ENPH 353 Final Report

2025 Clue Detective Competition

08/12/2025

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2025-2026

ENPH 353

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I - Shaft 2 Calculations

Net driving force on the timing belt pulley is given by:

$$F_N = \frac{T_C}{\frac{D_C}{2}} = 0.521 \text{ lbf} \tag{2.1.1}$$

Bending force on C is given by:

$$F_C = 1.5 F_N = 0.866 \text{ lbf} \tag{2.1.2}$$

Since z components of timing belt cancles out, we only consider x component of F_C.

$$F_{Cx} = F_C \cos(\varphi) = 0.819 \text{ lbf} \tag{2.1.3}$$

Where φ is the angle between the belt and horizontal plane, calculated in above section.

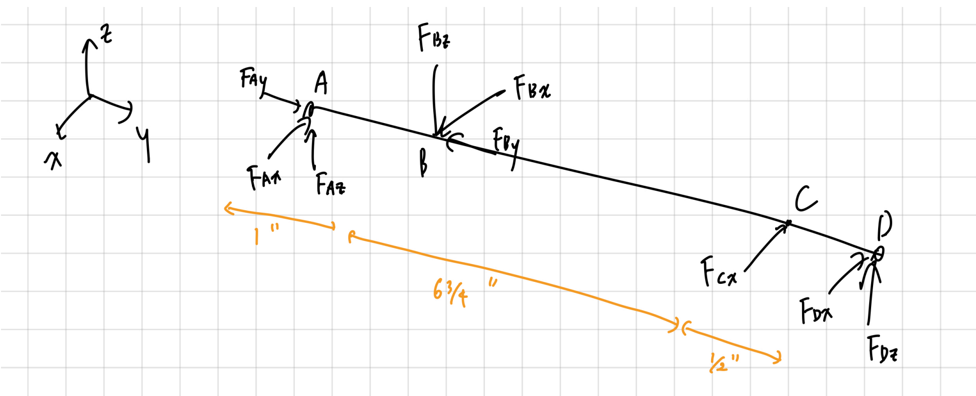

Figure 1 — FBD of shaft 2

Point A and D are the bushings, B is the worm gear, and C is the pulley for the timing belt.

Known forces from above calculations are:

$$F_{Bx} = 3.28 \text{ lbf} \qquad F_{Cx} = 0.819 \text{ lbf}$$
$$F_{By} = 2.67 \text{ lbf}$$
$$F_{Bz} = 12.5 \text{ lbf}$$

Forces on A and D are calcualated as follows:

$\Sigma F_x = 0:$

$$
\begin{aligned}
-F_{Ax} + F_{Bx} - F_{Cx} - F_{Dx} &= 0 \\
F_{Ax} + F_{Dx} &= F_{Bx} - F_{Cx} \\
F_{Ax} &= F_{Bx} - F_{Cx} - F_{Dx} \qquad (2.1.4)
\end{aligned}
$$

$\Sigma F_y = 0:$

$$
\begin{aligned}
F_{Ay} - F_{By} &= 0 \\
F_{Ay} &= F_{By} \qquad (2.1.5)
\end{aligned}
$$

$\Sigma F_z = 0:$

$$
\begin{aligned}
F_{Az} - F_{Bz} + F_{Dz} &= 0 \\
F_{Az} + F_{Dz} &= F_{Bz} \\
F_{Az} &= F_{Bz} - F_{Dz} \qquad (2.1.6)
\end{aligned}
$$

$\Sigma M_{Ax} = 0:$

$$
\begin{aligned}
-L_{AB}F_{Bz} + L_{AD}F_{Dz} &= 0 \\
F_{Dz} &= \frac{L_{AB}}{L_{AD}}F_{Bz} \qquad (2.1.7)
\end{aligned}
$$

$\Sigma M_{Az} = 0:$

$$
\begin{aligned}
-L_{AB}F_{Bx} + L_{AC}F_{Cx} + L_{AD}F_{Dx} &= 0 \\
F_{Dx} &= \frac{L_{AB}F_{Bx} - L_{AC}F_{Cx}}{L_{AD}} \qquad (2.1.8)
\end{aligned}
$$

Using the known forces, we get following forces on A and D:

$$
\begin{aligned}
F_{Ax} &= 3.01 \text{ lbf} & F_{Dx} &= -0.553 \text{ lbf} \\
F_{Ay} &= 2.67 \text{ lbf} & F_{Dy} &= 0.00 \text{ lbf} \\
F_{Az} &= 11.7 \text{ lbf} & F_{Dz} &= 0.812 \text{ lbf}
\end{aligned}
$$

Table 1 — Shear Forces

	$V_{\text{horizontal}}$ (lbf)	V_{vertical} (lbf)
A	−3.01	11.7
B	0.267	−0.812
C	−0.553	−0.812
D	0.00	0.00

Table 2 — Bending Moments

	$M_{\text{horizontal}}$ (lbf·in)	M_{vertical} (lbf·in)	M_{total} (lbf·in)
A	0.00	0.00	0.00
B	−3.01	11.7	12.1
C	−1.23	0.406	1.30
D	0.00	0.00	0.00

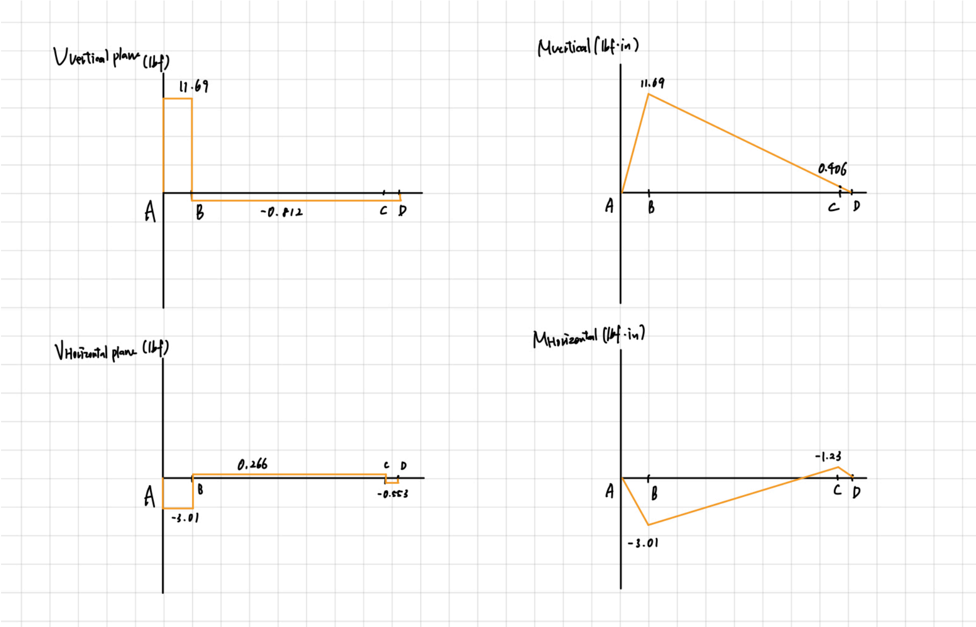

Figure 2 — Shear and bending moment diagram

Table 3 — Torque

	T (lbf·in)
A	0.00
B	0.521
C	−0.521
D	0.00

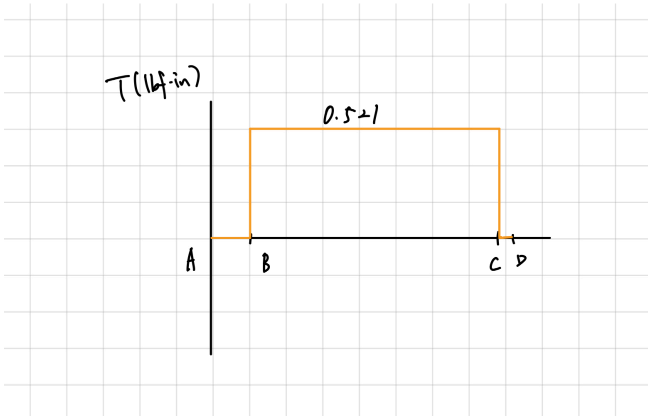

Figure 3 — Torque diagram of 2nd shaft

Table 4 — Summary of Moments and Torques

	M_{total} (lbf·in)	T (lbf·in)
A	0.00	0.00
B	12.1	0.521
C	1.30	−0.521
D	0.00	0.00

The constraint we have is the diameter sizes for the worm gear and the pulley. The mateiral is suitable for the shaft if the minimum diameter calculation at each location is below the allowable diameter determined by those components' bore diameter.

From Mott eqn 12-24,

$$D_{\min} = \left[\frac{32N}{\pi} \sqrt{\left(k_t \frac{M}{S_{n'}}\right)^2 + \left(\frac{3}{4}\right)\left(\frac{T}{S_y}\right)^2} \right]^{\frac{1}{3}} \tag{2.1.9}$$

For the material choice, we want to use an affordable, and easy to machine. Therefore, we will use Aluminum for the shaft material.
From Appendix B II, we choose Aluminum 2014 O for its high ductility, decent strength, and cheap cost of about $1 per inch.

Table 5 — Material Properties of Aluminum 2014 O

S_u	27 ksi
S_y	14 ksi
S_n	13 ksi

$S_{n'} = 10.608$ ksi The modified endurance strength is same as Shaft 1 calculations.
$K_t = 2.5$ as sharp fillet is used for the shaft shoulders.
$N = 2.0$ is chosen for our design factor since aluminum is a ductile material and the design factor is in the range of $1.5 < N < 2.5$.

Substituting the values into the minimum diameter based on moment and torque, we get:

$$D_{\min,i} = \left[\frac{64}{\pi} \sqrt{\left(2.5 \frac{M_{\text{total},i}}{10608}\right)^2 + \left(\frac{3}{4}\right)\left(\frac{T_i}{14000}\right)^2} \right]^{\frac{1}{3}} \text{ for } i = A, B, C, D \tag{2.1.10}$$

Minimum diameter based on shear:

$$D_{\text{min shear}} = \sqrt{\frac{2.95 K_t V_i N}{s'_n}} \text{ for } i = A, B, C, D \tag{2.1.11}$$

Using eqn (6.4.25), (6.4.26) and table 2,3, we calculate the minimum shaft diameter at each location:

Table 6 — Minimum and Allowable Shaft Diameters

	$D_{\min}$ (in)	$D_{\text{min shear}}$ (in)	$D_{\text{Allowable}}$ (in)
D_A	0.00	0.130	0.186
D_B	0.362	0.0345	0.75
D_C	0.172	0.0370	0.25
D_D	0.00	0.00	0.186

The minimum shaft diameter at each location is well below the allowable shaft diameter determined by the components. Thus, Aluminum 2014 O is a suitable material for the 2nd shaft.