GRACO ROBOTICS, INC.

OFFICE MEMO

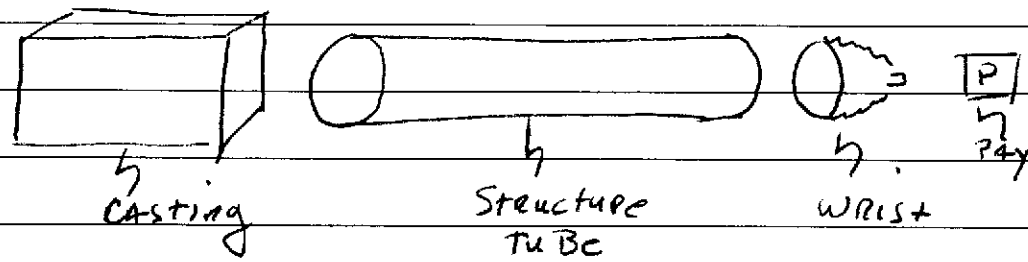
To _____ Date 6-28-90

From _____ Copies Page 1

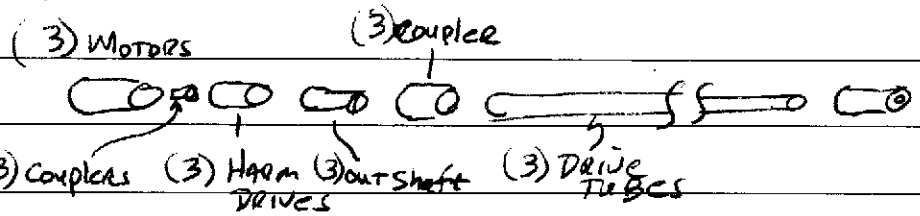
Subject Horiz Arm Calculations

Components - External

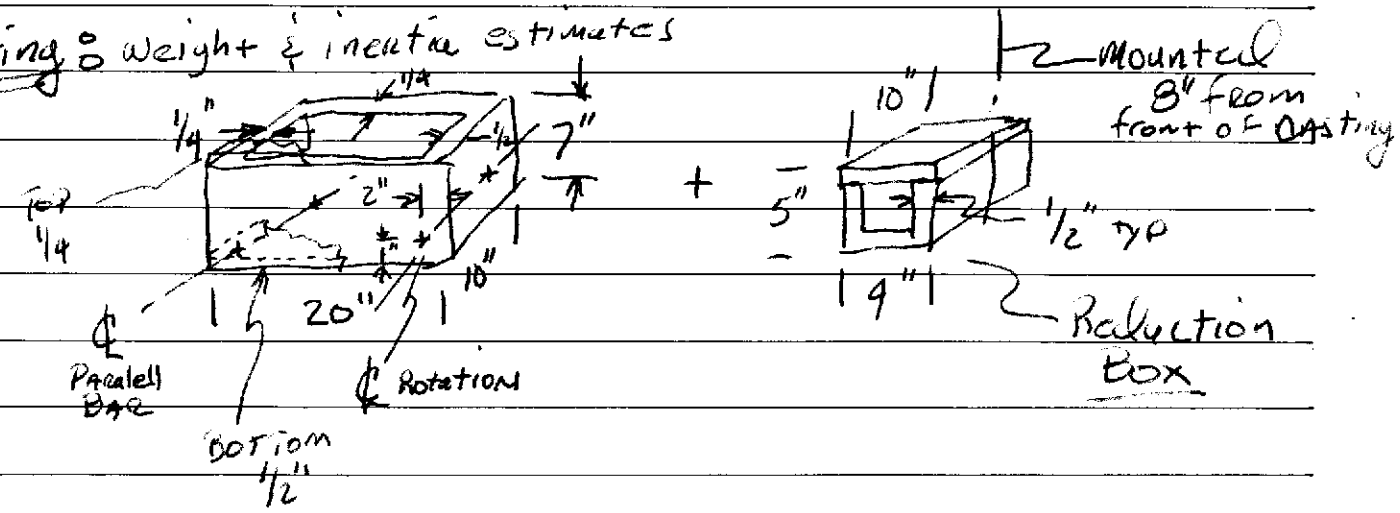
$\alpha_{ST} = .283\ lb/in^3$
$\alpha_{Al} = .099$



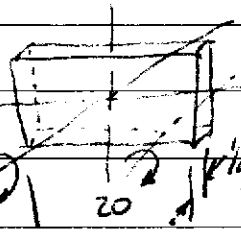
Components - Internal



Casting & weight & inertia estimates



(2) sides —



$J_{Rot} = \frac{m(20^2 + 7^2)}{12} =$

$J_{TRANS} = 8.38^2 \cdot m$

$R = 8.38$

$\pm 2\frac{1}{2}$

19"

$m = 7 \times 20 \cdot 0.25 \cdot 0.099\ lb/in^3 = 3.465\ lbf$

$J_{side} = m(8.29^2 + 37.42) = m \cdot 107.64\ in^2$ (2 forgot to ÷12)

$J_{side\ total} = 2(m \cdot 107.64) = m \cdot 43.29\ in^2$

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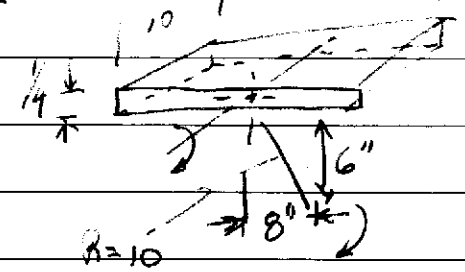
Subject Hose Item Calculations

Top



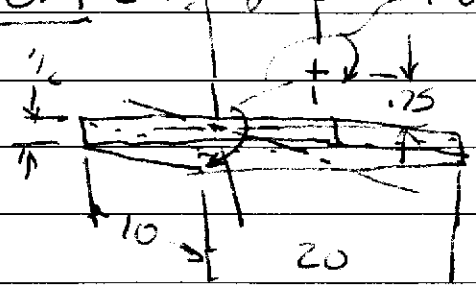
$W = 10 \times 20 \times .25 \times 0.099 = 4.95 lbf$

$J_{TRANS} = (10")^2 m = 100 m$

$J_{ROT} = \frac{m(.25^2 + 20^2)}{12}$

$\therefore J_{ROT} = m \cdot 33.34 in^2$ // $J_{TOT} = 133.34m$

Bottom



$J_{TRANS} = m \cdot 64.56 in^2$

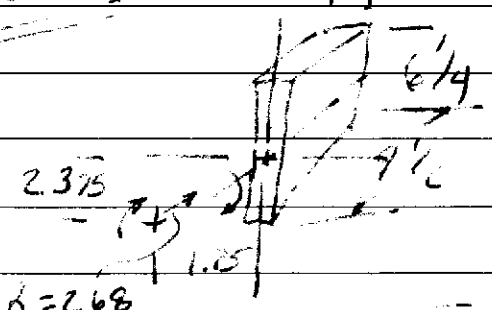
$J_{ROT} = \frac{m(.50^2 + 20^2)}{12}$

$\therefore J_{ROT} = m \cdot 33.354$

$J_{BOTTOM} = m \cdot (64.56 + 33.354)$

$\therefore J_{BOTTOM} = m \cdot 97.91 in^2$ [$W = 10 \cdot 20 \cdot 0.5 \cdot .099 = 9.9\#$]

Front



$W = 9.5 \cdot 6.25 \cdot 0.5 \cdot 0.099 = 2.94 lbf$

$J_{TRANS} = m \cdot (2.68in)^2 = m \cdot 7.18$

$J_{ROT} = \frac{m(.5^2 + 6.25^2)}{12}$

$J_{ROT} = m \cdot 3.28 in^2$

$J_{FRONT} = m(7.18 + 3.28) = m \cdot 10.46 in^2$

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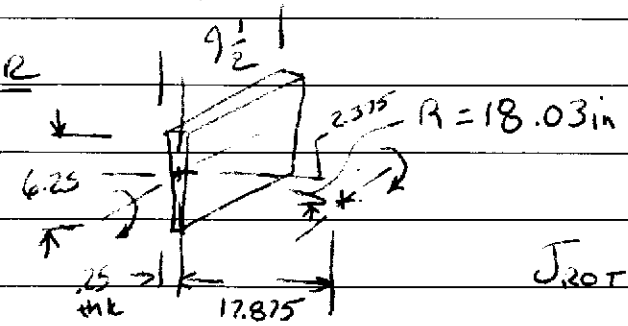
Subject Horiz Arm Calculations

Rear



$W = 6.25 \times 9.5 \times .25 \bullet 0.099$

$= 1.47\ lb =$

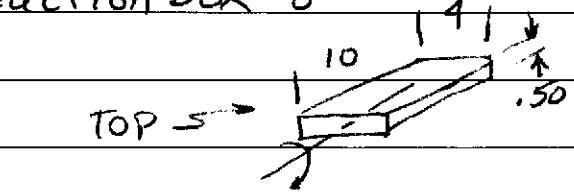
$J_{TRANS} = m(18.03)^2 = m \cdot 325.08\ in^2$

$J_{ROT} = m(.25^2 + 6.25^2)/12$

$= m \cdot 3.26\ in^2$

$J_{Rear} = m(325.08 + 3.26) = m \cdot 328.34\ in^2$

Reduction Box

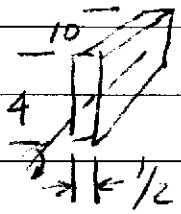


$W = 10 \cdot 4 \cdot .50 \cdot 0.099 = 1.98\#$

$J_{ROT} = m \cdot (.50^2 + 4^2)/12$

$= m \cdot 1.35\ in^2$

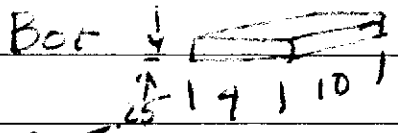
(2) sides



$W = 4 \cdot 10 \cdot .50 \cdot 0.099 = 1.98\#$

$J_{ROT} = m \cdot 1.35\ in^2$

Bot



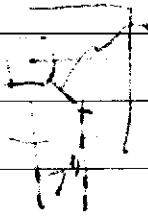
should be 0.50

$W = 1.98$

$J_{ROT} = m \cdot 1.35\ in^2$

$J_{ROT\ of\ Box} = 4(m \cdot 1.35\ in^2) = m \cdot 5.4$

$J_{TRANSLATION} = m \cdot r^2 = m \cdot 7.62^2 = m \cdot 58\ in^2$ Assumes Point Load.



$J_{BOX\ TOTAL} = m(5.4 + 58) = m \cdot 63.4\ in^2$

$W_{TOT} = 3\ W_{BOX} = 3 \cdot 1.98 = 7.92$

834 786

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Subject Horiz Arm Calculations

TOTAL Casting Inertia - (Less internal components)

$J_{TOTAL} = 2\,J_{Sides} + J_{TOP} + J_{BOT} + J_{Motor} + J_{Gear} + J_{Reducer}$

$= 2(3.465\,lb_f \cdot 107.64\,in^2) + (133.34\,in^2 \cdot 4.95\,lb_f) + (9.91\,lb_f \cdot 97.9\,in^2)$

$+ (2.941\,lb_f \cdot 10.46\,in^2) + (1.47\,lb_f \cdot 328.34) + (7.92\,lb_f \cdot 63.4\,in^2)$

$= 745.95\,lb_f in^2 + \overset{660.03}{\cancel{482.99}}\,lb_f in^2 + 969.21\,lb_f in^2$

$+ 30.75\,lb_f in^2 + 482.99 + 502.13$

$= 3,391.06\,lb_f in^2$

$(lb_f in^2)\left(\frac{ft^2}{144\,in^2}\right)\left(\frac{slug}{32.17\,lb_f}\right)\left(0.3731\,\frac{in\,lb\,sec^2}{lbs\,ft^2}\right)(32.7)$

$lb_f in^2 \times \frac{.3731}{144} = in\,lb\,sec^2$

Conversion factor $= 2.591 \times 10^{-3} \cdot lb_f in^2 = in\,lb\,sec^2$

$\therefore J_{TOTAL\ CASTING} = (3,391.06\,lb_f in^2)(2.591 \times 10^{-3}) = 8.786\,in\,lb\,sec^2$

$J_{TOTAL\ CASTING} = 8.786\,in\,lb\,sec^2$

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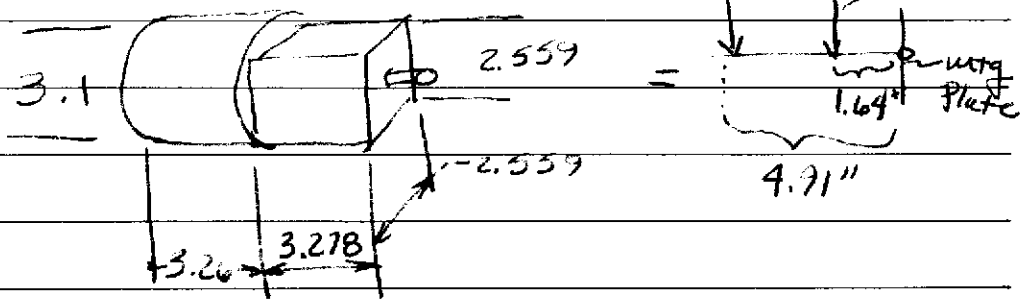
Subject Horizontal Arm Calculations

Casting - Internal Components.

(3) Motors

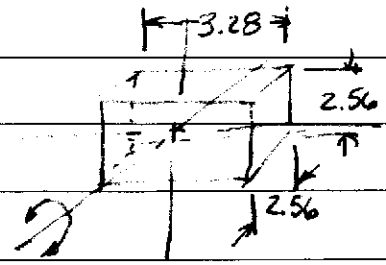


$W_{motor} = 3.3$ lbs

$W_{m+E} = 4.41$ lbs

$\therefore W_E = 1.11$ lbs

Motor



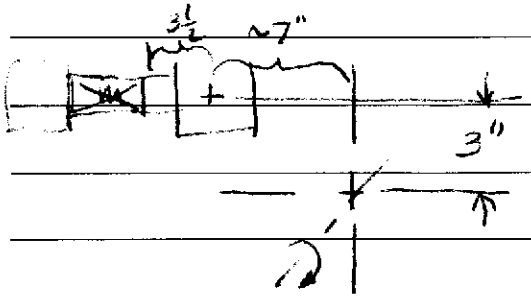
$W = 3.31$ #

$J_{Rot} = m(2.56^2 + 3.28^2)/12$

$= m \cdot 1.443\ in^2$

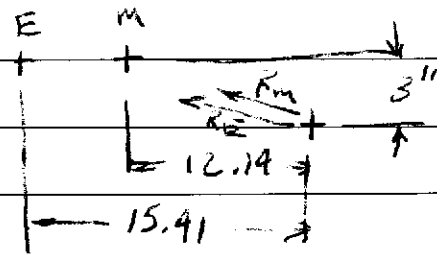
$J_{TRANS} = m \cdot (12.51\ in)^2$

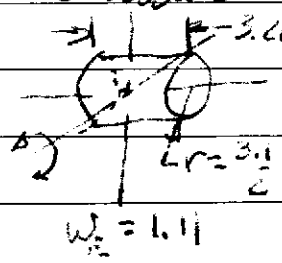
$= m \cdot 156.50\ in^2$



Encoder $J_{ROT} = \frac{m(3r^2 + \ell^2)}{12}$

$= \frac{m(3 + 1.55 + 10.63)}{12}$ (7.21)





$\therefore J_{ROT} = m \cdot 1.486\ in^2$

$J_{TRANS.} = m \cdot 237.47\ in^2$

$R_m = 12.51$

$R_E = 15.70$

$J_{M+E} = 3.31(1.443 + 156.5) + 1.11(1.486 + 237.47)$

$= 788.03\ in^2 lbs\ (2.041 \times 10^{-5})$

$= 2.042\ in\ lbs\ sec^2$

$J_{MOTORS\ \&\ ENCODERS} = 6.125\ in\ lbs\ sec^2$

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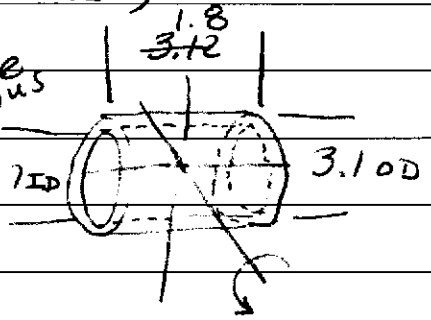
Subject Horizontal Item Calculations

Casting internal Components (cont'd)

Motor Mount Adapter



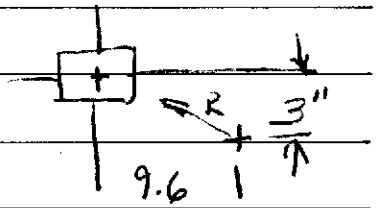
$W = 1.8 \times 0.099 \times \pi \times (3.1^2 - 2.7^2)$

$= 1.30\#$

$J_{ROT} = m\left(3\cdot\left(\frac{2.7}{2}\right)^2 + 3\left(\frac{3.1}{2}\right)^2 + (1.8)^2\right)/12.$

$= m(5.4675 + 7.2075 + 3.24)/12$

$m \cdot 1.326\ in^2$ $= m \cdot 0.3315$



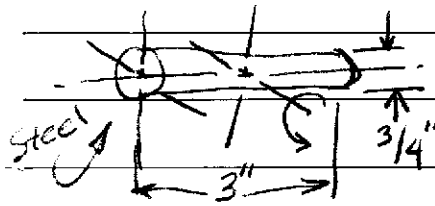
$J_{TRANS} = m(10.06)^2 = 101.16\ m\ in^2$ ~~25.29 M~~

$J_{MM\ Adapter} = (3)(101.16 + 1.326)(2.591 \times 10^{-3})$ $r = 10.06"$

$=$

$J_{MM\ Adapter} = 0.7966\ in\ lb\ sec^2$

Shaft Adapter to H.D. Wave Generator



$W = 3\cdot\left(\frac{.75}{2}\right)^2 \cdot \pi \cdot .099 = .283 = .04,375\ lb_f$

$J_{ROT} = m(3(.375)^2 + 9)/12 = .785\ m\ in^2$

$J_{TRANS} = m \cdot 116.95\ in^2$

$J_{TOTAL} = (3)(.375)(116.95)(2.591 \times 10^{-3}) = .341\ in\ lb\ sec^2$

$+ r = 10.8 + \frac{3}{4}$

10.91

$J_{Shaft\ Adapter\ TOTAL} = 0.341\ in\ lb\ sec^2$

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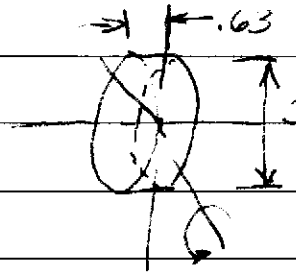
Subject Harmonic Drive Calculations

Casting Internal Components (cont'd.)

(3) Harmonic Drives - HD 5C - Bulk of weight is in the WAVE gen & Circular Spline - can approx geometry

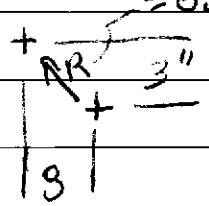


Weight = 1.2 lb

$J_{Rot} = \frac{mr^2}{4} = m\left(\frac{3.28}{2}\right)^2/4 = 1.2 \times .674$

$= (.807\ lb\text{-}in^2)(2.591 \times 10^{-3})$

$= 2.091 \times 10^{-3}$ in lb sec^2



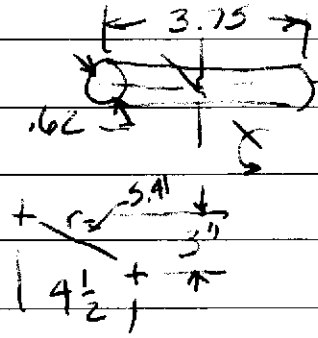
$J_{TRANS} = mr^2 = 1.2 \times (8.54^2) \times 2.591 \times 10^{-3}$

$= 0.227$ in lb sec^2

$J_{TOTAL|_{HD}} = (3)(2.091 \times 10^{-3} + 0.227)$

$= 0.687$ in lb sec^2

Harmonic Drive Output Shaft - 3



Weight = $\pi \cdot .283 \cdot 3.75 (.31)^2$

$= 0.320$ lbs

$J_{Rot} = m(3 \cdot (.31)^2 + 3.75^2)/12$

$= 0.320 \cdot (1.196)(2.591 \times 10^{-3})$

$= 9.915 \times 10^{-4}$ in lb sec^2

$J_{TRANS} = 0.320 \times 5.41^2 \times 2.591 \times 10^{-3} = 2.427 \times 10^{-2}$ in lbs^2

$J_{TOT\ OUT\ SHAFTS} = 2.52\text{?} \times 10^{-2}$ in lb sec^2

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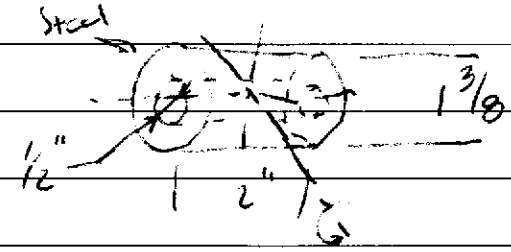
Subject Horiz Arm Calculations

Casting internal Components (cont'd.)

H.D. Output Shaft Coupler



$M = \pi \cdot .283 \cdot 2 \cdot \left(\left(\frac{1.375}{2}\right)^2 - (.25)^2\right)$

$= 0.729$ lbs

$J_{rot} = 0.729\left(3(.25^2) + 3(.6875^2) + 4\right)/12$

$= (.341)(2.591 \times 10^{-3}) = 8.823 \times 10^{-4}$ in lbs^2

$\pm$ 3"

$J_{trans} = 0.729 \cdot 9 \cdot 2.591 \times 10^{-3}$

$= 1.7 \times 10^{-2}$ in lb sec^2

$J_{coupler\ TOTAL} = 3 \cdot (1.7 \times 10^{-2} + 8.823 \times 10^{-4})$

$= 5.365 \times 10^{-2}$ in lb sec^2

TOTAL Casting internal Components.

$J_{internal} = J_{M+E} + J_{MMA} + J_{SA} + J_{HD} + J_{HDOS} + J_{coupler}$

$= 6.125 + 0.7966 + 0.341 + 0.687 + 2.526 \times 10^{-2} +$

$5.365 \times 10^{-2} = 8.029$ in lb sec^2

$J_{internal\ Components} = 8.029$ in lb sec^2

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Subject Horiz Arm Calculations

Total Casting & Internal Components Inertia

$$J_c = J_{cast} + J_{int.} = 8.786 + 8.029 \text{ in lb sec}^2$$

$$\boxed{J_c = 16.815 \text{ in lb. sec}^2}$$

Casting Moment Calculations

Sides	(2)(8")(3.465 lbs)	=	55.44 in lbs.
Top	(8)(9")(4.95 lbs)	=	39.6
Bottom	(8")(9.9 #'s)	=	79.2
Front	(-1.15")(2.94 #'s)	=	-5.145
Rear	(18.795")(1.47 #'s)	=	27.614
Rail Box	(7")(7.92 lbs)	=	55.44
Motor	(3)(12.14")(3.3 lbs)	=	120.186 in lbs.
Encoder	(3)(15.41")(+5.78 1.111 lbs)	=	51.315
Motor Mount Adapt.	(3)(9.6)(1.3 #'s)	=	37.44
Shaft Adapter	(3)(10.41)(.375 #'s)	=	11.71
Horiz Arm	(3)(8")(1.2 #)	=	28.8
H.D. Cut Shaft	(3)(9.3")(.52 #)	=	4.32
H.D. Cut Shaft Coupler	ϕ		

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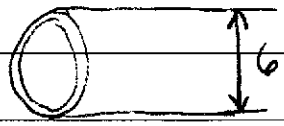
Subject Horiz Arm Calculations

Total Casting Moment = 505.92 in.lbs.

6061-T6

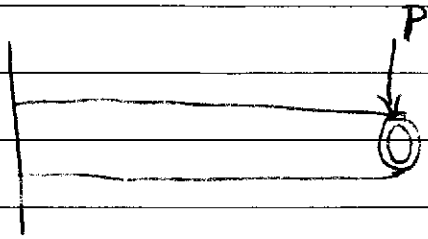


.125 wall - 2.713 #/ft

.188 wall - 3.996 #/ft

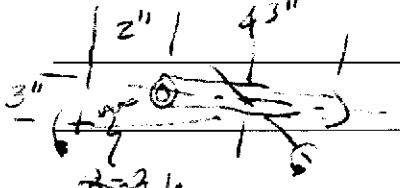
~~Et~~

Mod of Elast = 10×10^6 #/in²



estimate P at Plate + Twrist + Weight of Arm/2 + ½ weight of Drive Tubes

Drive Tubes 43" long - 1" od x .884 ID Steel



$W = 43 \times .283 \times \pi \left(.25^2 - \left(\frac{.884}{2}\right)^2\right)$

$= 2.09$ lbs.

$J_{BOT} = m\left(3(.5)^2 + 3(.442)^2 + 43^2\right)/12$

$= (322.27)(2.591 \times 10^{-3}) = 0.835$ in lb sec²

$J_{TUBES} = m r^2 = 2.09 \cdot 13 \cdot (2.591 \times 10^{-3}) =$

$= (2.09\#)(23.7)^2 = (49.51)(2.591 \times 10^{-3})$

$= .123$ in lb sec²

Total

$J_{Tubes} = 2.89$ in lb sec²

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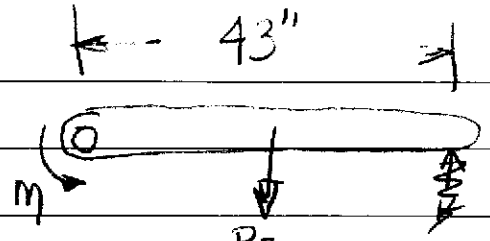
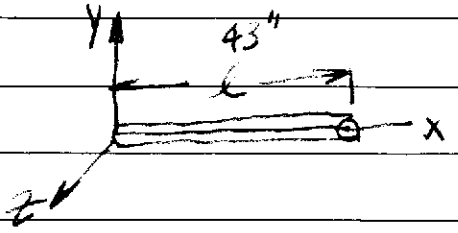
Subject Horiz Arm Calculations



STATIC moment
$= 2.09\# \cdot \frac{43"}{2}$
$M_s = 44.94\#$ in lbs.

slinder rod



$$I_y = \int x^2 dm = \int_0^L x^2 \frac{M}{L} dx = \left[\frac{M}{L}\frac{x^3}{3}\right]_0^L$$

$$= \frac{mL^2}{3} = \frac{m(43)^2}{3} = 2.09 \text{ lbs} \cdot 43^2/3$$

$$= \cancel{1406.67} \quad 1288.14 (2.591 \times 10^{-3})$$

$$= 3.337 \text{ in lb sec}^2$$

TOTAL ARM length from pivot to tool post = ~62"

WANT 6'/second in 0.350 seconds

6'/sec

$2\pi R = \pi D$ = circ of Axis path
$= \pi \cdot 10.3 \text{ ft} = 32.5 \text{ ft}$

@ 6 ft/sec Tip speed

$\omega = 6/32.5 \text{ (ft/sec)/(ft/rev)}$
$= 0.1848 \text{ rev/sec} \cdot 2\pi \text{ rad/rev}$
$= 1.1615 \text{ rad/sec}$

$\alpha = \frac{\omega}{t} = \frac{1.1615}{.350} = 3.319 \text{ rad/sec}^2$

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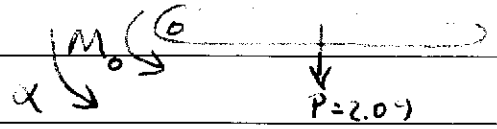


$\Sigma M = (-2.07)(\frac{43}{12}) + M_o = \bar{I}\alpha$

$\therefore M_o = \bar{I}\alpha + 44.935 \text{ in lbs}$

$= (3.337 \text{ in lbs sec}^2)(3.318 \text{ RAD/sec}^2) + 44.935 \text{ in lb}$

$\therefore M_o = 56 \text{ in lbs}$ TORQUE REQD TO ~~M0~~ ROTATE ONE DRIVE TUBE at REQ'D ACCEL.

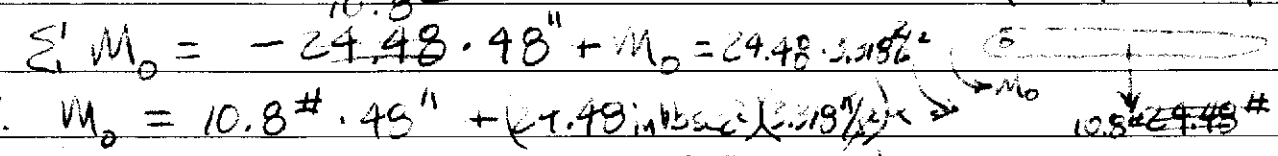
TOTAL FORCE at the end of tube to accel 3 drive tubes $= 3\,(56 \text{ in lbs}) = (168 \text{ in lbs} \div 43")$

$= 3.91 \text{ lbs}_f$

TOTAL FORCE FOR the STRUCTURE TUBE (ASSUMING SLENDER ROD) WEIGHT $4' \times 2.7\#/ft$

$= 10.8 \text{ lbs}$

$J = \frac{m\ell^2}{3} = \frac{10.8 \cdot (48)^2}{3} (2.951 \times 10^{-3}) = 24.48 \text{ in lbs sec}^2$



$\Sigma M_o = -24.48 \cdot 48" + M_o = 24.48 \cdot 3.318$

$\therefore M_o = 10.8\# \cdot 48" + (24.48 \text{ in lbs sec}^2)(3.318 \text{ RAD/sec}^2)$

$= 518.4 + 81.22 = 600 \text{ in lbs.}$

EQUIV FORCE @ END $= 600/48 = 12.5 \text{ lbs}$

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~~M r²~~ =

Payload & Wrist = 25#

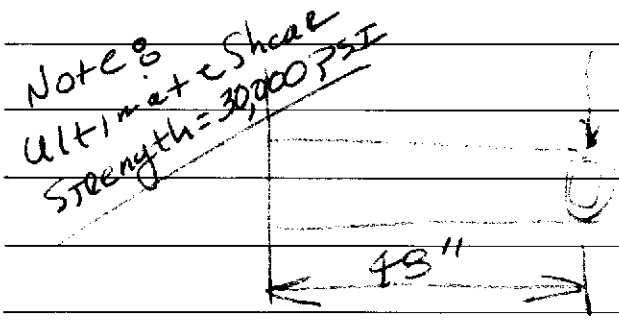
$\Sigma M = I\alpha = M - (25^{\#} \cdot 48'') = 25 \cdot (48)^2 \cdot 2.591 \times 10^{-3}$

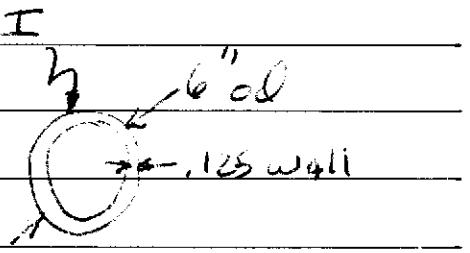
$\therefore M_o = 1200 + 149.24 = 1350$ in lb

$\therefore$ equiv force @ end = 1350/48 = 112.4 lbs

TOTAL forces in this model for deflection & STRESS estimates

$F = 3.91 + 12.5 + 112.4 = 128.41^{\#}$





for thin wall tubes $\tau = \frac{T}{2At} = \frac{128.41 \cdot 48''}{(2)\left(\frac{5.875}{2}\right)(0.125)}$ (T = Torque; $\frac{5.875}{2}$ = mean radius; 0.125 = thickness)

$= 8393.1$ PSI

$I_o = \pi R_{avg}^3 \cdot t$

$= \pi \left(\frac{5.875}{2}\right)^3 \cdot .125$

$= 9.954\ in^4$

deflection $= \frac{W\ell^3}{EI} = \frac{(128.41)(48^3)}{(10.0 \times 10^6)(9.958)}$

$= 0.1426$ inches

$I = \frac{\pi}{64}(D_o^4 - d_i^4)$

$= \frac{\pi}{64}(6^4 - 5.75^4) = 9.958\ in^4$

$\sigma = \frac{My}{I} = \frac{5827.68^{\#} \cdot in}{9.958\ in^4}$

$\sigma = 3511.4$ PSI

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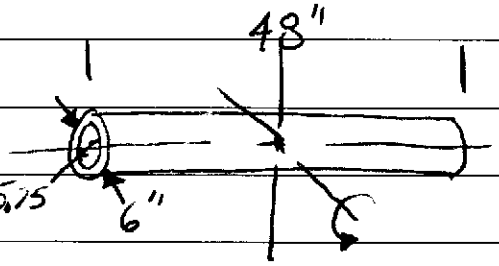
Subject Horizontal Arm Calc.

Total Horiz Arm

Loaded Casting ∴ T_c = 505.92 in lb sec²

J_c = 16.815 in lb sec²

Structure Tube ∴

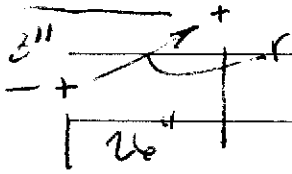


W = 10.8 lbf

$$J_{ROT} = \frac{m\left(3\left(\frac{5.75}{2}\right)^2 + 3(3^2) + 48^2\right)}{12}$$

$$J_{ROT} = \frac{10.8}{12}(2355.9)(2.591\times10^{-3}) = 5.49 \text{ in lb sec}^2$$

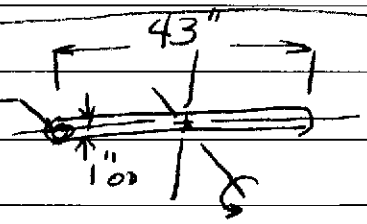
$$J_{TRANS} = 10.8 \cdot (26.2)^2 \cdot (2.591\times10^{-3}) = 19.17 \text{ in lb sec}^2$$



J_{ST} = 24.66 in lb. sec²

Torque = 10.8 · 26 = 280.8 in lb

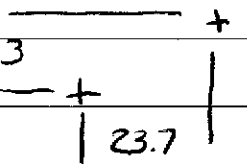
Drive Tubes ∴



J_{ROT} = 0.835 in lb sec²

J_{TRANS} = 0.1283 in lb sec²

$J_{DT.\,TOTAL}$ = (3)(.835 + .1283) = 2.890 in lb sec²



Torque = (23.7)(3)(2.09#) = 148.6 in lbs.

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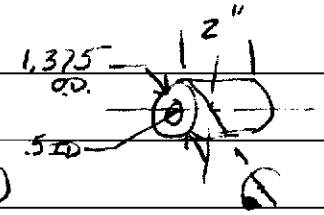
Subject Horiz Arm Calculations

Wrist Couplers @ (3)



$J_{ROT} = 8.823 \times 10^{-4}$ in lb sec^2

$J_{TRANS} = (0.729\#)(47^2)(2.591 \times 10^{-3})$

$= 4.172$ in lb sec^2

$J_{TOTAL} = (3)(8.823 \times 10^{-4} + 4.172) = 12.594$ in lb sec^2

$TORQUE = (3)(0.729\#)(47") = 102.8$ in lbs.

Wrist @ $w = 12\#$, $r = 54"$

$J = (12\#)(54in)^2(2.591 \times 10^{-3})$

$= 90.66$ in lb sec^2

$T = 12\# \cdot 54" = 648$ in lb.

Payload @ $w = 15\#$, $r = 66"$

$J = (15\#)(66)^2(2.591 \times 10^{-3})$

$= 169.3$ in lb sec^2

$T = 15 \cdot 66 = 990$ in lb

Horiz Arm Totals

Casting	$J = 16.815$	$T = 505.72$
Struct. Tube	$J = 24.66$	$T = 280.8$
Wrist Tube	$J = 2.840$	$T = 148.6$
Couplers	$J = 12.544$	$T = 102.8$
Wrist	$J = 90.66$	$T = 648$ in lb
Payload	$J = 169.3$ in lb sec^2	$T = 990$ in lb
TOTAL	$J_{TOT} = 316.81$ in lb sec^2	$T_{TOT} = 1664.28$ in lbs $= 138.69$ ft lbs.

834 786

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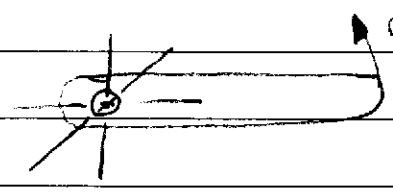
Subject Horiz Arm Calculations



6 ft/sec TIP Speed

$\omega = 0.1848^{REV}/_{sec} = 1.1613^{RAD}/_{sec}$

$J_{HOE\,ARM} = 316.87\ in\,lb\,sec^2$

$T_{STATIC} = 1664.28\ in.lb.$

Find GEAR Reduction BASED ON 6ft/second and an input of 3000 RPM

$\omega_{in} = 3000\left(\frac{REV}{min}\right)\left(\frac{min}{60sec}\right) = 50\ REV/sec$

$\omega_{out} = 0.1848\ REV/sec$

$N = \frac{50}{.1848} = 270.562706 : 1$

Use 2003.1 HARMONIC DRIVE

ϕ8 YASKAWA $T_{INST} = 65\ in\,lb$ $J_m = 2.53 \times 10^{-3}\ in\,lb\,sec^2$

$T_{cont} = 30\ in\,lb$

~~Accel~~ output TORQUE MAX = (200)(65 in lb) = 13,000 in lb.

Overestimated. using Peak TORQUE

using cont TORQUE outp. = (200)(.8)(30) =

USE 8M for ~~GEAR~~ INERTIA ($J_{gm} = 14.758\ lb\,in^2$)

~~$J_{8M} = 52.162\ lb\,in^2 = 0.1481\ in\,lb\,sec^2$~~

386.15 Reflected system inertia = $\frac{316.87}{(200)^2} = 7.922 \times 10^{-3}\ in\,lb\,sec^2$

$R_i = \frac{7.922 \times 10^{-3} + 0.1481}{2.53 \times 10^{-3}} = 61:1$

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Harmonic Drive Inertia

Size	J (inlbsec²)	Tmax
3C	1.502×10^{-4}	470@50:1
5C	4.274×10^{-4}	830@60:1
1M	1.580×10^{-3}	4000@100:1
2M	4.533×10^{-3}	6,600@100:1
4M	1.311×10^{-2}	15,500@100:1
8M	5.077×10^{-2}	24,000@100:1
15M	0.1334	50,000@100:1

Motor Inertia

Size	J (inlbsec²)
ϕ2	1.1×10^{-4}
ϕ3	4.5×10^{-4}
ϕ5	6.7×10^{-4}
ϕ8	2.53×10^{-3}
1.5	2.88×10^{-3}
3ϕ	5.09×10^{-3}

use 4M HD with 08 motor $T_{out} = 30 \cdot 200 \cdot .8 = 4800$

$$N_J = \frac{J_{mL}}{J_M} = \frac{2.53 \times 10^{-3}}{} = \frac{1.311 \times 10^{-2} + (316.81/(200^2))}{2.53 \times 10^{-3}}$$

$= 8.3$

use 4M with 15 motor $T_{out} = 55 \cdot 200 \cdot 0.8 = 8800$

$$N_J = \frac{J_L}{J_m} = \frac{2.103 \times 10^{-2}}{2.88 \times 10^{-3}} = 7.302$$

use 2M with 08 motor $T_{out} = 4800$

$$N_J = \frac{J_L}{J_m} = \frac{4.533 \times 10^{-3} + 7.922 \times 10^{-3}}{2.53 \times 10^{-3}} = 4.92$$