed applications. Moreover, teeth are angled there for better alignment, offering more efficiency and uniform load balance that makes the gearbox more durable (Wang et al. 2010).

Igba et al. (2015) emphasize about maintenance for gearbox durability and sustainability of other mechanical components. In this research, preventive maintenance and corrective maintenance have been discussed. Corrective maintenance refers to repairing the gearbox when a breakdown happens that is more expensive to repair because the gearbox has been running for a long time without maintenance, and lots of wearing and tearing inside the gearbox turns into a breakdown, where lots of parts need to be exchanged, which is expensive. On the other hand, preventive maintenance refers to scheduled maintenance after a certain period, lubrication inside the gear, and replacing minor components have been conducted for the longevity of the gearbox. It protects the gearbox from sudden downtime and saves unwanted costs. Based on the study, it is suggested that preventive maintenance should be followed instead of corrective maintenance to improve the durability, and sustainability of the gearbox, and reduce the operational & maintenance costs.

Shukla and Kumar (2021) emphasize the advancement of the design process due to the FEA software tools. In FEA Software, designers can create an operating environment, be capable of measuring the flow of simulations, identify the issues in the design process, and possibly get targeted feedback. FEA software can examine everything before implementing the design which is cost and time effective. FEA Software is capable of thermal analysis is important for measuring the efficiency of the system, also be able to predict suitable parameters to improve the efficiency. FEA software can detect vibration and noise during simulation, and is capable of presenting the main reason behind this, also indicates the alignment and misalignments of gears and bearings with Shafts. Moreover, FEA presents that high heat dissipation of the outer surface reduces heat inside and makes the system more efficient. Load distributions and stress concentrations can be measured and represented visually to understand the system's load balance & gear's overall performance.

In short, this study emphasizes the importance of the selection of suitable materials for gear, gearbox design, and analysis by using FEA software, and maintenance techniques for the enhanced durability and efficiency of the gearbox, also discusses different types of gear with their application.

Calculation

Given,

Power of output shaft = 2.1 kW

Input Speed (Steady State) = 1960 rpm

Output Speed (Steady State) = 560 $\pm$ 3 rpm

The Measurement of Number of teeth

Here, input to output gear ratio = 3.5, less than 1:10. It is possible to design it using a single gear pair, but as per the requirement, input and output shafts must be inline. That's why we need in 2 stages.

Here,

Minimum Number of teeth, $N_{min} = \frac{2K}{(sin\emptyset)^2} = 2 * \frac{1}{(\sin 20)^2} = 17.09$

$N_{min} = 18$ [by rounding off to the next integer]

Now the train value, $\frac{N_1}{N_2} \times \frac{N_3}{N_4} = \frac{1}{3.5}$

Now, distributing the ratio in 2 stages:

$\frac{N_1}{N_2} = \frac{1}{1.75}$ & $\frac{N_3}{N_4} = \frac{1}{2}$

So, $N_2 = 1.75\ N_1 \qquad (1)$ & $N_4 = 2\ N_3 \qquad (2)$

For inline output & input shaft, Center distances are equal.

$C_1 = C_2$

$\frac{mN_1}{2} + \frac{mN_2}{2} = \frac{mN_3}{2} + \frac{mN4}{2}$

$N_1 + N_2 = N_3 + N_4$

$2.75\ N_1 = 3\ N_3$

$11\ N_1 = 12\ N_3 = K$

Table 1: Gear Sizes for the value of K

		Ratio 1: 1.75		Ratio 1:2	
Count	K	N_1	N_2	N_3	N_4
1	198	18	31.5	16.5	33
2	264	24	42	22	44
3	396	36	63	33	66

The best Outcome:

$N_1 = 24, N_2 = 42, N_3 = 22, N_4 = 44$

The Measurement of Torque

100% efficiency is assumed.

We know,

$P = T\omega \quad \& \quad \omega = \frac{2\pi N}{60}$ [P = Delivered Power, T = Torque]

By calculation,

$T_{input} = 10.23\ Nm$ & $T_{output} = 35.81\ Nm$

Here,

$\frac{T_b}{T_a} = \frac{N_2}{N_1}$

$T_b = \frac{N_2}{N_1} \times T_a = \frac{42}{24} \times 10.23 = 17.904\ Nm$ [countershaft]

Gear has been chosen from KHK gear catalog from the number of teeth & module, m= 3.

Table 2: Details of Gear Specifications (KHK Gears Catalogue)

Catalog Number	Gear Wheel Number	Number of teeth	Shape	Bore (mm)	Hub Dia. (mm)	Pitch Dia. (mm)	Outside Dia. (mm)	Face width (mm)	Hub width (mm)	Total Width (mm)
SSG3-24	N_1	24	S1	20	58	72	78	30	20	50
SSG3-42	N_2	42	S1	25	80	126	132	30	20	50
SSG3-22	N_3	22	S1	20	54	66	72	30	20	50
SSG3-44	N_4	44	S1	25	80	132	138	30	20	50

Calculation of Radial Forces on Countershaft

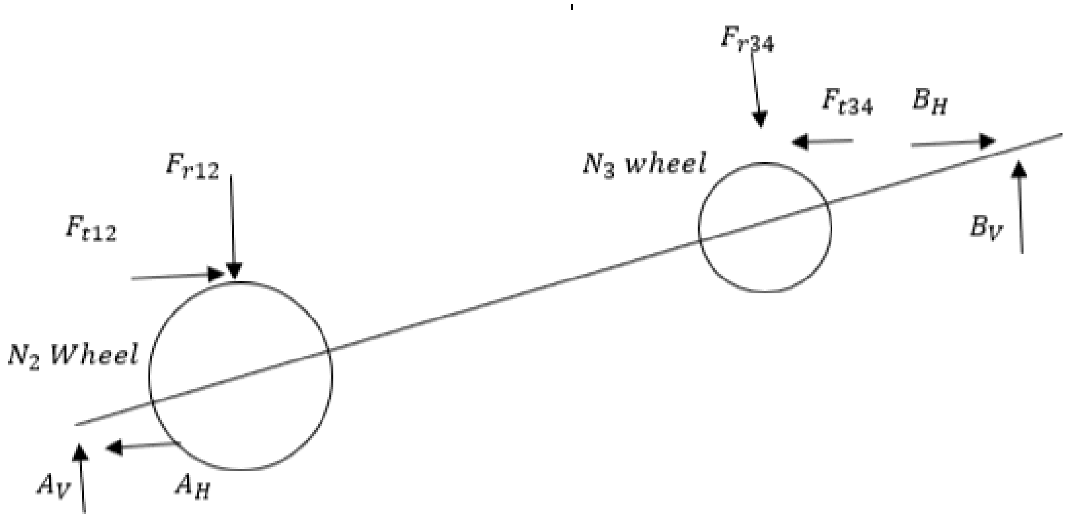

Figure 1: Free Body Diagram (FBD) of countershaft

Tangential Forces acting on Countershaft wheels,

$$F_{t12} = \frac{T_{input}}{Pitch\ diameter/2} = \frac{10.23}{\frac{72}{2}\times 10^{-3}} = 284.17\ N$$

$$F_{t34} = 542.58\ N$$

Radial Forces acting on the countershaft wheel,

$F_{r12} = F_{t12} \times tan\emptyset = 284.17 \times tan20° = 103.43\ N$

$F_{r34} = F_{t34} \times tan\emptyset = 542.58 \times tan20° = 197.48\ N$

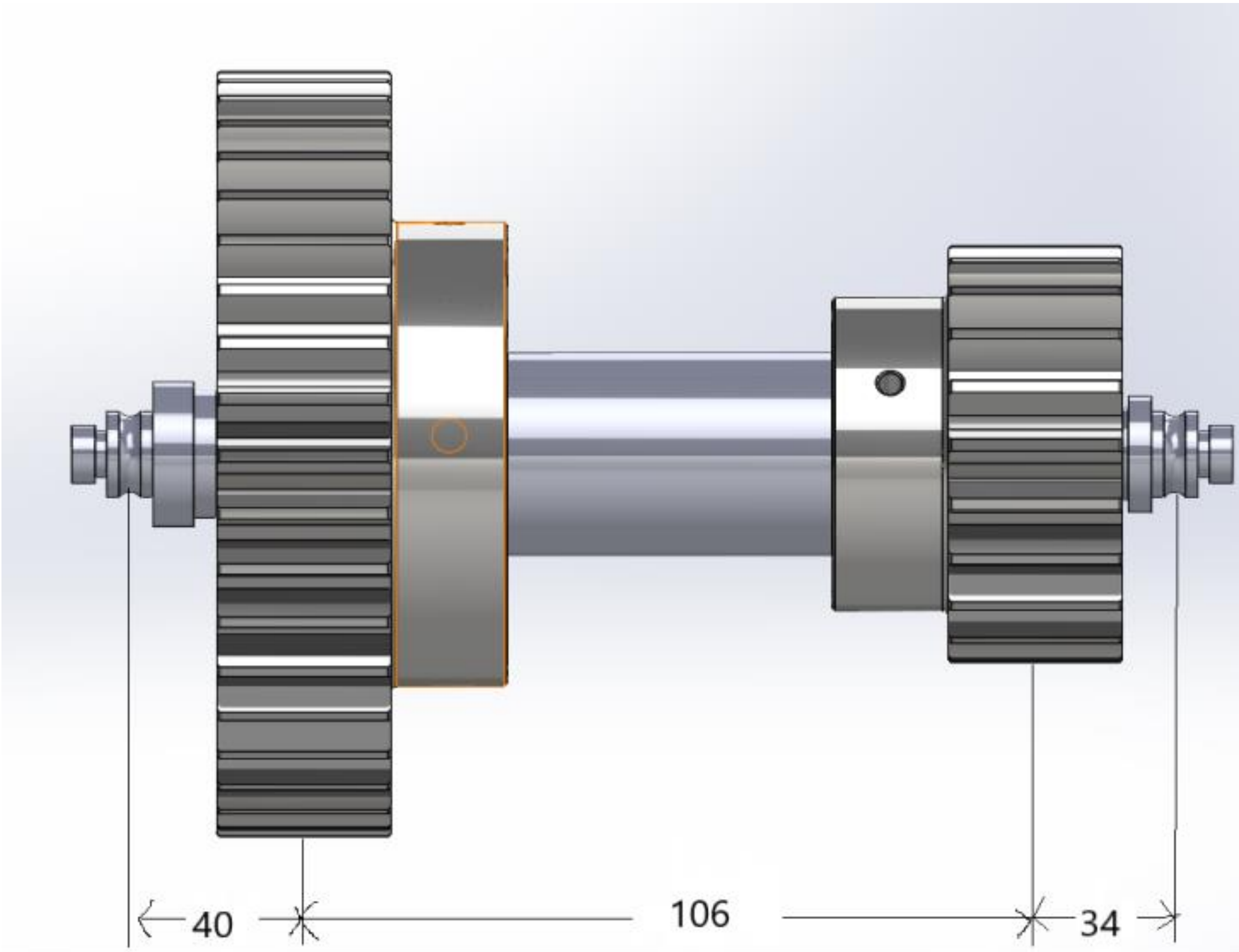

Figure 2: Countershaft with gears

Calculation of horizontal and vertical forces for Bearing A & Bearing B:

From the Moment Equilibrium formula, we get, $\Sigma M = 0$

$(-284.17 \times 40) + (542.58 \times 146) - (B_H \times 180) = 0$

$\therefore B_H = 376.94\ N$

From the force equilibrium condition, we get, $\Sigma F = 0$

$A_H - 284.17 + 542.58 - 376.94 = 0$

$\therefore A_H = 118.53\ N$

Similarly, by following the moment equilibrium formula,

$(-103.43 \times 40) + (-197.48 \times 146) - (B_v \times 180) = 0$

$\therefore B_V \ = 183.16\ N$

Similarly,

$A_V - \ 103.43 + \ 197.48 + 183.16 = 0$

$\therefore A_V = 117.75\ N$

The resultant radial forces acting on the Bearing,

$$A_r = \ \sqrt{A_H^2 + A_V^2} = 167.08\ N$$

$$B_r = \ \sqrt{B_H^2 + B_V^2} = 419.08\ N$$

Graphical Representation of Shear Force & Bending Moment Diagram

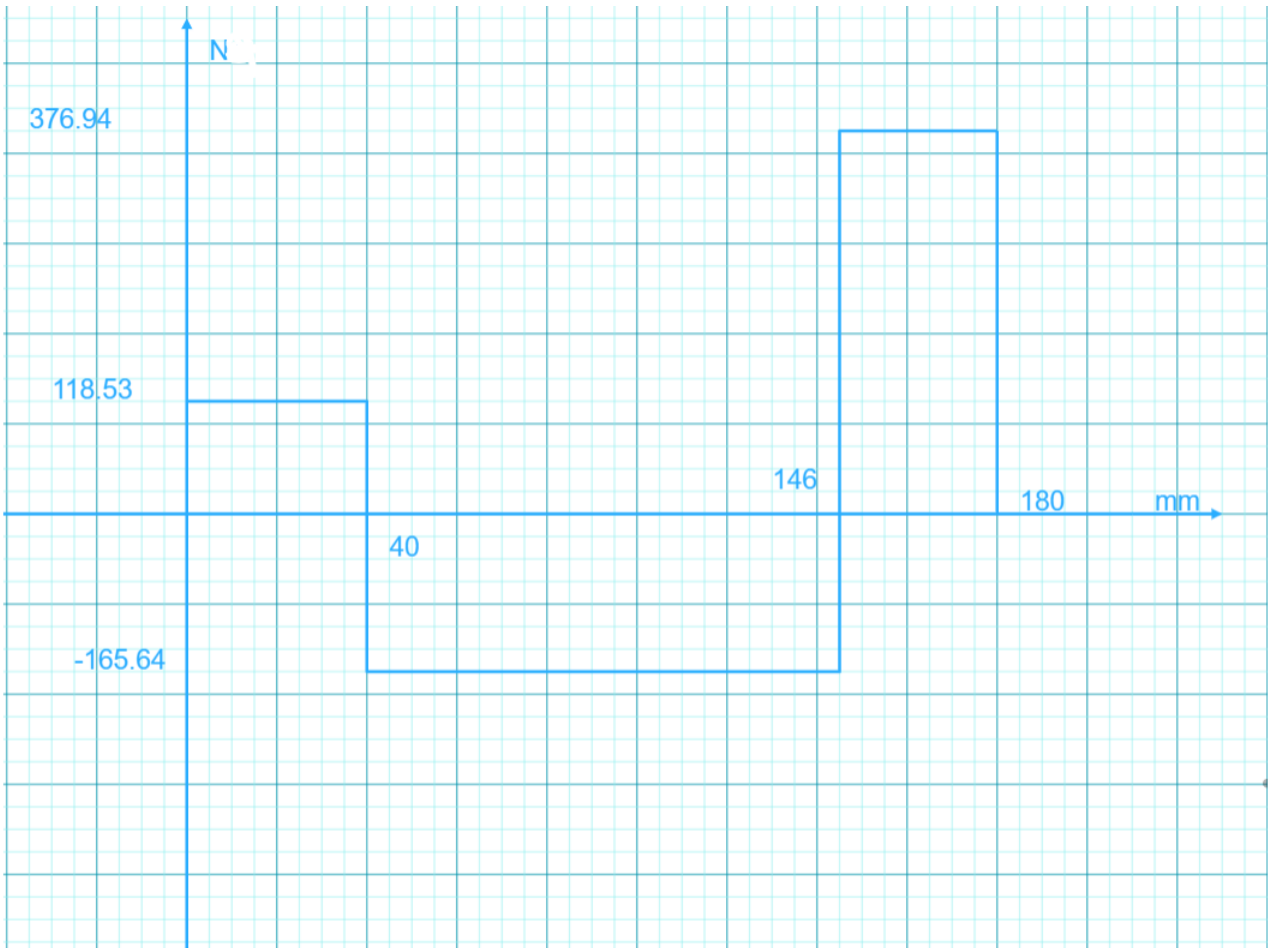

Figure 3: Shear Force Diagram for Horizontal Plane

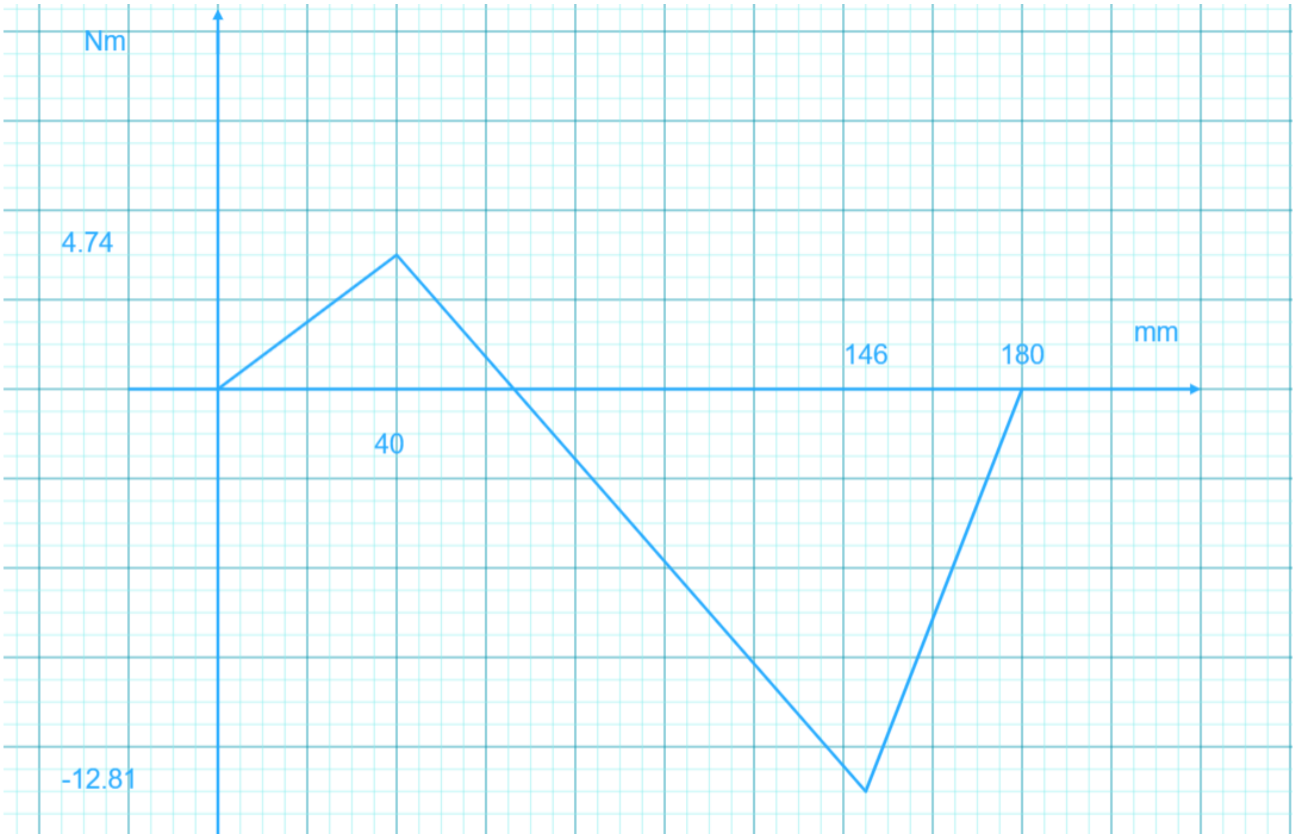

Figure 4: Bending Moment Diagram for Horizontal Plane

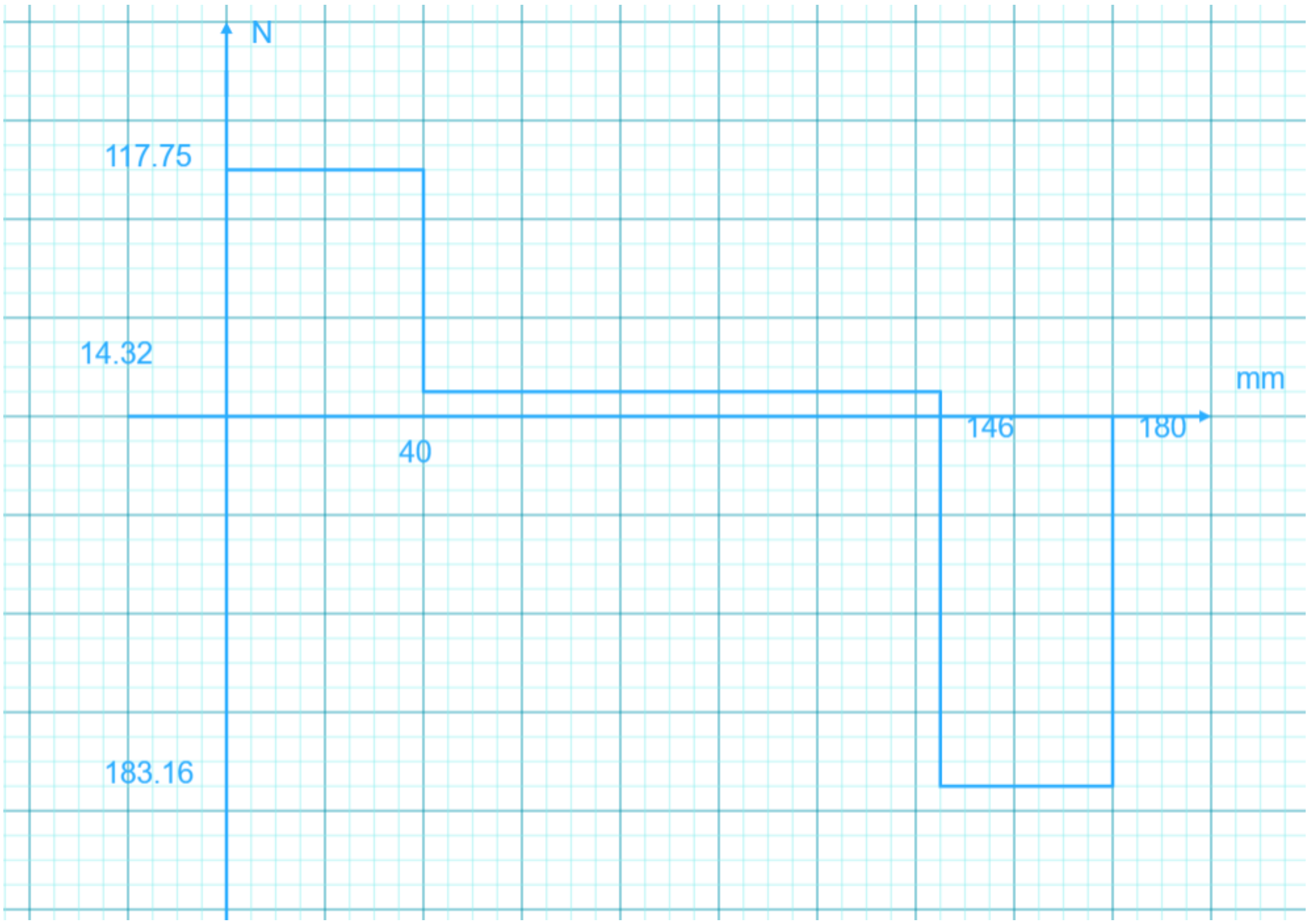

Figure 5: Shear Force Diagram for Vertical Plane

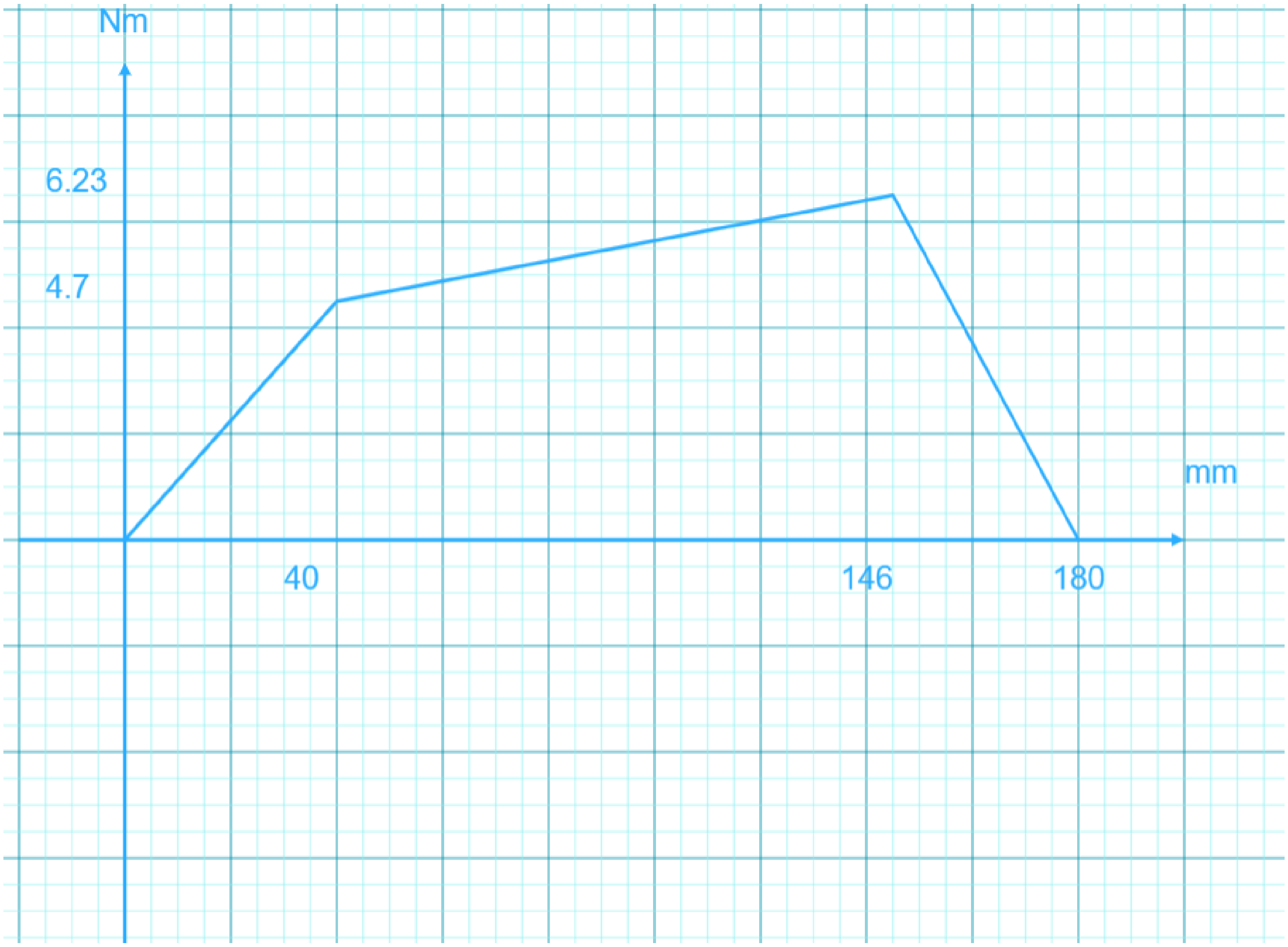

Figure 6: Bending Moment Diagram for vertical plane

Calculation for Bearing Selection

The resultant radial forces for Bearing A, $F_{eA} = 167.08\ N$ & for Bearing B, $F_{eB} = 419.08\ N$

We know,

$$C = F_e K_a \left(\frac{L}{K_r L_r}\right)^{0.3}$$

Here, light & moderate impact is assumed. So, application factors, $K_a = 1.5$

As reliability rate is 96%, reliability factor, $K_r = 0.53$

Rotation of countershaft = $\frac{N_1}{N_2} \times input\ Speed = \frac{24}{42} \times 1960 = 1120\ rpm$

$L = 7.5 \times 6 \times 52 \times 10 \times (1120 \times 60) = 1.57 \times 10^9 rev$

$L_R = 90 \times 10^6\ rev$

For Bearing B,

$C = F_e K_a \left(\frac{L}{K_r L_r}\right)^{0.3} = 419.08 \times 1.5 \times \left(\frac{1.57\times10^9}{0.53\times90\times10^6}\right)^{0.3} = 1.793\ KW$

For Bearing A,

C = 0.715 KW

From Table,

10 mm bore bearing is selected for Bearing A & Bearing B & Bearing Basic Number is L00 and width is 8 mm.

Calculation for Shaft Material Selection:

EN8 Carbon steel is selected for shaft material.

Ultimate yield strength (S_y) is 700 MPa & tensile strength (S_n) is 350 MPa.

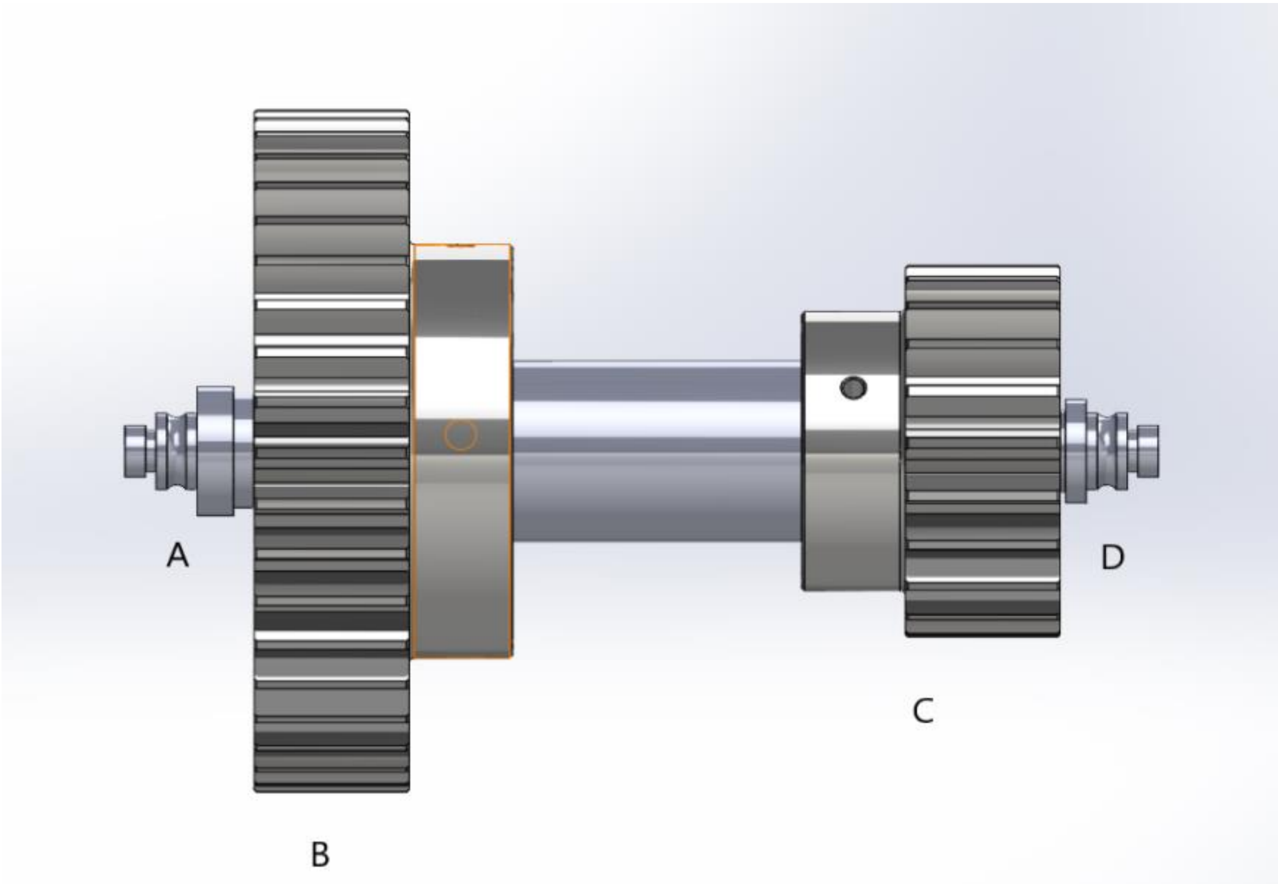

Figure 7: Countershaft with critical points

For Point A,

$K_t = 1.5$ (well-rounded fillet)

Factor of Safety, FOS = 2, V = 117.75 N

$$D_{min} = \sqrt{2.94 \times K_t \times V \times \frac{FOS}{S_n}}$$

$$= \sqrt{2.94 \times 1.5 \times 117.5 \times \frac{2}{350}}$$

$$= 1.72\, mm$$

For point B,

FOS = 2, $T_b = 17.904\, Nm$, M = 6.23 Nm

$$D_{min} = \left[\frac{32FOS}{\pi} \times \sqrt{\left(K_t \times \frac{M}{S_n}\right)^2 + \frac{3}{4} \times \left(\frac{T_b}{S_y}\right)^2}\right]^{\frac{1}{3}}$$

$$= \left[\frac{32 \times 2}{\pi} \times \sqrt{\left(1.5 \times \frac{6.23}{350}\right)^2 + \frac{3}{4} \times \left(\frac{17.904}{700}\right)^2}\right]^{\frac{1}{3}}$$

$$= 9\ mm$$

For point C,

FOS = 2, $T_b = 17.904\ Nm$, M = 6.23 Nm

$$D_{min} = \left[\frac{32FOS}{\pi} \times \sqrt{\left(K_t \times \frac{M}{S_n}\right)^2 + \frac{3}{4} \times \left(\frac{T_b}{S_y}\right)^2}\right]^{\frac{1}{3}}$$

$$= 10.18\ mm$$

For point D,

FOS = 2, V = 183.16 N

$$D_{min} = \sqrt{2.94 \times K_t \times V \times \frac{FOS}{S_n}}$$

$$= 2.14\ mm$$

Calculation of keys for gears

S45C is selected as a material for the key, the yield strength is 410 MPa and the key shape will be rectangular.

For Gear 2,

$$L_{min} = \frac{4 \times T_b \times FOS}{D \times W \times S_y}$$

$$= \frac{4\times17.904\times2}{25\times8\times410}$$

$$= 1.75\ mm$$

The same length will work for gear 2 also.

The Calculation for Gear & Bearing fitting

For point B gear,

ISO- H7/K6 [Fit's symbol]

D = 25 mm

Hole dimension calculation:

The hole dimension is 25H7 and it's 0.021 mm.

$\Delta D = \Delta d = 0.021\ mm$

D_{max} = 25 + 0.021 = 25.021 mm

$D_{min} = 25\ mm$

The shaft dimension: The shaft dimension is 25K6.

$\delta_F =$ Fundamental deviation = +0.002 mm

$d_{min} = d + \delta_F$ = 25+ 0.002 = 25.002 mm

$d_{max} = d + \delta_F + \Delta d$ = 25 + 0.002+ 0.021 = 25.023 mm

Same will go for point C.

For Bearing at point A,

Fit's symbol is H7/s6

The hole designation is 10H7.

Here,

$\Delta D = \Delta d = 0.015\ mm$

D_{max} = 10 + 0.015 = 10.015 mm

$D_{min} = 10\ mm$

Shaft Dimension: The shaft designation is 10s6.

$\delta_F =$ Fundamental deviation = +0.023 mm

$d_{min} = d + \delta_F$ = 10 + 0.023 = 10.023 mm

$d_{max} = d + \delta_F + \Delta d$ = 10 + 0.023 + 0.015 = 10.038 mm

Same value will go for Bearing B.

Literature Review on Shaft

The shaft plays an important role in transmitting power between the components of the gearbox. It's important to understand the importance of the selection of shaft material, hub connection, and reasons for shaft failure to enhance the performance & sustainability of the gearbox. In this section, detailed observation of the selection of shaft material, hub connection, root cause analysis, and reasons behind the shaft failure have been discussed according to the peer-reviewed articles.

According to the research of Schulze (2016), the shaft and hub connection is a crucial element in distributing uniform loads, protecting the gearbox from wearing and tearing, and ensuring sustainability of the gearbox. It's an important element during gearbox design because faulty connections can lead to shaft deflection, uneven load balance, tearing and wearing inside the gearbox, increased system loss and diminished efficiency, and even may lead to gearbox failure. That's why optimized connections can make the gearbox more efficient, reduce energy losses, diminish tearing and wearing and enhance the durability of the machine.

En8 carbon steel is a medium-grade carbon steel. It is selected as a material for the shaft because it's known as a good material for well-balanced Hardness, Tensile Strength & Fatigue resistance. Moreover, it performs better when the gearbox is heated for prolonged operation. EN8 material can meet the target requirement as it has a good durability record of performance and enhances the efficiency of the gearbox (Singh et al. 2023).

According to the findings of Shi et al. (2024), Shaft failure happens due to different factors such as overloading, corrosion, occasional maintenance & sudden fatigue. Fatigue failure occurs due to regular cyclic loading for a long, creates a fracture in a specific point, leading to a crack on the surface, and even may create a hole inside the shaft, reducing efficiency. Corrosion is another big reason for the failures of a shaft. It accelerates fatigue and creates a surface rough, gradually filled with pitting on the surface which leads to the shaft failure. It happens for the moisture environment of the weather and sometimes for the chemical reaction. It reduces 40% the lifetime of a shaft compared to an uncorroded shaft. Stress concentration plays a secondary role in shaft failure. When the shaft begins to fracture and corrode the surface, stress concentration accelerates the corroded surface into shaft failure. Moreover, uneven distribution of loads & stresses, shaft deflection & misalignment of bearings & gears can lead to premature failure and increase losses and reduce efficiency.

In short, the selection of shaft material, the connections of shaft and hub & root cause analysis for shaft failure are crucial discussions to have a better understanding to improve the durability & performance of a shaft.

Conclusion

This study emphasizes on the gearbox design, analysis, the importance of material selection of gears, bearings & shaft, different types of gear and applications, challenges for misalignment bearings & shafts, reasons behind gearbox failure & significance of FEA software during the design process. This report not only offers the mathematical calculation of gearbox design but also examine through FEA software to validate that the design is accurate. Moreover, it focuses on the protection of environment from the initial stage to disposal. Mainly, it focuses on designing the gearbox by considering other factors.

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