

A11: Motor Section Design

Motor Selection and attachments

Speed Range 1-50 mm/min

max Torque (From A10) 5.408 N-m

DC vs. stepper vs. gear motor

Stepper with gears

reason: precision, torque, control

omc-stepperonline.com

holding torque w/o gearbox only goes up to 4.5 Nm
we need 5.408 N-m so determine desired gear ratio

$$\text{Gear ratio} = \frac{N_F}{N_D} = \frac{T_{out}}{T_{in}} = \frac{\omega_{in}}{\omega_{out}}$$

$$T_{in} \leq 4.5 \quad T_{out} \geq 5.408$$

$$\frac{5.408}{4.5} = 1.2 \quad \text{higher} = \text{better}$$

$$\frac{6}{4} = 1.5$$

min gear ratio
1.2

From site minimum gear ratio sold
for geared stepper = 3 ✓

$$3 = \frac{T_{out}}{T_{in}} \quad T_{in} = \frac{T_{out}}{3} = \frac{5.408}{3} = 1.803 \text{ min holding torque}$$

rpm	1 mm/rev	0.0318 rpm
	50 mm/rev	1.592 rpm

$$3 = \frac{w_{in}}{w_{out}} \quad w_{in} = 3 w_{out} = 0.0954 \text{ rpm} \\ 4.776 \text{ rpm}$$

Nema 23 Stepper motor L=55 mm
Gear ratio 15:1 High Precision Planetary Gearbox

holding torque w/o gearbox = 1.03 N.m

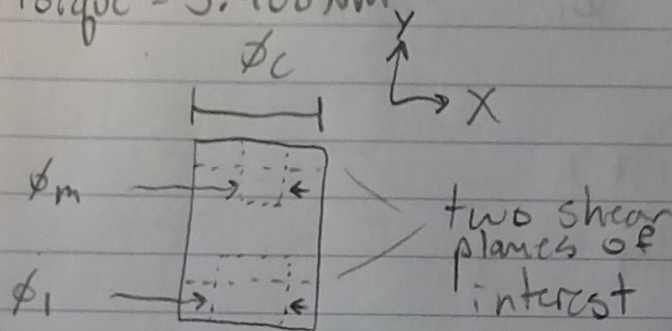
Gear ratio 15:1 Torque out = 15.45 N.m ✓

Design/Select coupler

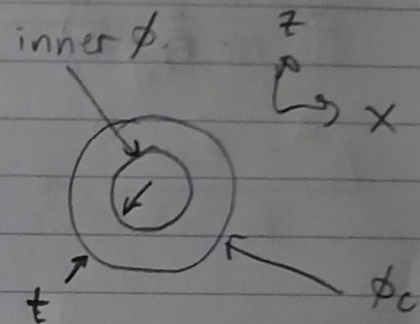
known
SF=4

$\frac{1 \text{ in}}{25.4 \text{ mm}}$

- motor shaft = 14mm $\approx 0.55''$
- lead screw = $\frac{5}{8}'' \approx 15.875 \text{ mm}$
- Torque = 5.408 Nm



unknown
shear stress
coupler outer
diameter ϕ_c



$$\tau = \frac{T r}{J}$$

$$J = \frac{\pi d^4}{32}$$

$$\tau = \frac{T \frac{\phi_c}{2}}{\frac{\pi (\phi_c^4 - \phi_{inner}^4)}{32}} = \frac{16 T \phi_c}{\pi (\phi_c^4 - \phi_{inner}^4)}$$

Assumption

medium alloy

Material is steel with $\sigma_y \approx 250 \text{ MPa}$ (minimum)
and von-mises yield criterion. $\frac{\tau_y}{\sigma_y} \approx 0.577$

$$\tau_y = 0.577 \sigma_y \approx 0.577 (250 \text{ MPa}) \approx 144.25 \text{ MPa}$$

$$\frac{\tau_y}{SF} = \frac{16 T \phi_c}{\pi (\phi_c^4 - \phi_{inner}^4)}$$

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$$\frac{\tau_y}{SF} = \frac{16T\phi_c}{\pi(\phi_c^4 - \phi_{inner}^4)} = \frac{\tau_y}{SF}$$

$$\boxed{\frac{\phi_c}{\phi_c^4 - \phi_{inner}^4} = \frac{\pi \tau_y}{16T(SF)}}$$

$$\frac{\phi_c 16T(SF)}{\pi \tau_y} = \phi_c^4 - \phi_{inner}^4$$

$$\frac{\phi_c^4 - \phi_{inner}^4}{\phi_c} = \frac{16T(SF)}{\pi \tau_y}$$

$$\phi_c - \phi_{inner} = 2t$$

$$\phi_c = 2t + \phi_{inner}$$

$$\phi_c^4 = (2t + \phi_{inner})^4$$

$$\text{N/mm}^2$$

$$\left(\frac{1}{\text{mm}^3}\right) \frac{\phi_c}{\phi_c^4 - \phi_{inner}^4} \geq \frac{\pi (144.25 \text{ MPa})}{16(5,408 \text{ N-mm})(4)} \rightarrow \left(\frac{1}{\text{mm}^3}\right)$$

$$\phi_{inner} = 14 \text{ mm} \quad \phi_c \geq 0.0013 \frac{1}{\text{mm}^3}$$

$$= \phi_m \quad \phi_c^4 - (14 \text{ mm})^4$$

$$\text{try } \phi_c = 2 \phi_m = 28 \text{ mm}$$

$$\frac{28 \text{ mm}}{(28 \text{ mm})^4 - (14 \text{ mm})^4} = 0.000048 \quad \text{too small!}$$

$$T_{ry} \quad \phi_c = 3 \phi_m = 42 \text{ mm}$$

$$\frac{42 \text{ mm}}{(42 \text{ mm})^4 - (14 \text{ mm})^4} = 0.0000137$$

shouldn't get smaller, something is wrong!

$$\frac{T}{SF} = \frac{T r}{J} = \frac{T \phi_c}{2J} = \frac{T \phi_c}{2 \left(\frac{\pi (\phi)^4}{32} \right)}$$

$$\frac{T}{SF} = \frac{T \phi_c}{\frac{\pi (\phi)^4}{16}} = \frac{16 T \phi_c}{\pi (\phi)^4}$$

for solid $\phi = \phi_c$
for hollow $\phi^4 = \phi_c^4 - \phi_{inner}^4$

realization! mistake was my inequality sign was flipped

$$\frac{\phi_c}{\phi_c^4 - \phi_{inner}^4} < \frac{\pi T_{ry}}{16 T (SF)} = 0.0013 \text{ /mm}^3$$

for $\phi_{inner} = \phi_m = 14 \text{ mm}$

$$28 \text{ mm} \rightarrow 0.00048 \quad \checkmark$$

$$22 \text{ mm} \rightarrow 0.000112 \quad \checkmark$$

$$20 \text{ mm} \rightarrow 0.000164 \quad \checkmark$$

Anything over 14mm is sufficient

any thickness is sufficient !?

Analyze and Design a Frame

Affects of twist by motors to select bracket for vertical standoffs of the frame to the top of the frame.

Known

load: 2 kN

top beam 13 in

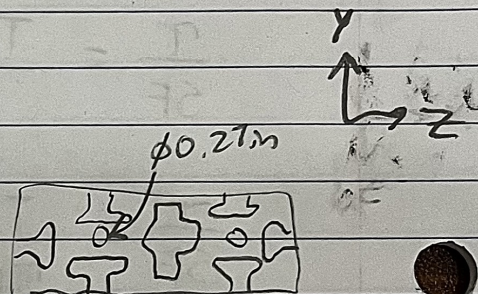
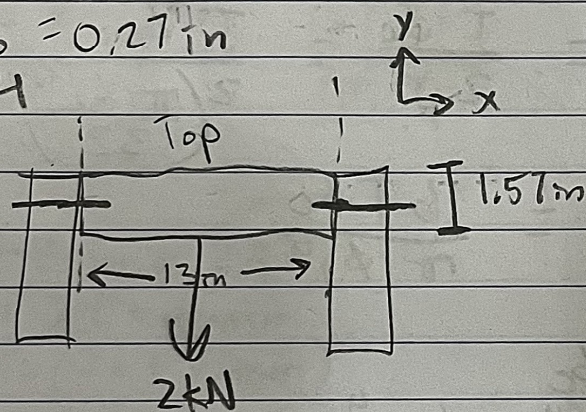
height = 1.57 in

diameters = 0.27 in

SF = 4

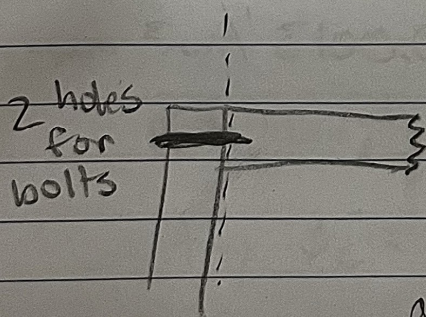
unknown

of bolts/screws



Assumption

2 kN point load @ center instead of 2 1 kN loads at lead screws - simplification



Assume

only 1 side will reach failure not both simultaneously

assume 3/8-24 Bolt

$$\text{shear area} = \sqrt{2} \left(\pi \frac{d^2}{4} \right)$$

Grade 2 - 3/8-24 - single shear shank = 4,904 lbf
 $\tau = 60,000 \text{ psi}$

$$\frac{\tau}{SF} = \frac{V}{A} = \frac{2,000N \left(\frac{1.16}{4.15N} \right)}{2 \left(\pi \left(\frac{0.375^2}{4} \right) \right)} = 60,000 \text{ psi}$$

$$2,034.64 \text{ psi} \leq 15,000 \text{ psi} \quad \checkmark$$

~~Two Grade 2 3/8-24 bolts
should be sufficient for
connecting the top beam to
the frame~~

New updated connectors use

M5 screws

assumption → M5 screws with
shear resistance per shear plane of
2.73kN for lowest grade bolt
(eurocodeapplied.com)

$$\frac{\tau}{SF} = \frac{V}{A} = \frac{2,000N}{2 \left(\pi \left(\frac{5\text{mm}^2}{4} \right) \right)} = 50.93 \text{ MPa}$$

$$\frac{\tau}{SF} = \frac{n F_v(SF)}{A} = \frac{(2)(2,730N)(4)}{\pi \left(\frac{5\text{mm}^2}{4} \right)} = 1112.3 \text{ MPa}$$

$$\frac{\tau}{SF} = \boxed{278.07 \text{ MPa} \geq 50.93 \text{ MPa}} \quad \checkmark$$

FEA

Top Frame Verification

mesh 1 - coarser than default

$$SF = \min 1.635 \rightarrow \text{connector rounds}$$

$$\sigma_{\max} = 29.48 \text{ MPa}$$

$$\delta_{\max} = 0.1141 \text{ mm}$$

mesh 2 - default mesh

$$SF = \min 1.532$$

$$\sigma_{\max} = 33.66 \text{ MPa}$$

$$\delta_{\max} = 0.1143 \text{ mm}$$

mesh 3 - finer than default

$$SF = \min 1.362$$

$$\sigma_{\max} = 36.80 \text{ MPa}$$

$$\delta_{\max} = 0.1156 \text{ mm}$$

← not ignoring stress concentrations
 $< \sigma_y = 145 \text{ MPa}$
 $\sim \delta_{\text{allow}} = 0.1 \text{ mm}$

Convergence:

$$SF: 2 \left(\frac{|1.362 - 1.635|}{(1.635 + 1.362)} \right) = 18.2\%$$

$$\sigma_{\max}: 2 \left(\frac{|36.80 - 29.48|}{(29.48 + 36.80)} \right) = 22.1\%$$

$$\delta_{\max}: 2 \left(\frac{|0.1156 - 0.1141|}{(0.1141 + 0.1156)} \right) = 1.3\%$$

δ converges

SF and $\sigma_{\max}$ diverge

↑
reason stress concentrations

Optimization $\rightarrow$ connector Fillet
radius $3x \rightarrow 4.5\text{mm}$

Optimization - default mesh

SF: min 2	improved $\checkmark$
$\sigma_{\max}$: 33.45 MPa	unchanged
$\delta_{\max}$: 0.1148 mm	unchanged