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PRELIMINARY DESIGN ANALYSIS FOR THE SOLAR OPTICAL TELESCOPE MAIN MIRROR ACTUATOR

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This study was performed under the auspices of the One Meter Solar Telescope Definition Team (Agreement S-64177A between NASA and National Science Foundation) for the Shuttle/Spacelab Payloads Project, NASA Goddard Space Flight Center.

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PRELIMINARY DESIGN ANALYSIS

FOR THE SOLAR OPTICAL TELESCOPE

MAIN MIRROR ACTUATOR

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DESIGN ANALYSIS

SOT MAIN MIRROR ACTUATOR

1.0 BACKGROUND

The resolution of the SOT Gregorian telescope is maintained if the conic foci of the elliptical secondary and parabolic primary are made to coincide within ± 38 microns across the prime focus plane and to within 5 microns in focus. An error in coincidence across the focal plane causes all point images to show additional coma with all the comatic tails pointing in the same direction. An error in focus becomes magnified by the square of the magnification of the secondary and simply increases the diameter of the point source. Offsetting or rastering the sun may be accomplished by swinging the primary in an arc about the point of coincidence of the conic foci so long as the coincidence is kept to within the tolerance stated. A ± .5° offset (two solar diameters) must be accommodated.

The alignment telescope detects the lack of coincidence of the conic foci and interprets the measurement as an angular tilt of the primary although the error might have come from decentering the primary, or tilting or decentering the gregorian. Correction of the error will affect the line-of-sight (LOS) pointing.

The objective mirror of the line-of-sight (LOS) detector is mounted on the primary and so it detects line-of-sight angular errors whether they arise from tilt or decentering of the primary or pointing of the telescope truss. To correct this line-of-sight error the vertex of the primary may be rotated or swung about the conic foci so long as tilts are not introduced that destroy the coincidence of the conic foci. When used in conjunction with an offset in the LOS detector this swing can be used to offset point or raster the sun without repointing the truss itself. It can even be used for internal motion compensation (IMC) if it can be done fast enough. Alternatively the telescope truss can be repointed.

In determining the requirements of sensitivity of the actuators of the primary mirror mount, the principal driver is the need to prevent cross coupling between tilt and translation of the primary mirror as the mirror is moved to correct the error signal generated by the LOS detector. For example, it is attractive for rastering and correcting LOS errors to set up the mirror mount so the vertex of the mirror is swung about the conic foci. The plate scale at the prime focus is 21 microns per sec of arc so that swinging the primary 2 microns about the conic foci would correct a LOS error of 0.1 sec of arc. One can visualize a system that swung the mirror this 2 microns as soon as the LOS detector showed an error of 0.1 sec of arc. If during this 2 micron step the mirror tilted in the right direction by 0.1 sec of arc, which corresponds to only 0.6 microns at the edge of the mirror, the LOS detector would show its error corrected and so should not have commanded a 2 micron step. One way to prevent this cross coupling is to make all increments or sensitivities in swinging the mirror about the conic foci small enough that if a tilt does occur that satisfies the LOS detector the correction can be stopped. This requirement would appear to be satisfied if the increment of motion in translation or focus were so small that it could not cause an error in pointing greater than 0.1 sec of arc.

The coincidence of the conic foci is not a driver since the ± 38 microns tolerance at the prime focus of the conic foci corresponds to ± 1.7 sec of arc tilt of the primary or about ± 10 microns at the edge of the primary. Focus is also not a driver since its tolerance is ± 5 microns.

Note that if all LOS errors are corrected by the truss pointing system instead of by swinging the mirror then the sensitivity for focus and coincidence of the conic foci become the drivers.

2.0 SPECIFICATION OF MIRROR MOUNT POINTING CAPABILITIES

2.1 DEGREES OF FREEDOM: The prime focus mirror must be capable of the following motions:

2.1.1 Rotation of the vertex about the conic foci: This motion will be used to offset and raster the telescope and to provide internal motion compensation (IMC) at slow rates without moving the telescope truss. The motion must be ± 0.5° which corresponds to a translation or decentering of the mirror of approximately ± 4 cm. The maximum rate must be not less than ± 0.5° in one minute. The increment must be 0.1 sec of arc or smaller. For commanding the mirror position without servos the repeatability must be less than 1 sec of arc.

2.1.2 Tilt about the vertex: This motion will be used to bring the conic foci into coincidence. The sensitivity must be 0.2 sec of arc. The range must be at least ± 20 sec of arc about the radius vector from the conic foci to the vertex as translated in 2.1.1. The acquisition range to bring the radius vector to the conic foci must be ± 500 sec of arc.

2.1.3 Focus: The focus must have a range of ± 1 cm and a sensitivity of 1 micron. Focus rate must be variable with a maximum rate of 1 mm/second. The direction of focus should occur along the radius vector from the conic foci to the vertex as translated in 2.1.1

to avoid upsetting the alignment detector.

2.2 <u>CROSS COUPLING</u>: The motions in 2.1 shall be independent, or appear to the operator to be independent, to the following degree: Rotation of the primary mirror vertex about the conic foci shall not introduce more than 2 sec of arc error in the tilt about the vertex for each 0.1° of offset and not more than 2.5 microns in focus for the full ± 0.5°. The tilt about the vertex shall not influence the focus by more than 2.5 microns. The focus shall not effect LOS pointing by more than 1 sec of arc for each millimeter of focus.

3.0 BASELINE MIRROR MOUNT: The A frame (Figure 1) has been chosen as the baseline mount for primary mirror in SOT, although other schemes are possible. The A frame is very rigid and precise and solves the problem of matching the expansion of the truss structure to the main mirror so that there will not be any over constraint. Expansion of an actuator will cause the mirror to move in one or more of its six degrees of freedom, but it should not introduce any stresses. The disadvantage of the A frame is the requirement for a complex control system.

3.1 CONFIGURATION: The configuration used for this analysis is shown in Figure 2. This layout is for edge-mounted actuators. Rear-mounted actuators are also possible.

3.2 ACTUATOR LENGTHS FOR A + 0.5° OFFSET: The lengths of the six actuators may be calculated exactly for any view point on the sun by using the procedure that follows. The origin of the coordinate system (Figure 3) is chosen at the conic foci so that any offset on the sun is accomplished by rotating the mirror about an angle $\Delta\alpha$. The position angle of this rotation is θ. The steps are as follows.

Step 1 Determine the coordinates for any point on the mirror X_0, Y_0, Z_0 from layout

$r_0 = \sqrt{X_0^2 + Y_0^2} = 70.5$, for example in Figure 2

$$\theta_o = \arc\tan \frac{Y_o}{X_o} = 0, 60, 120, 180, 240, 300 \text{ degrees},$$

for example.

Step 2 Determine the radius, ρ, and angle α, between the point on the mirror and the axis of rotation of the mirror.

$$d = r_o \sin (\theta_o - \theta)$$

$$\rho = \sqrt{d^2 + z_o^2}$$

$$\alpha = \arc\tan \frac{d}{z_o}$$

Step 3 Rotate the mirror through $\Delta\alpha$ and locate the point on the mirror with respect to the original coordinate system.

$$\psi = \alpha + \Delta\alpha$$

$$Y_\theta = \rho \sin \psi$$

$$X_\theta = r_o \cos (\theta_o - \theta)$$

$$Z_\theta = \rho \cos \psi$$

$$x = X_\theta \cos \theta - Y_\theta \sin \theta$$

$$y = X_\theta \sin \theta + Y_\theta \cos \theta$$

$$z = Z_\theta = \rho \cos \psi$$

Step 4 Calculate the length of the actuator

$$L = \sqrt{(x - X)^2 + (y - Y)^2 + (z - Z)^2}$$

where X, Y, Z are the coordinates of the fixed end of the actuator.

Table 1 shows the lengths of the actuators for different α and θ angles. $\theta = 45°$ shows the greatest change in length.

TABLE 1 ACTUATOR LENGTHS FOR + 0.5° AND - 0.5° ( ) OFFSETS FOR DIFFERENT VALUES OF θ. L_o = 61.61168 cm.

Actuator	θ					
	0°	45°	60°	90°	120°	150°
1-7	63.339	64.101	64.054	63.510	62.493	61.259
	(60.135)	(59.319)	(59.370)	(59.954)	(60.716)	(62.255)
2-8	59.370					
	(64.054)					
3-9						
4-10			64.054			
			(59.370)			
5-11	59.370					
	(64.054)					
6-12	63.339			59.954		
	(60.135)			(63.510)		

3.3 ACTUATOR LENGTHS FOR A 10 ARC SECOND TILT: Tilting the mirror about its vertex 10 seconds of arc about the X axis changes the lengths of the actuators by the amount shown in Table 2.

TABLE 2: Change in length of the actuators for a + 10 sec of arc rotation about the X axis.

Actuator	Δ cm
1-7, 6-12	+ .002528
3-9, 4-10	- .002260
5-11, 2-8	- .000284

This motion would be used as a differential to correct the tilt error, and force the conic foci to coincide. The Δ is applicable to all tilts if the three alignment telescopes are assumed to be symmetrically placed with respect to the actuators. The same amplitude signal is sent to the four actuators but the sign differs.

3.4 CONTROL CONCEPT: Assuming the actuators step in increments, the control concept is to first zero all the actuators and then count steps to place the mirror close enough to the correct position that the alignment and focus detectors can lock on. The output of each alignment telescope is fed to a specific set of four actuators. For example, in Table 2 to correct a positive error the same number of negative steps would be sent to actuators 1-7 and 6-12 while an equal number of positive steps were sent to

5-11 and 2-8. The actuators 3-9 and 4-10 would not be actuated. For focus the same number of steps would be sent to all actuators. After the alignment and focus detectors were zeroed, the LOS detector would be turned on. Its X signal, for example, would be sent to each of the six actuators in proportion to the actuator's influence on the X motion. This proportion is within $\pm$ 4% over the $\pm$ 0.5° field. If the system is looking at a stellar source the rastering would be open loop and the length of the actuators would be continuously calculated for each point in the field. Alternatively, for both solar and stellar pointing the entire truss could be repointed with the IPS.

3.5 LOADS: The actuators make an angle of arc tan $\frac{36}{50}$ = 35.7° with respect to the mirror. With the mirror on its back each actuator sees 1/6 of the 1650 lb mirror resolved along 35.7° or 338 lb. With the mirror on edge the entire downward force is taken by two actuators, for example, 2-8 and 5-11 in Figure 2, and the loads become

$$\frac{1650}{2 \sin 35.7°} = 1413 \text{ lb}$$

The combined emergency landing load of 4.5 g forward (x) and 4.5 g downward (z) would subject the two side actuators to

$$4.5 \times 1413 + 4.5 \times 338 = 7879 \text{ lb.}$$

Similarly launch load is 1.5 x 1413 + 2.9 x 338 = 3099 lb and the landing load 2.8 x 1413 + 1 x 338 = 4294 lb.

The force to move the mirror in space is much smaller. To track a 10 sec of arc p-to-p LOS error at 1 Hz by swinging the mirror about the conic foci takes the following force:

5 sec of arc amplitude = 105 micron shift = .00413 inches

$$a = A(2\pi f)^2 = .0041\ (2\pi f)^2 = .162\ \text{in/sec}^2$$

$$F = \frac{W}{g} \times a = \frac{1650}{32 \times 12} \times .162\ \text{in/sec}^2 = .696\ \text{lb}$$

which is very small and represents forces during IMC.

To accelerate the mirror about the conic foci to the maximum scan velocity in 0.1 sec takes the following force:

Velocity max = 60 sec of arc/sec = 1.26 mm/sec displacement = .0496 inches/second

$$\text{average } a = \frac{.0496}{.1} = .496\ \text{in/sec}^2$$

$$F = \frac{W}{g} \times a = \frac{1650}{32 \times 12} \times .496 = 2.1\ \text{lb}$$

4.0 BASELINE ACTUATOR: The baseline actuator is shown in Figure 4. The device is a preloaded 0.2 inch lead ball screw coupled to a 400 step per revolution Slosyn through a 80:1 harmonic drive. Dog stops on the screw serve as mechanical stops. No electrical stops are used. The design parameters are calculated in the following sections and are summarized as follows:

Resolution: 0.158 microns (.06 sec of arc on sun)

Speed: 5400 steps/sec (crosses sun in 30 sec), .0337 in/sec

Range: 76.2 mm

Thrust: 2000 lb each

Backlash: In space, removed by a 100 lb spring. On the ground, removed by the weight of the mirror.

Acceleration: Up to 1.77 in/sec^2 in space.
Up to .674 in/sec^2 in one g.

Stiffness: 2.2 x 10^6 lb/inch load capability.

4.1 RESOLUTION: The step resolution is as follows:

$$\text{steps/rev} \times \text{gear reduction} \times \text{lead} = \frac{1}{400} \times \frac{1}{80} \times 0.2 \times 25.4 = .000158 \text{ mm} = .158 \text{ microns}$$

A single step on two adjacent actuators would tilt the mirror 0.03 sec of arc. In the control scheme suggested in section 3.4 one would set in steps of .06 sec of arc. If the opposite set of actuators were not turned on half this angle could be set in.

4.2 SPEED: In the worst case (45°; Table 1) an actuator has to be moved 4.8 cm to cover ± 0.5°. The sun's diameter is half the full range, so that at a 5.4 KHZ stepping rate the time to scan the sun is as follows:

$$\frac{24 \text{ mm}}{.158 \times 10^{-3}} \times \frac{1}{5400 \text{ steps/sec}} = 28.1 \text{ seconds}$$

4.3 THRUST: The M061-FC08 motor in half step mode puts out 20 in oz at 5400 steps per second with one winding one. The thrust at 90% efficiency for the Ball screw and 80% for the harmonic drive is as follows:

$$\text{Thrust} = \frac{\text{Torque} \times 2\pi \times \text{eff}}{\text{lead}} = \frac{20 \text{ in } \theta z \times 80 \times 2\pi \times .80 \times .90}{0.2} =$$

$$36191 \text{ oz} = 2261 \text{ lbs}$$

This thrust can be increased by 1 1/2 times by activating two windings but at the penalty of twice as coarse a step. The thrust in the actuator during one G checkout with the telescope horizontal is 1413 lb (see Section 3.5).

4.4 PRELOAD: The harmonic drive has 8.5 min of lost motion for a resulting torque of 10 in-lb which represents 2 microns or 12 steps and so must be removed with a preload across the actuator. To put 10 in-lb on the harmonic drive output to take out the "backlash" would take the following:

$$\text{Thrust} = \frac{10 \times 2\pi}{.2 \times .9} = 349 \text{ lb}$$

The residual torque of the motor is 5 in-oz. To drive the motor backwards would take the following:

$$\text{Thrust} = \frac{\text{Torque} \times 2\pi}{\text{lead} \times \text{eff}} = \frac{5 \times 80 \times 2\pi}{.2 \times .8 \times .9 \times 16} = 1090 \text{ lb.}$$

The actual preload required will have to be determined, but in view of the low force requirements in space a preload across the actuator of several hundred lb would seem appropriate. The spring must also take into account the back pressure from the air enclosed in the bellows.

4.5 ACCELERATION: The acceleration available is as follows:

Inertia

Load Inertia at the Motor =

$$W \frac{L^2}{(2\pi)^2} \frac{1}{G^2} = \frac{825 \times (.2)^2}{(2\pi)^2 \times (80)^2} = 1.3 \times 10^{-4} \text{ lb-in}^2$$

W = weight the actuator sees ∿ 1/2 mirror weight

L = screw lead

G = gear reduction in harmonic drive

Motor Inertia = .04 lb-in^2 (catalog value)

Harmonic Drive Wave Generator Inertia = .07 lb-in^2 (catalog value)

Lead Screw Inertia = $\frac{D^4 \times \text{length} \times .028}{G^2} = \frac{1.25^4 \times 8 \times .028}{80^2} =$

8.54×10^{-5} lb-in^2

Total Inertia, I = .11 lb-in^2 and is totally dominated by the motor and wave generator in the harmonic drive.

In space, since the friction is low and the loads negligible, the entire 20 in-oz is available to accelerate the inertia and the time to reach 5400 steps/second (84.82 r/sec) which moves the actuator at .0337 in/sec as follows:

$t = \frac{I\omega}{T} = .11 \text{ lb-in}^2 \times 84.82 \text{ r/sec} \times \frac{16}{20} \text{ in-lb} \times \frac{\sec^2}{32 \times 12 \text{ in}} =$

.0190 sec, which, because of the angle of the actuator to to the mirror, corresponds to accelerating the mirror to a velocity of .04 inches/sec in .019 sec, which is 2.1 in/sec^2. This would require 8.9 lb push on the mirror and would be split between two actuators. This would be more acceleration than is necessary and could possibly effect the IPS, in which case a slower acceleration ramp could be programmed. The Slosyn controller used to test the actuator has an acceleration range adjustable from 50 ms to 1 sec which is considerably longer than that needed. The 50 ms range would reduce the acceleration on the mirror from 2.1 to 0.81 in/sec^2 and the force on the mirror to 3.42 lb.

On the ground only 7.5 in-oz of the 20 in-oz is left to overcome the inertial load and it will take .050 sec to accelerate to the maximum velocity of 5400 steps/sec or .04 inches/sec of mirror motion which is then an acceleration of 0.8 in/sec^2.

4.6 STIFFNESS AND SPRING CONSTANT: The stiffness or spring constant of the assembly is estimated as follows:

Nut assembly (from p14, 1972 Beaver Catalog), 300 lb. load.

$$K = 9.5 \times 10^6 \text{ lb/in}$$

Screw (from p14, 1972 Beaver Catalog), 5 in long, bearings on one end only.

$$K = \frac{25 \times 10^6}{4} = 6.25 \times 10^6 \text{ lb/in}$$

Harmonic Drive: The catalog gives a stiffness of k = 116,000 lb-in/radian to the rated load of 320 in-lb. With 10 in-lb torque from the preload (Section 4.4) the stiffness will be much lower. Judging from their typical curve it may be down by a factor of three. The thrust, P, needed to rotate the screw 1 radian is $\frac{2\pi T}{L}$ and the screw advances $\frac{L}{2\pi}$ so that K = $\frac{(2\pi)^2 k}{L^2} = \frac{(2\pi)^2}{(.2)^2} \times \frac{116000}{3} = 38 \times 10^{-6}$ lb/in.

Stepper Motor (from catalog): Use 1.8° step values. 1000 lb on the screw results in a 5.1 in-oz torque on the motor (using a 0.81 efficiency). The holding torque is 53 in-oz so the windup is 10% of the holding torque and is 0.12° which represents $K = \frac{360}{.12} \times 80 \times \frac{1}{.2} \times 1000 = 1200 \times 10^6$ lb/in.

Bellows: Specified at greater than 50,000 in-lb/radian. The actual design value is 3 arc min windup per 400 in-lb torque which gives

$$k = 400 \times 3437 \text{ min/rad} \times \frac{1}{3 \text{ min}} = 458{,}366 \text{ in-lb/rad}$$

$$K = \frac{1}{32 \text{ in-lb}} \times \frac{458{,}366 \text{ in-lb}}{\text{rad}} \times \frac{2\pi \text{ rad}}{\text{rev}} \times \frac{1000 \text{ lb}}{.2} = 450 \times 10^6 \text{ lb/inch}$$

Ball Bearing: The thrust ball bearing is a special 60° contact angle preload pair designed for ball screws. It is designed to have a stiffness of 6.7×10^6 lb/inch.

Overall Stiffness: The overall stiffness not including the connections on the ends is calculated by summing the reciprocal K values for all the parts.

$$\frac{1}{k} = \frac{1}{10^6}\left(\frac{1}{9.5} + \frac{1}{6.25} + \frac{1}{38} + \frac{1}{1200} + \frac{1}{450} + \frac{1}{6.7} = \frac{1}{2.25 \times 10^6} \right)$$

Overall Stiffness $K_{system} = 2.2 \times 10^6$ lb/inch

Discussion of Stiffness: Clearly the stiffness will be given by the preloaded ball bearing, the screw, and possibly the harmonic drive. One step of the motor corresponds to an extension of 6.2×10^{-6} inches of the actuator which is equivalent to a change in force of 13.6 lb. This would suggest that "stiction" in the system should result in less than 13.6 lbs thrust.

The torque to overcome preload in the ball screw is $T_p = \frac{0.2\ L\ P_L}{2\pi}$, and for P_L = 300 lb preload. $T_p = \frac{0.2 \times .2 \times 300}{2\pi} = 1.91$ in-lb at the output of the harmonic drive. The bearing drag is 4 in-lb and must be added to this value for a total drag friction at the output of the harmonic drive of 5.9 in-lb which is 1.18 in-oz at the stepper. For a harmonic drive stiffness of 1/3 the catalog value or 38,666 lb-in/rad the windup is 1.5×10^{-4} rod which is almost equal to the step value of 1.9×10^{-4} rod. Clearly there is a tradeoff between stiffness, drag and preload that will have to be determined experimentally.

There is a stiction load that originates in the 12 rod end connections to the mirror and the base plate. All 12 rod ends are moved by the movement of one actuator so the stiction in each joint should result in less than 1 lb variation in the thrust on the actuator.

Teflone lined rod ends have been considered for the attachment points. The ball in a teflon-lined, 0.75 ID rod end would have a diameter of 1.18 inches and a coefficient of friction of .19. The friction in a one G checkout would be determined by the two actuators with the 1413 lb load on them (see Section 3.5). This would be $P \times R \times f = 1413 \times .59 \times .19 = 158$ in-lb which would appear to be way too high since the stiction could be expected to be 10% of the friction. In space teflon rod ends might be acceptable since the friction would come from a 15 lb spring loading across the rod ends. The friction would then be 1.7 in-lb and the stiction a small part of that.

This suggests that a more sophisticated rod end may have to be incorporated. Note that the movements come in in all orientations around the rod end and so the ball bearing rod end shown in the BBRC alignment study will not work. Flexures are shown in the Itek study but it would be better if the mirror were free from moments so that its optical figure were preserved.

A gimbal on the end of the actuator with small diameter ball bearings looks attractive at this point. It could employ four small diameter ball bearings or spherical rollers and would look like one end of a universal joint. This unit could be lightly preloaded, which would eliminate the preload springs across the joint.

The friction in each 1 inch diameter race would be 1413 x .5 x .002 = 1.41 in-lb and stiction in ball bearings is low. Two bearings in each gimbal would be active but each carries only half the load.

4.7 STOPS: Dog stops on the ball bearing screw engage the ball nut to mechanically stop the drive. This method ensures that the actuator can be backed off and that the screw and its thrust bearing are not loaded. The torque is absorbed across the bellows and harmonic drive, which then must stand the inertial load and driving torque of the motor. Consider that the motor is operating at 5400 steps per sec when the dog hits.

The velocity at the output of the harmonic drive is 1.06 rad per sec and the motor and harmonic wave generator inertia transferred to the output is equal to $0.11 \times 80^2 = 704$ lb-in^2. The harmonic drive can stand momentary overloads up to two times its rated torque and the problem is to determine if the motor is stopped by the time the harmonic drive is wound up against its spring constant to two times the rated torque. Since the average torque is half the maximum, the time to stop the motor is given by

$$\Delta t = \frac{2\ I\omega}{T_{max}} = \frac{2\ I}{T_{max}} \times \frac{sps \times .9}{G} \times \frac{\pi}{180}$$

where G = gear ratio = 80:1

ω = angular velocity of motor at output

The average angle moved by the motor during Δt is half the maximum speed times Δt divided by the gear ratio which is 80:1. The spring constant, K, is 116,000 in-lb/rad so that

$$T_{max} = \frac{sps}{2} \times \Delta t \times \frac{1}{G} \times \frac{.9^\circ}{step} \times \frac{\pi}{180} \times \frac{lb}{rad}$$

Solving for Δt and equating

$$T_{max} = I^{\frac{1}{2}} \times \frac{I}{(32 \times 12)^{\frac{1}{2}}} \times sps \times .9 \times \frac{\pi}{180} \times \frac{I}{G} \times K^{\frac{1}{2}}$$

$$T_{max} = 8.015 \times 10^{-4} \, \frac{I^{\frac{1}{2}} \times sps \times K^{\frac{1}{2}}}{G} = 488.9 \text{ in-lb}$$

where sps = 5400

The motor torque (20 in-oz with one winding on) will have to be added to this value to give a total torque of 588.9 in-lb which is 10% higher than the two times rating. The harmonic drive bearings and the bellows will be compliant enough to make up this difference and the efficiency is not calculated in. If necessary, an "A" type harmonic drive cup made from 4340 steel can be used with 2.5 times the rating. Another approach would be to greatly limit the speed as the dogs are approached.

The time to stop the drive in this example is 8 ms.

4.8 LAUNCH LOAD CAPACITY: The actuator does not drive backwards very effectively. In section 4.4 it was shown that over 1000 lb thrust is required to overcome the friction of the motor. Shorting the motor leads enormously increases the viscous damping of the motor. Thus there is the possibility that the actuators can be left attached during launch and landing, and that they can withstand the 7900 lb emergency landing load in section 3.5 without coming apart. The static rating of the ball screw is 26,700 lb. Its rated load is 6270 lb. The ball bearing is rated in thrust at 3700 lb working load and 6700 lb maximum. Whether or not the balls would pop out at 7900 would have to be determined. It would appear that the actuators themselves could withstand launch and landing loads.

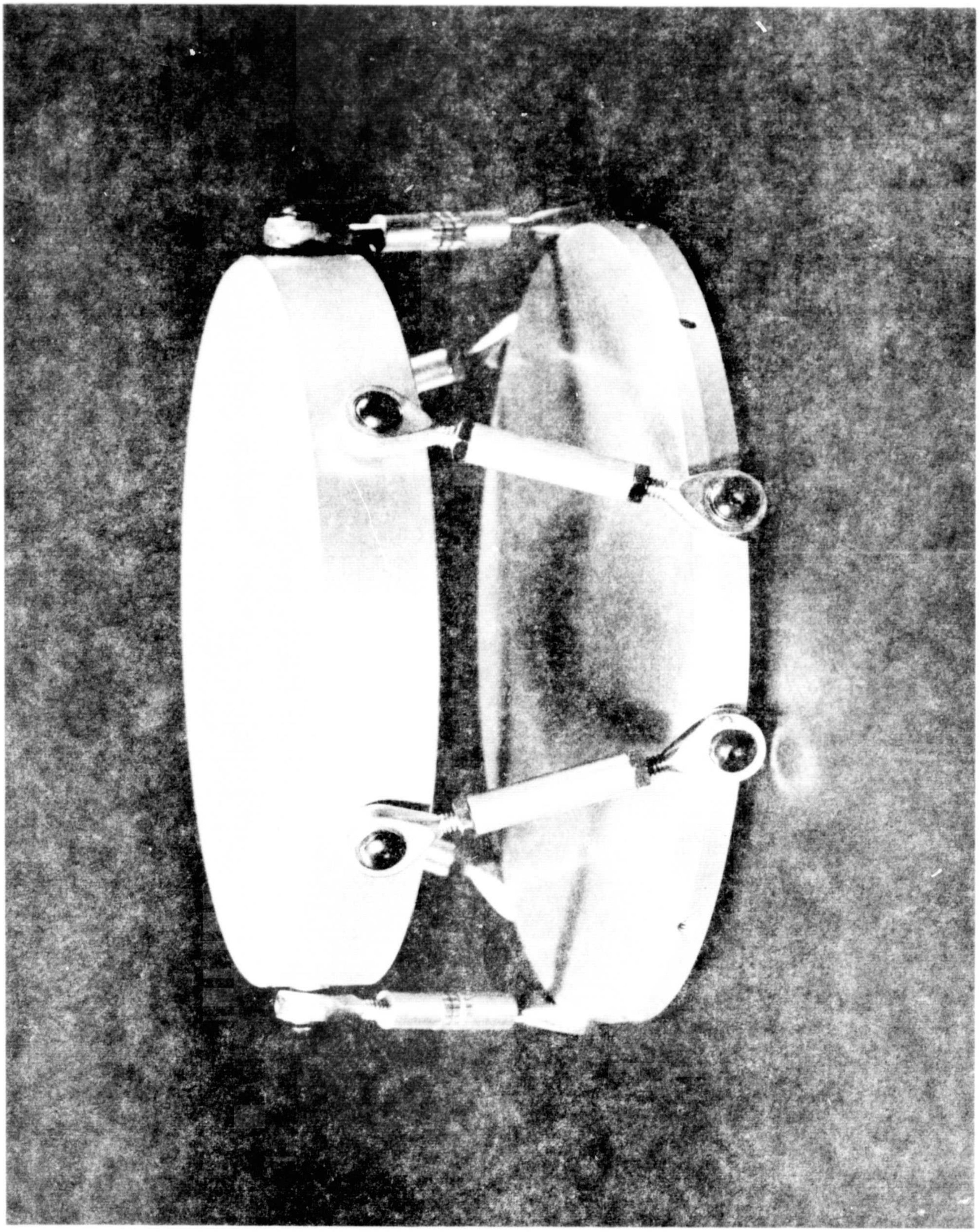

FIG. 1

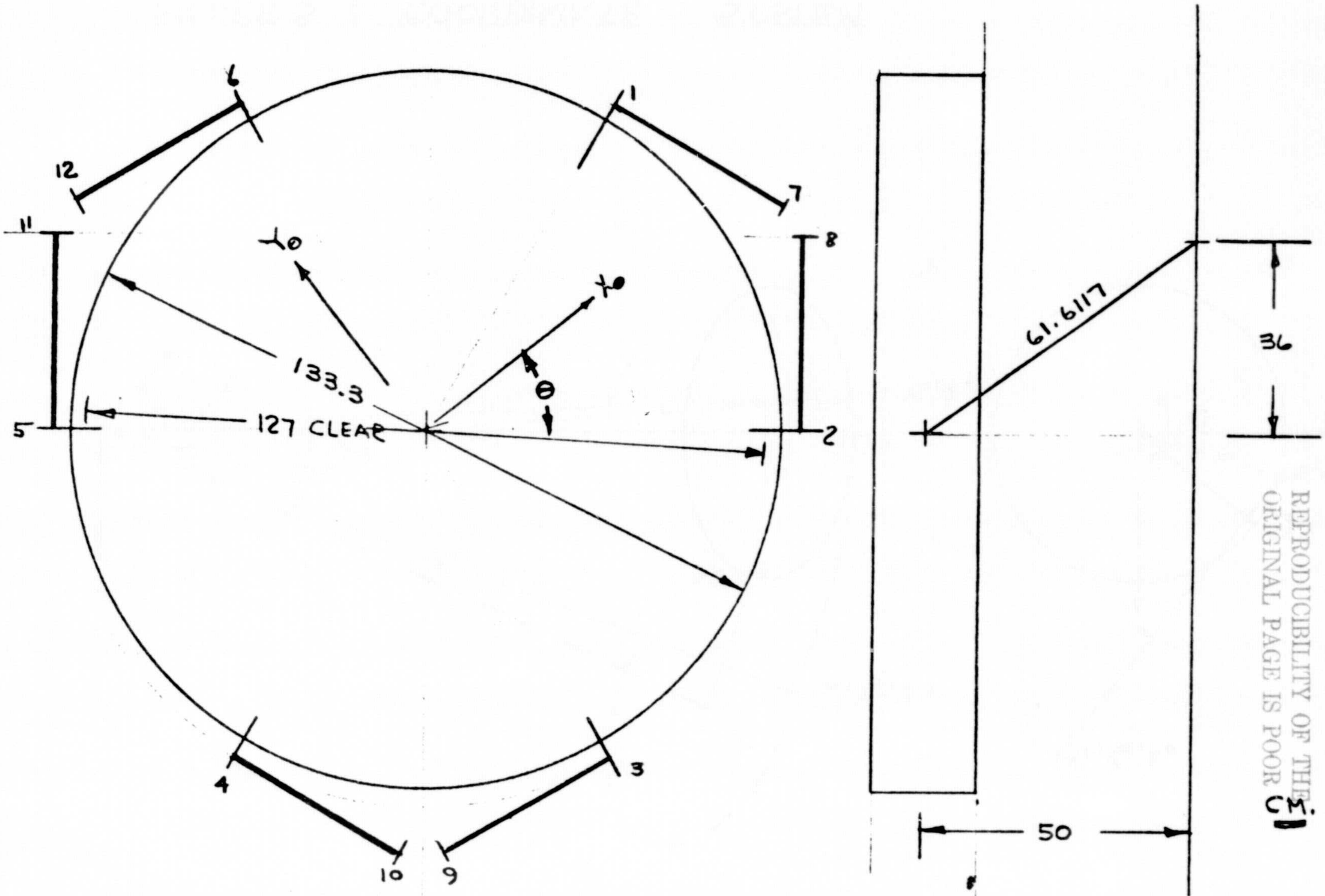

FIGURE 2. CONFIGURATION (EXAMPLE - EXTERNAL ACTUATORS)

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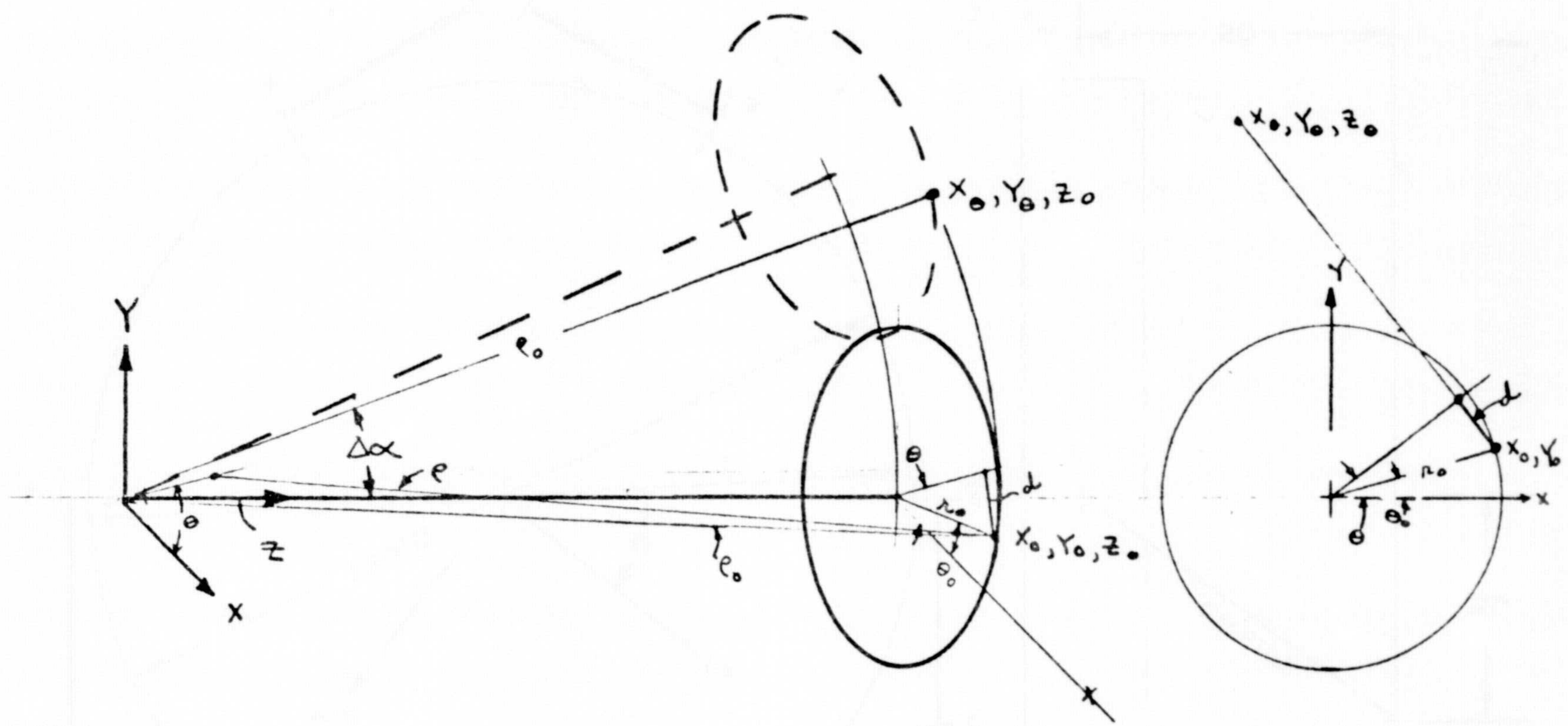

FIGURE 3 : COORDINATE SYSTEM

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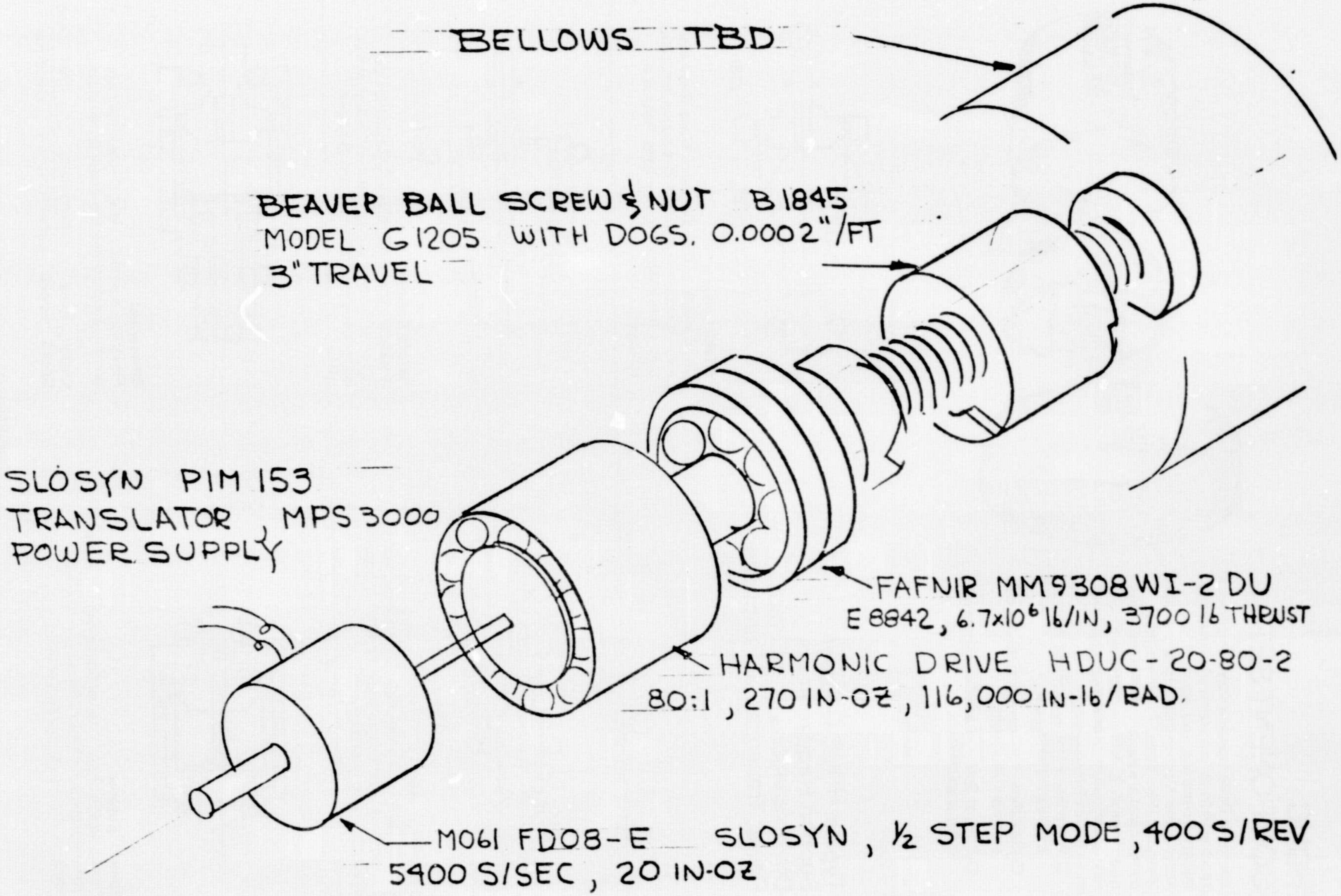

FIGURE 4: BASELINE ACTUATOR

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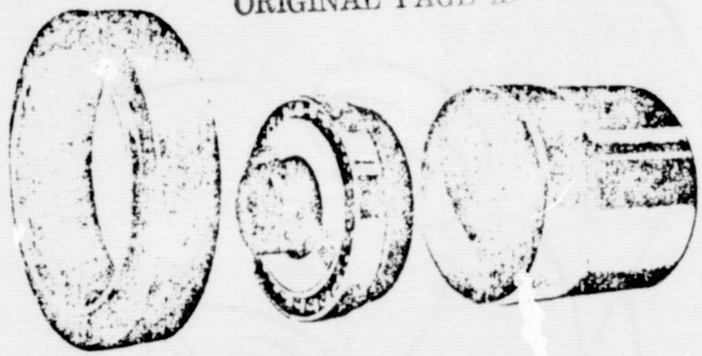
appendix

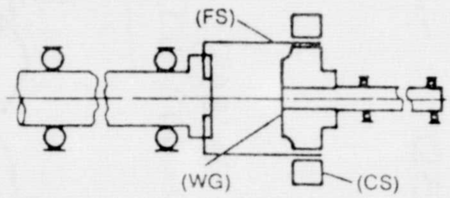
HDUC COMPONENT SETS

Harmonic Drive Transmission Components serve worldwide in a variety of demanding military, aerospace, and industrial applications. Mechanically similar to USM's Harmonic Drive Speed Reducers, these components are easier to install than other types of gearing. And they achieve a high-ratio speed reduction or increase with only three basic elements:

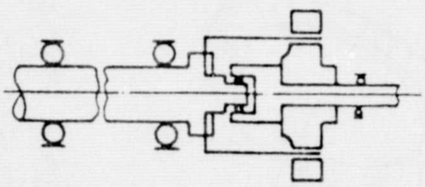
- ☐ Wave Generator — an elliptic steel ball bearing assembly
- ☐ Flexspline — a thin-wall steel cup with external spline teeth
- ☐ Circular Spline — a thick-wall ring with internal spline teeth



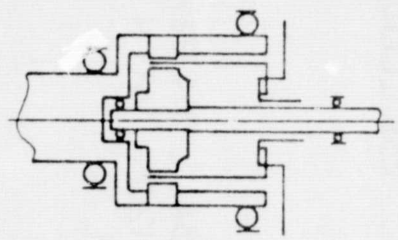
Typical HDUC Component Bearing Support Requirements and Drive Variations to accomplish Power Transmission Functions



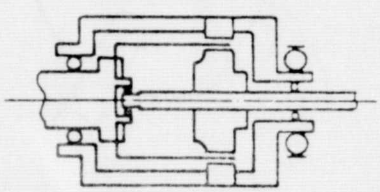
Speed Reducer
Circular Spline (CS) stationary. Wave Generator (WG) is input, Flexspline (FS) is output. Input and output turn in opposite directions. Ratio is as tabulated.



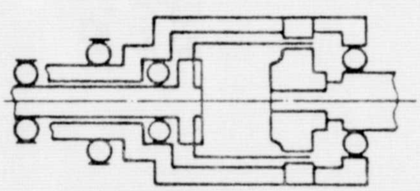
Speed Increaser
Circular Spline stationary. Flexspline is input. Wave Generator is output. Input and output turn in opposite directions. Ratio is as tabulated.



Speed Reducer
Flexspline stationary. Wave Generator is input, Circular Spline is output. Input and output turn in same direction. Ratio is as tabulated plus 1.



Speed Increaser
Flexspline stationary. Circular Spline is input, Wave Generator is output. Input and output turn in same direction. Ratio is as tabulated plus 1.



Differential
Flexspline is primary input, Circular Spline is primary output. Wave Generator is trim input.

$$\text{Ouput Speed} = \text{Input Speed} \times \frac{\text{Listed Ratio}}{\text{Listed Ratio} + 1} \pm \frac{\text{Trim Speed}}{\text{Listed Ratio} + 1}$$

Special brochure, Designing Differential Transmissions, available on request.

Rating Tables

Harmonic Drive Component Sets
Size 14 - 100

INPUT RPM		3500			1750**			1150			500			Maximum Running Output Torque lb./in.	
Size	Ratio	Input hp	Output rpm	Output lb./in.	Input hp	Output rpm	Output lb./in.	Input hp	Output rpm	Output lb./in.	Input hp	Output rpm	Output lb./in.	STD.	TYPE A***
14	88	.07	39.8	87	.03	19.9	87	.02	13.1	87	.01	5.7	87	87	N.A.
	110	.06	31.8	87	.03	15.9	87	.02	10.5	87	.01	4.5	87	87	
20	80	.21	43.8	260	.11	21.9	270	.07	14.4	270	.03	6.2	270	270	400
	96	.21	36.5	270	.11	18.2	320	.08	12.0	320	.03	5.2	320	320	480
	128	.15	27.3	278	09	13.7	372	07	9.0	380	.03	3.9	380	380	570
	160	.13	21.9	286	.09	10.9	372	.07	7.2	430	.03	3.1	430	430	650
25	80	.34	43.8	408	.20	21.9	500	.14	14.4	500	.06	6.2	500	500	750
	100	.29	35.0	434	.20	17.5	590	.16	11.5	700	.07	5.0	700	700	1050
	120	.27	29.2	560	.17	14.6	616	.14	9.6	713	.07	4.2	850	850	1280
	160	.22	21.9	477	.13	10.9	622	.11	7.2	713	.06	3.1	940	940	1400
	200	.19	17.5	486	.12	8.8	622	.09	5.8	713	.05	2.5	940	940	1400
32	78	.75	44.9	890	.41	22.4	970	.27	14.7	970	.11	6.4	970	970	1450
	104	.65	33.7	990	.42	16.8	1250	.31	11.0	1400	.13	4.8	1400	1400	2100
	131	.53	26.5	990	.33	13.3	1250	.26	8.7	1430	.13	3.8	1800	1800	2700
	151	.46	22.2	990	.29	11.1	1250	.22	7.3	1430	.13	3.2	1900	1900	2850
	208	.37	16.8	990	.24	8.4	1250	.18	5.5	1430	.10	2.4	1900	2100	3150
	260	.31	13.5	990	.20	6.7	1250	.15	4.4	1430	.09	1.9	1900	2100	3150
40	80	1.40	43.8	1700	.70	21.9	1700	47	14.4	1700	.19	6.2	1700	1700	2550
	96	1.47	36.5	2090	.81	18.2	2300	42	12.0	2300	.22	5.2	2300	2300	3450
	128	1.15	27.3	2090	.72	13.7	2610	55	9.0	3000	.25	3.9	3300	3300	4950
	160	.96	21.9	2090	.60	10.9	2610	.45	7.2	3000	.26	3.1	4000	4000	6000
	194	.82	18.0	2090	.51	9.0	2610	39	5.9	3000	.22	2.6	4000	4000	6000
	258	.67	13.6	2090	.42	6.8	2610	.33	4.5	3000	.18	1.9	4000	4000	6000
50	80	2.6	43.8	3100	1.27	21.9	3100	85	14.4	3100	.35	6.2	3100	3100	4650
	100	2.6	35.0	3880	1.65	17.5	4900	1.10	11.5	4900	.46	5.0	4900	4900	7350
	120	2.3	29.2	3880	1.42	14.6	4900	1.09	9.6	5600	.48	4.2	5900	5900	8850
	160	1.8	21.9	3880	1.12	10.9	4900	86	7.2	5600	.48	3.7	7500	7500	11300
	200	1.5	17.5	3880	.94	8.8	4900	.72	5.8	5600	.40	2.5	7500	7500	11300
	242	1.3	14.5	3880	.83	7.2	4900	63	4.8	5600	.35	2.0	7500	7500	11300
65	78	5.7	44.9	6770*	2.9	22.4	6800	1.9	14.7	6800	.80	6.4	6800		10200
	104	4.7	33.7	7220*	3.0	16.8	9100	2.3	11.1	10400	1.0	4.8	10500		15800
	132	3.0	26.5	7220*	2.4	13.3	9100	1.9	8.7	10400	1.0	3.8	13900	N.A.	20700
	158	3.4	22.2	7220*	2.1	11.1	9100	1.6	7.3	10400	.90	3.2	13900		20900
	208	2.7	16.8	7220*	1.7	8.4	9100	1.3	5.5	10400	.70	2.4	13900		22500
	260	2.3	13.5	7220*	1.5	6.7	9100	1.1	4.4	10400	.60	1.9	13900		22500
80	80				5.0	21.9	12150	3.3	14.4	12150	1.3	6.2	12150.		18200
	96				5.6	18.2	16000	3.7	12.0	16000	1.6	5.2	15900		23900
	128				5.0	13.7	18000	3.8	9.0	20700	1.8	3.9	24000		36000
	160		N.A.		4.1	10.9	18000	3.2	7.2	20700	1.8	3.1	27700	N.A.	41600
	194				3.5	9.0	18000	2.7	5.9	20700	1.5	2.6	27700		41600
	258				2.9	6.8	18000	2.2	4.5	20700	1.2	1.9	27700		41600
	320				2.4	5.5	18000	1.8	3.6	20700	1.1	1.6	27700		41600
100	80				8.9	21.9	21900	6.0	14.4	21900	2.5	6.2	21800		32700
	100				11.1	17.5	33000	7.4	11.5	33000	3.1	5.0	33000		49500
	120		N.A.		9.7	14.6	33150	7.4	9.6	38000	3.4	4.2	42000		63000
	160				7.6	10.9	33150	5.8	7.2	38000	3.3	3.1	50700	N.A.	76000
	200				6.4	8.8	33150	4.9	5.8	38000	2.7	2.5	50700		76000
	242				5.6	7.2	33150	4.3	4.8	38000	2.4	2.0	50700		76000
	320				4.5	5.5	33150	3.4	3.5	38000	2.0	1.5	50700		76000

*Thermal Limited — 60% duty cycle recommended with on time not to exceed 30 minutes.

**Momentary occasional overloads of up to 2.0 x rated torque at 1750 RPM input are permissible on standard units and 2.5 x rated torque on Type A units.

Ratings given are based on a Service Factor of 1. See pg. 6 for recommended AGMA Service Factor Application.

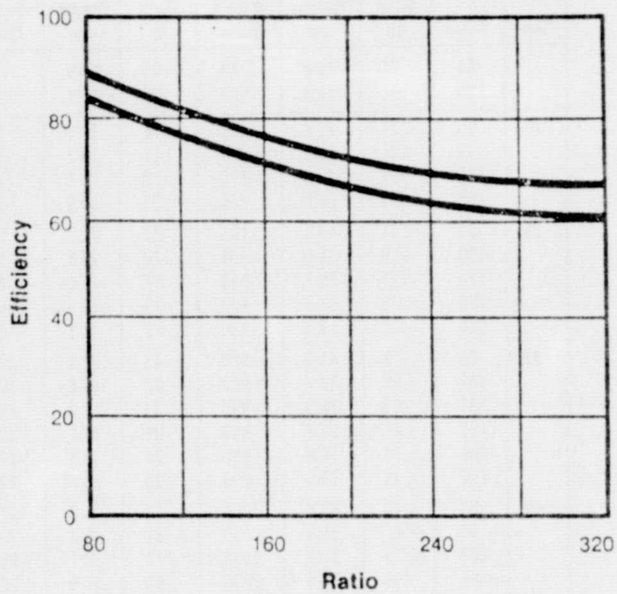
***Type A Units furnished on special order in Sizes HDUC 20-50

Type A standard in Sizes 65, 80 and 100

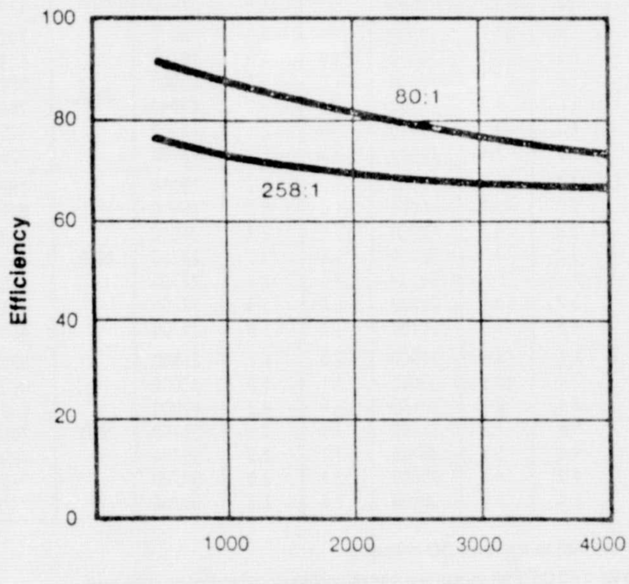
Performance Data
HDUC Components

Size	Wave Generator Inertia (lb.-in.^{2})	No-Load Starting Torque (Approx.) oz.-in.	Maximum Recommended Input Speed (R.P.M.)*
14	.011	2	13,000
20	.07	2.2	10,000
25	.21	5.3	7,500
32	.66	8.5	7,000
40	1.81	16.6	5,600
50	5.18	31.2	4,500
65	20.2	68	3,500
80	54.2	153	3,500
100	159.0	278	2,500

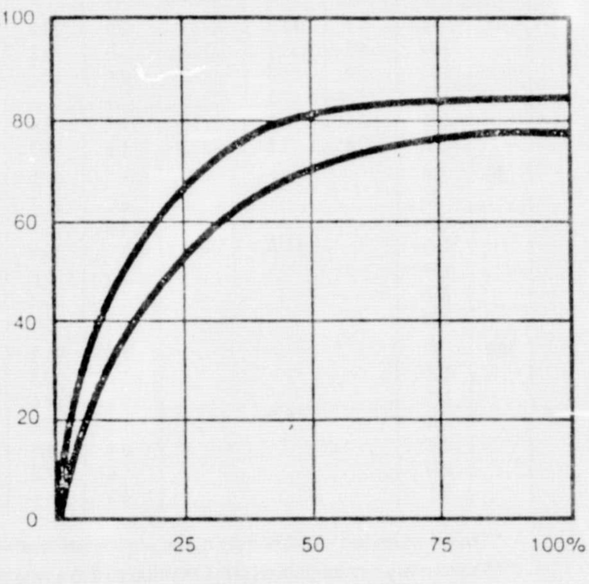
*Consult factory before using.



@ Rated Torque & 1750 RPM

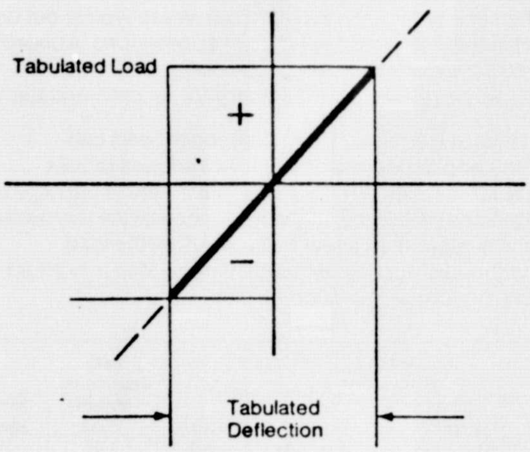


@ Rated Output Torque

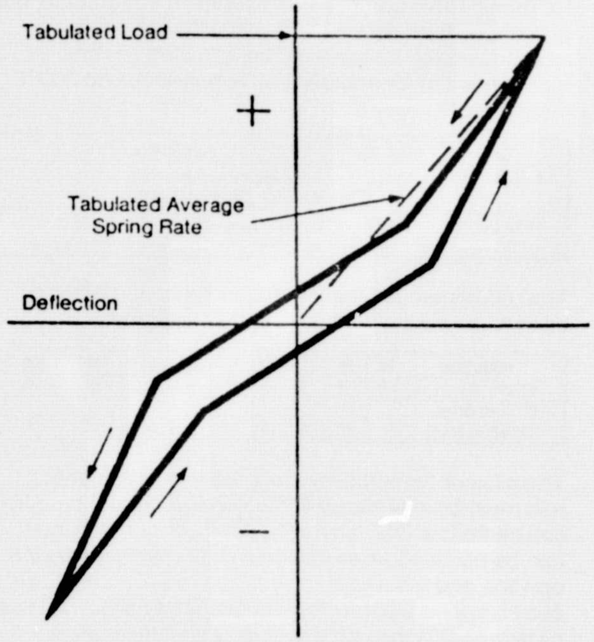


Percent of Rated @ 1750 RPM 100:1 Ratio

Lost Motion and Torsional Stiffness



Lost Motion



Torsional Spring Rate

The above curve and the chart below describe "lost motion". This characteristic is analogous to the pure backlash which occurs in conventional gearing. Since pure backlash cannot be measured accurately in Harmonic Drives, total deflection under a relatively light reverse load is listed. This value includes backlash plus soft windup for standard and optimized units. Optimized units can be specified on order by adding the suffix "BL30" (i.e., HDUC 20-100-2 BL30).

The above load/deflection curve shows typical torsional spring characteristics for Harmonic Drive Components with the input shaft locked. The chart below lists approximate average spring rates. Addition of typical input and output shafts reduces these values by approximately 1/2. Load/deflection information on specific sizes is available on request.

Lost Motion (arc min.)				Average Torsional Spring Rate (lb.-in./radian)	
Size	**± Load (lb.-in.)**	**Standard**	**Optimized**	**Load (lb.-in.)**	**Spring Rate**
14	3.5	8.5	3	109	40,000
20	10.	8.5	3	320	116,000
25	19.5	8.5	3	625	226,500
32	40.	8.5	3	1,370	475,000
40	80.	8.5	3	2,560	928,000
50	150.	8.5	3	5,000	1.8×10^6
65	340.	8.5	3	11,000	4×10^6
80	640.	8.5	3	20,500	7.4×10^6
100	1,250.	8.5	3	40,000	14.5×10^6

Lubrication Requirements
HDUC Transmission Components

Harmonic Drive components operate in any attitude, but deliver optimum performance when horizontally mounted and oil lubricated. The following oils are recommended for operating oil temperatures to 200°F maximum.

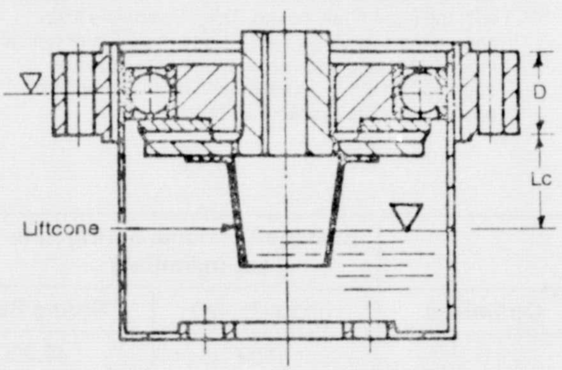
Duty	HDUC Size	Lubrication
Normal Duty	14-100	Automatic Transmission Fluid, Mobil ATF 220 or equivalent
Heavy Duty	65-100	Compound Gear Oil – Mobil Gear 626 or equivalent

The recommended minimum oil volume and required oil level below the horizontal drive centerline are:

HDUC Size	14	20	25	32	40	50	65	80	100
Volume (fl. oz.)	1.0	1.5	3	5	8	16	1 qt.	2 qts.	4 qts.
Oil Level Below Centerline (mm)	7	12	15	19	24	30	61	75	94

The oil level for vertically mounted units as a general rule must be maintained at the wave generator bearing ball centerline D/2. However, optimum performance can be obtained when the input shaft is vertical, facing upward, and running at speeds above 960 rpm by use of a Harmonic Drive Liftcone (illustrated below). A lower oil level (Lc) is then permissible as specified below.

HDUC Size	14	20	25	32	40	50	65	80	100
Lc Oil Level (mm)	N.A.	28	34	43	54	62	93	100	127



Oil changes under normal operating conditions are recommended after the first 100 operating hours and thereafter every 1,000 hours or 6 months, whichever occurs first.

Harmonic Drive components also can be grease lubricated, but typically will have a lower thermal capacity than with oil lubrication. As a general rule, the continuous input speed should be limited to the values specified below. All grease lubricated applications should be reviewed by the factory as a precaution.

HDUC Size	14	20	25	32	40	50	65	80	100
Maximum Input RPM	3,600	3,500	2,800	2,100	1,700	1,400	1,000	900	700

Service Factors
and Ordering Data

Before selecting a component set for a given application, an equivalent horsepower or torque rating should be computed by multiplying the required normal system horsepower or output torque by the recommended AGMA service factor. This equivalent value is then used to select a unit from the rating tables. The service factors tabulated below are typical but do not include all possible types of applications. Abnormal load conditions require special consideration and should be referred to the factory for recommendations.

Standard Harmonic Drive component sets can withstand periodic momentary overloads of 2.0x tabulated rating at 1750 rpm input speed (Type A, 2.5x tabulated). However, if the frequency of the momentary load is more than a few times per day, the load magnitude must not exceed the tabulated maximum running torque value for the unit.

Service Classification		Load Classification		
Prime Mover*	Service Duration*	Uniform	Moderate Shock	Heavy Shock
Electric Motor	3 hrs./day (intermittent)	0.80	1.00	1.50
	10 hrs./day	1.00	1.25	1.75
	24 hrs./day	1.25	1.50	2.00
Internal Combustion Engine (multi-cylinder)	3 hrs./day (intermittent)	1.00	1.25	1.75
	10 hrs./day	1.25	1.50	2.00
	24 hrs./day	1.50	1.75	2.25

*For other prime movers or unusual duty cycles, consult the factory for the proper service factor.

Ordering Data

Harmonic Drive Component sets are identified by Model, Size, Ratio, Type, and Special Requirements. Type is always specified "–2". Special Requirements are specified as follows:

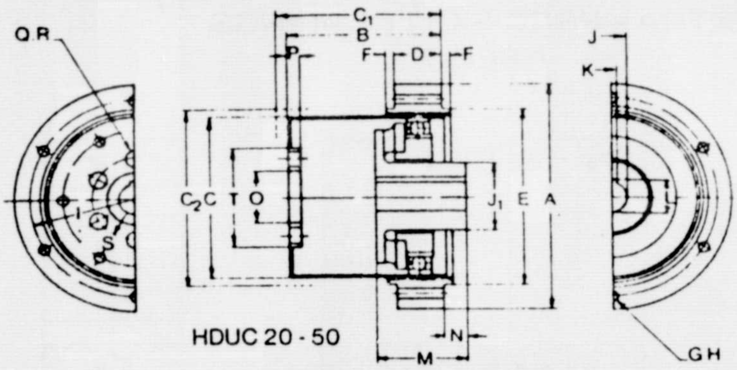
Requirement	Specify
Optimized Lost Motion	30
Liftcone	Liftcone
High-Capacity Flexspline	Type A

Example: A standard size 40, 128:1 reduction ratio set is specified HDUC-40-128-2. The same set with high-capacity flexspline and Liftcone is specified HDUC-40-128-2 Type A Liftcone.

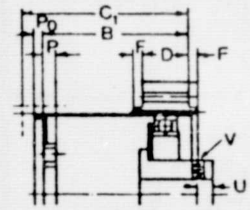
NOTE:
These catalog dimensions are for reference and are suitable for preliminary layout purposes and for evaluation. Detailed specifications, recommended fits, concentricity limits and lubrication requirements are available on dated prints on request.

Dimensions Harmonic Drive Components HDUC Size 14 to 100

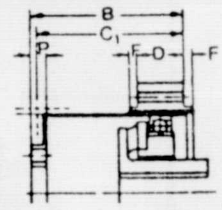
Installation Drawings and Specifications Available on Request



HDUC 20 - 50



HDUC 14



HDUC 20-100 Type A
(High Capacity Type)

Dimensions in millimeters

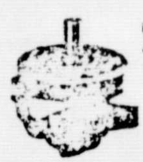
SIZE HDUC		14	20	25	32	40	50	65**	80**	100**
ENVELOPE										
A Circular Spline OD	(h7)	50 (g7)	70	85	110	135	170	215	265	330
B Axial Mounting Dim.		29	45	56	72	88	110	140	169	213
C Flexspline OD		35	51	63	82	102	125	163	202	251
C1 Axial Flexing Clearance		33	47	58	74	91	113	128	160	202
C2 Diametral Flexing Clearance		38	53	66	84	104	130	169	208	260
D Circular Spline Width		8	14	16	20	25	30	40	50	60
MOUNTING										
E Pilot O.D. (Typ.)	(g7)	38	54	67	90	110	135	177	218	272
F Pilot Width (Typ.)		2	3	3	3	4	4	5	6	6
G No. of Holes		6	6	6	6	6	6	6	8	8
H Hole Size	(g7)	3.5	3.5	4.5	5.5	6.6	9	11	11	14
I Bolt Circle Diam.		44	60	75	100	120	150	195	240	290
INPUT										
J Hub I.D.	(h7)	6	9	11	14	14	19	24	28	28
J1 Hub O.D.		14	21	26	26	32	32	48	55	65
K Keyway Width		–	3	4	5	5	6	8	8	8
L Keyway Height		–	10.4 $^{+0.1}$	12.8 $^{+0.1}$	16.3 $^{+0.1}$	16.3 $^{+0.1}$	21.8 $^{+0.1}$	27.3 $^{+0.2}$	31.3 $^{+0.2}$	31.3 $^{+0.2}$
M Hub Length		15	27	32	32	40	40	52	65	70
N Axial Mounting Diam.		5	7	8	6	8	7	7	9	8
U Set Screw		3.5	–	–	–	–	–	–	–	–
V Set Screw Size		M3	–	–	–	–	–	–	–	–
OUTPUT										
O Flexspline Pilot Diam.	(h7)	11	16	20	26	32	40	52	65	80
P Mounting Width		2.3	3.4 (5.4)*	3.5 (6.5)*	4.7 (8.6)*	6.8 (9.5)*	7 (13)*	16.3	14.6	18
Po Diaphragm Flange		2	–	–	–	–	–	–	–	–
Q No. of Holes		6	6	6	6	6	6	6	12	12
R Hole Size		3.4	4.5	5.5	6.6	9	14	14	11	14
S Bolt Circle Diam.		17	24	30	40	50	60	80	104	130
T Hub Diam.		23.5	32 (31.6)*	40 (39.5)*	52	64	80 (79)*	103	126	158
Weight – Lbs.		.22	.88	1.5	2.9	5.5	10.1	19.8	39.2	71.9

*Numerals in parenthesis are Type A **Available in Type A only

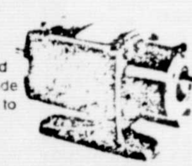
Other Harmonic Drive Products Brochures available on request

Pancake Speed Reducer Component Sets
Gear ratios from 78:1 to 160:1. Output torque capacities to 2,950 lb.-in.

Shaft Phase Adjusting Couplings
Torque ratings from 500 to 20,000 lb./in. For shaft sizes from 0.25" to 2.5" diameter



Manual Valve Actuators
Lightweight and compact. Provide torque outputs to 5,420 lb.-ft.



Speed Reducers
Gear ratios from 78:1 to 320:1. Output torque capacities to 76,000 lb.-in.

Harmonic Drive Division

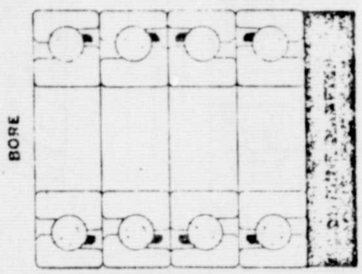
Building 3G, Sixth Road, Woburn Industrial Park, Woburn, Mass. 01801
Tel. (617) 935-6740, TWX710/348-6855 Telex 94-9442

USM Corporation

Printed in U.S.A. HDC 1000-2m-10/76

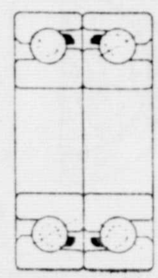
appendix

EXTRA – PRECISION BEARINGS
ABEC-7



SET WIDTH ①

QUADRUPLEX MOUNTING



SET WIDTH ①

DUPLEX MOUNTING

To meet the requirements of the servo-controlled machinery field, The Fafnir Bearing Company has developed a new series of ball bearings specially designed for ball screw applications. Design criteria for these bearings were maximum axial rigidity, low drag torque, and extreme control of lateral eccentricity.

These bearings are manufactured to ABEC-7 tolerances and are of the non separable angular-contact type design with a 60° contact angle and maximum complement of balls. Seven basic sizes are available and are stocked and packaged as duplex pairs or quadruple sets. These bearings are designed primarily for ball screw applications and should not be considered in other areas such as spindles or gear-box shafting without approval by the Fafnir Engineering Department.

DIMENSIONS • TOLERANCES

BEARING NUMBER	BORE inches	BORE tolerance +.0000 to minus, in.	OUTSIDE DIAMETER inches	OUTSIDE DIAMETER tolerance [illegible]	WIDTH (BRG. SET) inches ①	LATERAL ECCENTRICITY maximum in inches	BALLS no.	BALLS size in.	WT. lbs.
DUPLEX									
MM9306WI-2 DU E-8842	.7874	.00015	[illegible]	[illegible]	1.2500	.0001	15	¼	—
MM9308WI-2 DU E-8842 ②	.9385	.00015	[illegible]	[illegible]	1.2500	.0001	21	¼	—
MM9310WI-2 DU E-8842	1.5000	.0002	[illegible]	[illegible]	1.2500	.0001	24	¼	—
MM9311WI-3 DU E-8842	1.7510	.0002	[illegible]	[illegible]	1.2500	.0001	26	¼	—
MM9313WI-5 DU E-8842	2.2500	.0002	[illegible]	[illegible]	1.2500	.0001	32	¼	—
MM9316WI-3 DU E-8842	3.0000	.0002	[illegible]	[illegible]	1.2500	.0001	41	¼	—
MM9321WI-3 DU E-8842	4.0000	.00025	[illegible]	[illegible]	1.7500	.0001	37	⅜	—
QUADRUPLEX									
MM9306WI-2 QUAD E-8809	.7874	.00015	[illegible]	[illegible]	2.5000	.0001	15	¼	—
MM9308WI-2 QUAD E-8809	.9385	.00015	[illegible]	[illegible]	2.5000	.0001	21	¼	—
MM9310WI-2 QUAD E-8809	1.5000	.0002	[illegible]	[illegible]	2.5000	.0001	24	¼	—
MM9311WI-3 QUAD E-8809	1.7510	.0002	[illegible]	[illegible]	2.5000	.0001	26	¼	—
MM9313WI-5 QUAD E-8809	2.2500	.0002	[illegible]	[illegible]	2.5000	.0001	32	¼	—
MM9316WI-3 QUAD E-8809	3.0000	.0002	[illegible]	[illegible]	2.5000	.0001	41	¼	—
MM9321WI-3 QUAD E-8809	4.0000	.00025	[illegible]	[illegible]	3.5000	.0001	37	⅜	—

① See "Width Tolerances," page 12.

② MM9308WI-3 same as MM9308WI-2 except for .9843 bore.

EXTRA – PRECISION BEARINGS
ABEC-7

BALL SCREW SUPPORT SERIES

PHYSICAL CHARACTERISTICS • LOAD RATINGS

BEARING NUMBER	AXIAL SPRING CONSTANT $\times 10^6$ lbs./inch	DRAG TORQUE OF PRELOADED SET inch lbs.	THRUST LOAD RATING (C_a) lbs.	LIMITING THRUST CAPACITY (T_L) lbs.
DUPLEX				
MM9306WI-2DU	4.76	3	3200	4700
MM9308WI-2DU	6.7	4	3700	6500
MM9310WI-2DU	8.34	4	3900	7500
MM9311WI-3DU	9.80	5	4000	8200
MM9313WI-5DU	11.6	7	4200	10000
MM9316WI-3DU	14.3	9	4800	12900
MM9321WI-3DU	16.7	12	9500	26100
QUADRUPLEX				
MM9306WI-2QUAD	10	6	5600	9400
MM9308WI-2QUAD	13.3	7	6400	13000
MM9310WI-2QUAD	19.6	8	6900	15000
MM9311WI-3QUAD	22.2	10	7000	16400
MM9313WI-5QUAD	25.0	14	7140	20000
MM9316WI-3QUAD	30.8	18	8500	25800
MM9321WI-3QUAD	36.4	24	16500	52200

Note: For life and load calculations, use X and Y factor given below:

X_1, X_2 & Y_1, Y_2 Factors

$X_1 = 1.90$	$Y_1 = .54$
$X_2 = .92$	$Y_2 = 1.00$

life calculation

The 90% survival life of ball bearings may be calculated from the relation:

$$L = \frac{50000}{N}\left(\frac{C_a}{T_E}\right)^3$$

where: L = life in hours
N = speed of application in rpm
C_a = basic load rating in lbs. at 33⅓ rpm
T_E = equivalent thrust load in lbs.

equivalent thrust load (T_E)

$$\left.\begin{array}{l} T_E = X_1 R + Y_1 T \\ T_E = X_2 R + Y_2 T \end{array}\right\} \text{whichever is greater}$$

where: T_E = equivalent thrust load in lbs.
R = radial load on bearing in lbs.
T = thrust load on bearing in lbs.
X_1 and X_2 = radial load factors
Y_1 and Y_2 = thrust load factors

	SHAFT & HOUSING DIMENSIONS				SHOULDER DIMENSIONS			
	BEARING BORE	SHAFT	BEARING O.D.	HOUSING	BEARING SIZE	SHAFT ±.005	HOUSING ±.005	FILLET RADIUS (max.)
MM9306WI-2	.78740 .78725	.7873 .7871	1.8504 1.8502	1.8507 1.8504	MM9306WI-2	1.078	1.636	.024
MM9308WI-2	.93850 .93835	.9384 .9382	2.4409 2.4407	2.4412 2.4409	MM9308WI-2	1.316	2.174	.024
MM9310WI-2	1.5000 1.4998	1.4998 1.4996	2.8346 2.8344	2.8349 2.8346	MM9310WI-2	1.860	2.474	.024
MM9311WI-3	1.7510 1.7508	1.7508 1.7506	3.0000 2.9998	3.0003 3.0000	MM9311WI-3	2.052	2.667	.024
MM9313WI-5	2.2500 2.2498	2.2498 2.2496	3.5433 3.5431	3.5436 3.5433	MM9313WI-5	2.572	3.191	.024
MM9316WI-3	3.0000 2.9998	2.9998 2.9995	4.3307 4.3304	4.3311 4.3307	MM9316WI-3	3.375	3.995	.024
MM9321WI-3	4.00000 3.99975	3.9998 3.9995	5.7087 5.7083	5.7091 5.7087	MM9321WI-3	4.413	5.296	.039

FAFNIR
BEARINGS

appendix

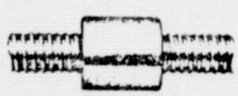
lecting A Standard Precision Ball Bearing Screw

SPECIFICATIONS

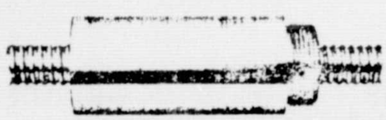
Model Number	P-0405	P-0410	P-0610	P-0805	P-0810	P-1210	G-0705	G-1004	G-1205	G-1505	G-1504	G-2005	G-2004	G
Rated Dynamic Load (lbs)* @ 100.000 " travel	31	39	84	46	98	127	4 460	7 500	6 270	7.080	9 820	8 600	11 900	
@ 1.000.000 " travel	15	18	39	22	46	59	2 072	3.480	2 912	3.290	4 560	3 984	5 523	
@ 10.000.000 " travel	–	–	–	–	–	–	962	1.615	1.352	1.527	2.117	1.849	2.564	
Rated Static Load (lbs)	170	170	370	370	530	800	16.000	25 600	26.700	32.000	38.400	42 600	51.300	1
Screw Diameter (inches)	250	250	375	500	500	750	750	1 000	1 250	1 500	1 500	2 000	2 000	2
Lead (inches)**	050	100	100	050	100	100	200	250	200	200	250	200	250	[illegible]
Maximum Standard Length	See Critical Speed Curves. page 13. and Column Load Curves. page 12 for maximum desirable length for your application													
Nominal Backlash (inch (non-preloaded)	002	002	004	002	004	004	007	009	007	007	009	007	009	

		P models	G models
Accuracy		Standard: 0 0005 inch per foot cumulative	Available in four standard accuracies 0 0002 inch per foot cumulative. 0 001 inch per foot cumulative. 0 006 inch per foot cumulative
Material	Screw	17-4 PH Stainless Steel	4150 HVDS aircraft quality vacuum degassed steel
	Nut	17-4 PH Stainless Steel	8620 HVDS aircraft quality vacuum degassed steel
Hardness	Surface	38-45 Rockwell C	56-62 Rockwell C
	Core	38-45 Rockwell C	25-35 Rockwell C
Finish		32 microinch normal	32 microinch normal. Also available if desired with phosphate coat black
Temperature Range (° F)		−100° F to + 200° F	−100° F to + 300° F

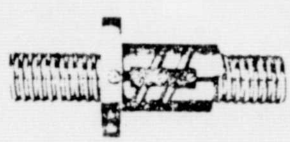
Nuts



Single Nut



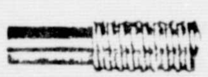
Double nut preloaded housing



Single Nut

Double Nut Preloaded

Ends



Universal End

For Single Bearing

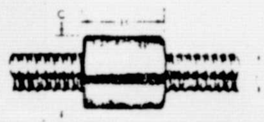
For Duplexed Bearings

* For preloaded units refer to chart, page 11.

** Right hand thread standard. Left hand thread available on request.

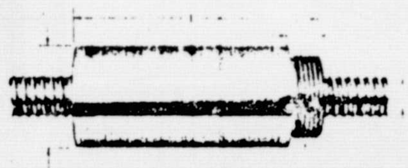
Dimensions: Series P

Single Nut Non-Preloaded



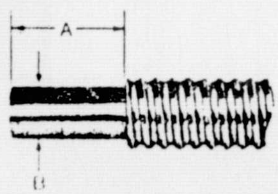
Model No	A Inches	B Inches	C Inches	Nominal Backlash (inch)
P-0405	250	687	5625	.002
P-0410	250	875	5625	.002
P-0610	375	937	.7500	.004
P-0805	500	737	8437	.002
P-0810	500	937	9062	.004
P-1210	750	937	1.2500	.004

Double Nut Preloaded Housing



Model No	A Inches	B Inches	C Inches	D Thread	E Inches
P-0405	.250	2.093	.750	11/16-24 UNEF-2A	31
P-0410	250	2.468	.750	11/16-24 UNEF-2A	31
P-0610	375	2.687	1.000	13/16-20 UNEF-2A	.37
P-0805	500	2.281	1.093	15/16-20 UNEF-2A	37
P-0810	500	2.718	1.187	1-20 UNEF-2A	37
P-1210	.750	2.750	1.500	1-5/16-18 UNEF-2A	37

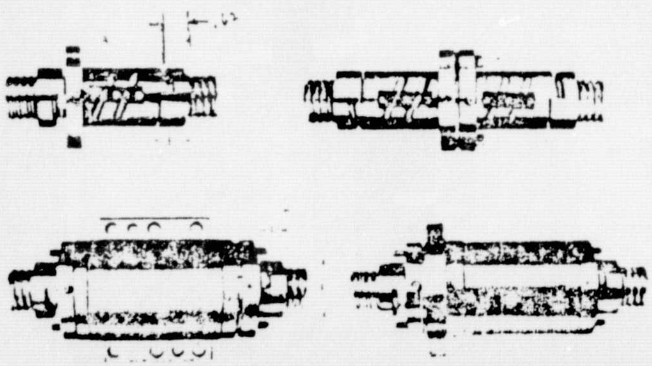
Universal End



Model No	A Inches	B Inches
P-0405	.500	.1876/.1873
P-0410	500	.1876/.1873
P-0610	.750	2501/.2498
P-0805	.750	.3751/.3748
P-0810	.750	.3751/.3748
P-1210	1.000	5002/.4999

Dimensions: Dog Stops

When using dog stops, determine ball thread length by adding desired travel to dimensions shown.



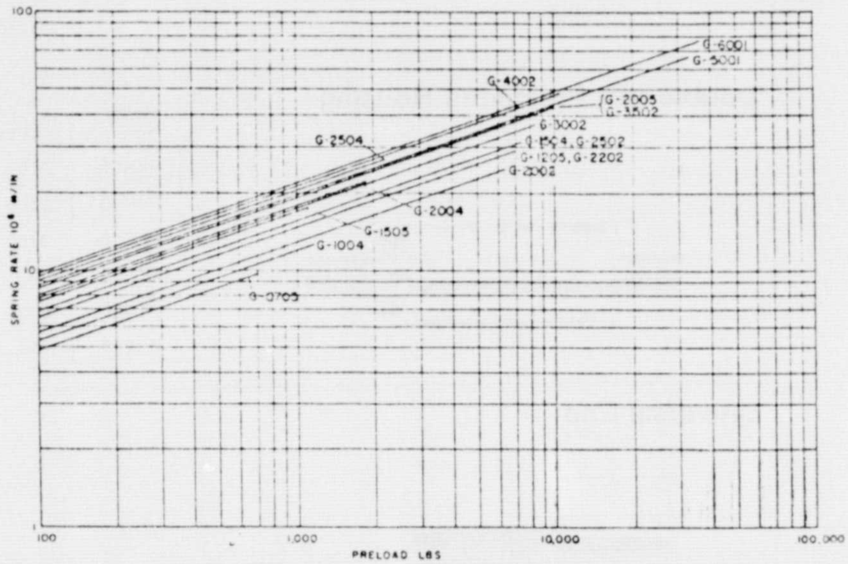
Model No	A	B	C	D	E	F
G-0705	3.65	6.06	6.25	6.25	.53	1.12
G-1004	4.34	7.25	7.43	7.43	.59	1.43
G-1205	4.12	6.75	6.93	6.93	.53	1.62
G-1505	4.37	7.00	7.15	7.15	.65	1.93
G-1504	4.75	7.75	8.00	8.00	.71	2.00
G-2005	4.75	7.37	7.50	7.50	.78	2.43
G-2004	5.12	8.12	8.37	8.37	.81	2.50
G-2002	7.75	13.00	13.50	13.50	.93	3.18
G-2202	7.75	13.00	13.50	13.50	93	3.43
G-2504	5.12	8.12	8.37	8.37	.81	3.06
G-2502	7.62	12.87	13.37	13.37	.93	3.68
G-3002	7.62	12.87	13.37	13.37	.93	4.18
G-3502	8.25	13.50	14.00	14.00	1.06	4.68
G-4002	9.06	14.50	15.12	15.12	1.18	5.18
G-5001	15.06	25.25	25.87	25.87	1.50	7.43
G-6001	15.06	25.25	25.87	25.87	1.62	8.43

Selection Factors

SPRING RATE

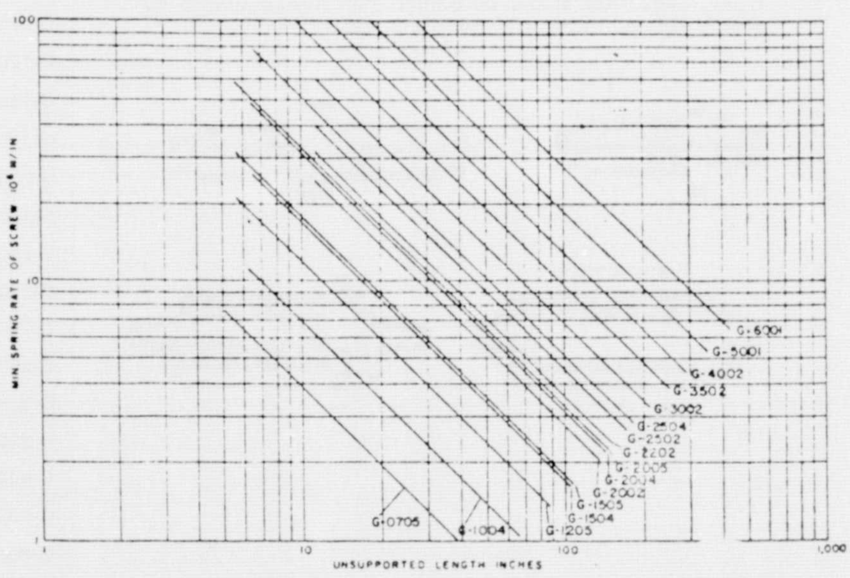
Spring Rate vs. Preload

Spring rate (in millions of pounds per inch) is the applied load divided by the linear deflection of the ball nut under that load. This chart gives the rate for each Beaver Precision Standard ball bearing screw set at a preload of one-third the working load.

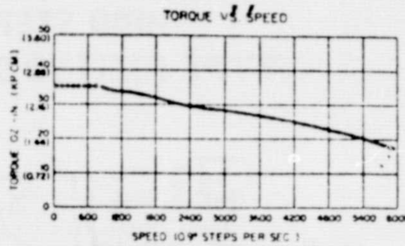


Spring Rate vs. Length

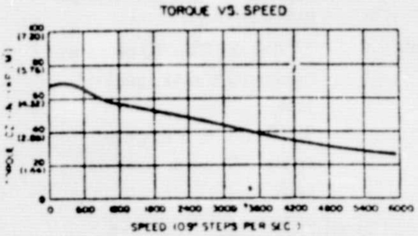
This chart shows the spring rate of each Beaver Precision Standard ball bearing screw considering the screw only as a bar under compression or tension loading. The values are based on thrust bearings at both ends. If bearings are used at one end only, divide values by four. Center of ball nut package is considered as mounting on one end or the other.



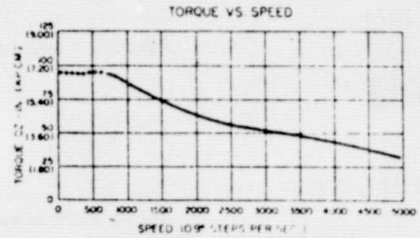
SPEED VS. TORQUE CHARACTERISTICS
STM103 TRANSLATOR MODULE AND
PIM153 PRESET INDEXER MODULE



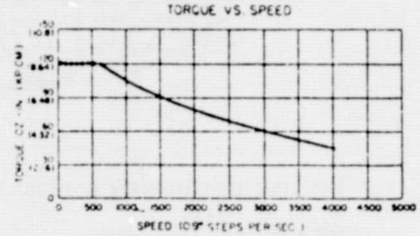
M061-FC08 or M061-FD08 MOTOR
HALF-STEP MODE



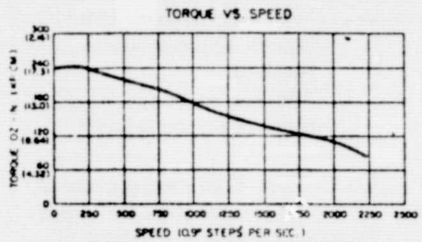
M062-FC09 or M062-FD09 MOTOR
HALF-STEP MODE



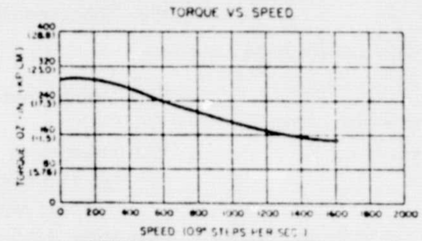
M063-FC09 or M063-FD09 MOTOR
HALF-STEP MODE



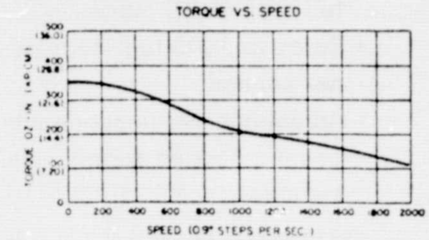
M091-FC09 or M091-FD09 MOTOR
HALF-STEP MODE



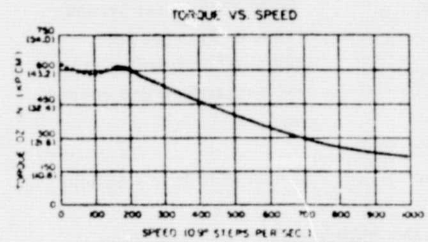
M092-FC09 or M092-FD09 MOTOR
HALF-STEP MODE



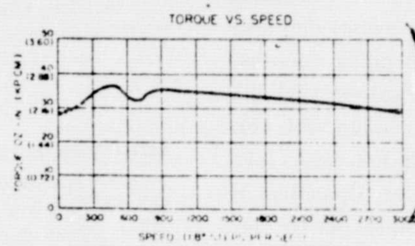
M093-FC11 or M093-FD11 MOTOR
HALF-STEP MODE



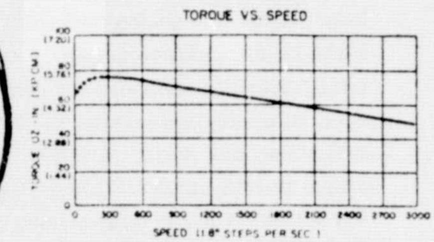
M111-FD12 MOTOR
HALF-STEP MODE



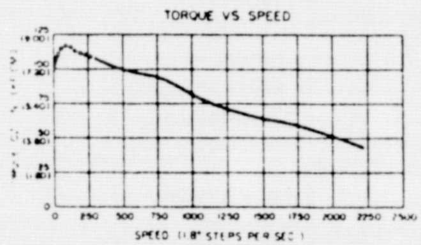
M112-FD12 or M112-FJ12 MOTOR
HALF-STEP MODE



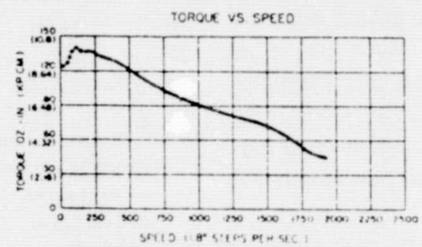
M061-FC08 or M061-FD08 MOTOR
FULL-STEP MODE, TWO WINDINGS ON



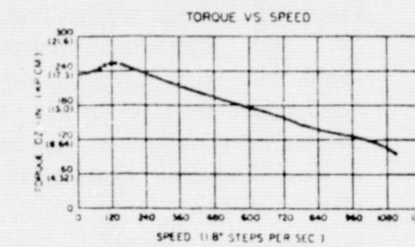
M062-FC09 or M062-FD09 MOTOR
FULL-STEP MODE, TWO WINDINGS ON



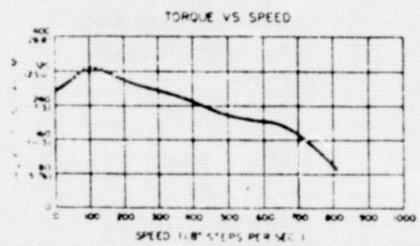
M063-FC09 or M063-FD09 MOTOR
FULL-STEP MODE, TWO WINDINGS ON



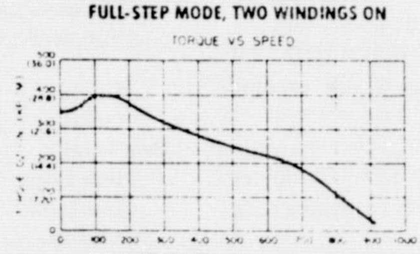
M091-FC09 or M091-FD09 MOTOR
FULL-STEP MODE, TWO WINDINGS ON



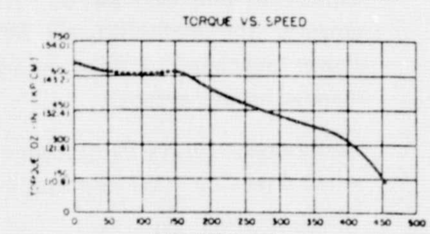
M092-FC09 or M092-FD09 MOTOR
FULL-STEP MODE, TWO WINDINGS ON



M093-FC11 or M093-FD11 MOTOR
FULL-STEP MODE, TWO WINDINGS ON

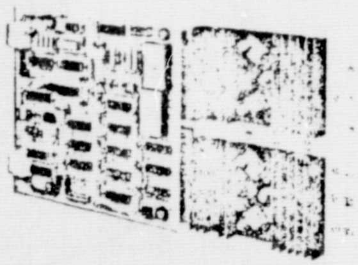


M111-FD12 MOTOR
FULL-STEP MODE, TWO WINDINGS ON



M112-FD12 or M112-FJ12 MOTOR
FULL-STEP MODE, TWO WINDINGS ON

3000 STEP PER SECOND MOTOR CONTROL
TYPE PIM153 SLO-SYN® PRESET INDEXER MODULE



- **Precise positioning control of SLO-SYN Stepping Motors**
- **Drive SLO-SYN motors in half-step (0.9°) or full-step (1.8°) mode**
- **Rates to 3000 full-steps or 6000 half-steps per second**
- **Adjustable acceleration and deceleration**
- **Count selection from simple BCD logic switches**

The PIM153 preset indexer module is a single printed circuit board which incorporates the translator functions of sequencing and switching logic and also includes an internal oscillator and pulse counting circuitry to provide complete control of the stepping rate, direction and number of steps taken. The unit will drive the motor in either the full-step (1.8° steps) or half-step (0.9° steps) modes. Operation in the half-step mode allows finer positioning resolution with no sacrifice in positioning speed.

External BCD logic switches (not supplied) are used for count insertion. Switches such as BCD thumbwheel types containing 5-digits plus the direction function are ideal for this purpose. Other input data includes Index Start, Run and Single-Step Jog. A "Count Complete" signal is issued upon completion of motor motion.

The PIM153 requires an external power supply capable of providing 24VDC, 10 ampere/5VDC, 1 ampere. The MPS3000 and MPS3000X SLO-SYN Power Supplies described on page 7 are recommended for this purpose.

Performance curves for appropriate SLO-SYN motors when driven by PIM153 preset indexer modules are shown on page 11.

SPECIFICATIONS

Board Dimensions	5¾" (146mm) x 11" (279mm)
Edge Connector (Supplied)	36-pin, Elco part number 00-6114-036-433-001; Superior Electric part number BM144878-G1
Required Power Supply	24VDC ±10%, 10 amperes, ripple: 10% max. peak-to-peak 5VDC ±5%, 1 ampere, ripple: 2% max. peak-to-peak
Temperature Range	operating: 0°C to +50°C storage: −55°C to +85°C
Internal Oscillator Range	0 to 6000 pulses per second
High Speed Control	500K ohm, ten-turn, CCW logarithmic potentiometer (supplied)
Base Speed Control	10K ohm, single-turn, linear potentiometer (supplied)
High Speed Range	
Full-Step Mode	100 to 3000 steps per second
Half-Step Mode	200 to 6000 steps per second
Base Speed Range	
Full-Step Mode	0 to 1000 steps per second
Half-Step Mode	0 to 2000 steps per second
Oscillator Stability	±10% or 20 steps per second, whichever is greater, over temperature and voltage range
Acceleration/Deceleration Range (Adjustable)	50 milliseconds to 1 second
External Functions	
Index Start, Run, Jog, High Speed:	
High Level	open circuit, +10VDC to +20VDC
Low Level	0 to 1.7VDC
Loading	10 mA sink max.
Pulse Width	20 milliseconds min.
Rise and Fall Times	1 millisecond max.
Bounce (Settling Time)	10 milliseconds max.
Stepping Mode Selection Controls:	
High Level	2VDC to 5.25VDC
Low Level	0 to 0.5VDC
Loading	2 mA sink max.
Count Complete Signal:	
High Level	open collector rated 30VDC max., clamped to 24VDC
Low Level	0 to 1VDC
Loading	100 mA sink max.
Clear Signal:	
High Level	2VDC to 5.25VDC
Low Level	0 to +0.5VDC
Loading	7 mA max.
Minimum Duration	20 milliseconds

3000 STEP PER SECOND MOTOR CONTROL

Count Insertion:
- Method . . . . external BCD logic switches (customer supplied) or voltage levels
- Maximum Count . . . . . . 99,999 motor steps

Number Insertion Lines:
- High Level. . . . . open circuit, +10VDC to +20VDC
- Low Level . . . . 0 to 1.7VDC
- Loading. . . . . 10 mA sink max.
- Rise and Fall Times . . . . 100 microseconds max.

Data Input Command Lines:
- High Level. . . . . open collector, rated at 30VDC
- Low Level . . . . 0 to 0.7VDC
- Loading. . . . . 40 mA sink max.

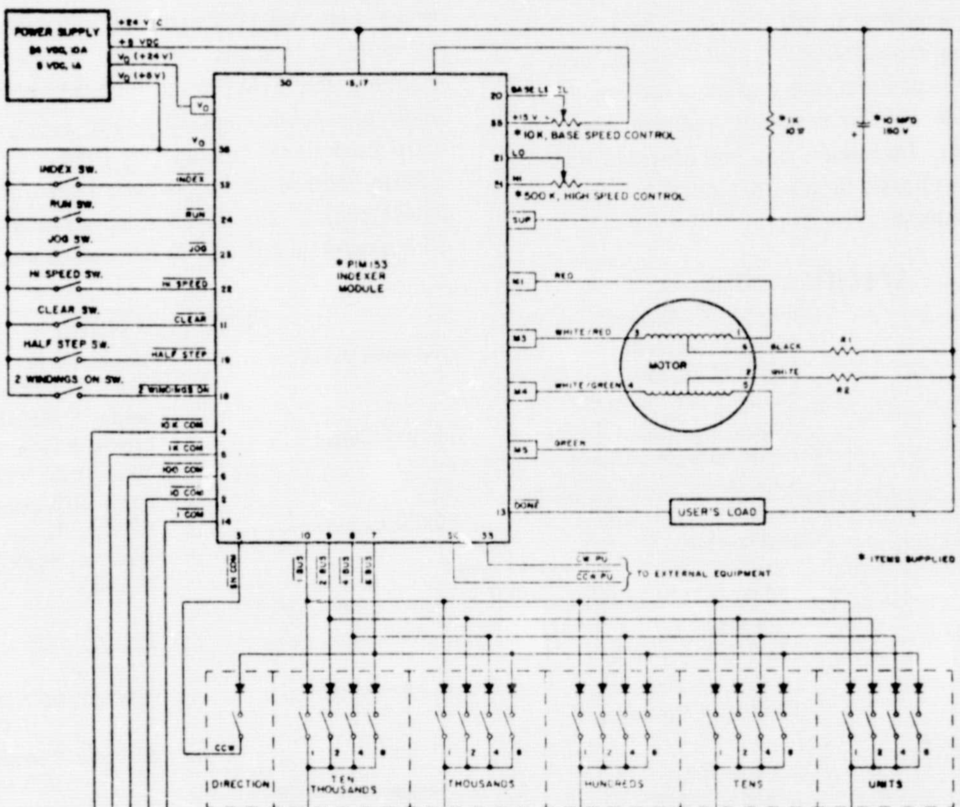
Directional Pulse Output:
- High Level. . . . . open collector, rated at 30VDC
- Low Level . . . . 0 to 0.8VDC
- Loading. . . . . 5 mA sink max.

Motor Compatability . . . . drives M061 through M112 motors (using appropriate series resistors)

Stepping Mode . . . . full-step, one winding or two windings on, 2-phase, bifilar; half-step, 2-phase, bifilar

DROPPING RESISTORS

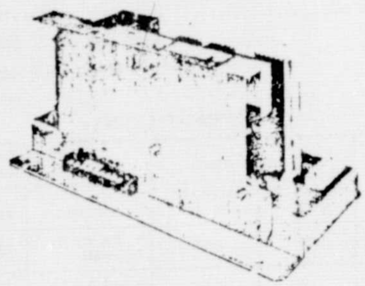
MOTOR	STEP INCREMENT		DROPPING RESISTOR (2 REQUIRED)	
	HALF-STEP MODE	FULL-STEP MODE	RATING	PART NUMBER
M061-FC08 M061-FD08	0.9°	1.8°	6 ohm ±5%, 100 watt	DR103788-G9
M062-FC09 M062-FD09	0.9°	1.8°	4.5 ohm ±5%, 160 watt	BM133832-G6
M063-FC09 M063-FD09	0.9°	1.8°	4.5 ohm ±5%, 160 watt	BM133832-G6
M091-FC09 M091-FD09	0.9°	1.8°	4.5 ohm ±5%, 160 watt	BM133832-G6
M092-FC09 M092-FD09	0.9°	1.8°	4.5 ohm ±5%, 160 watt	BM133832-G6
M093-FC11 M093-FD11	0.9°	1.8°	4 ohm ±5%, 160 watt	BM133832-G9
M111-FD12	0.9°	1.8°	4.5 ohm ±5%, 160 watt	BM133832-G6
M112-FD12 M112-FJ12	0.9°	1.8°	4 ohm ±5%, 160 watt	BM133832-G9



CONNECTION DIAGRAM
PIM153 PRESET INDEXER MODULE

SLO-SYN® POWER SUPPLIES FOR TRANSLATOR MODULES AND PRESET INDEXER MODULES

TYPES MPS1000 and MPS1000X



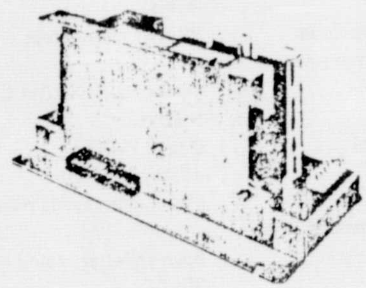
- For use with STM101 Translator Module or PIM151 Preset Indexer Module
- STM101 or PIM151 can be mounted on power supply to form a single unit

The MPS1000 and MPS1000X are open chassis, base mounting power supplies which have output voltage and current ratings compatible with STM101 translator modules and PIM151 preset indexer modules. The power supply chassis has provisions for mounting the STM101 or PIM151 to form a single unit. If desired, the translator or preset indexer module can be mounted separate from the power supply. Terminal strips are provided on the power supply chassis for all a-c input, d-c output and motor connections.

SPECIFICATIONS

Dimensions	length: 17" (432mm) width: 8" (203mm) height: 8" (203mm)
24VDC Output	24VDC ±10%, up to 6 amperes maximum ripple: 10% peak-to-peak
5VDC Output	5VDC ±5%, up to 1 ampere, maximum ripple: 2% peak-to-peak
Power Input	
MPS1000	120VAC ±10%, 60 hertz, 3 amperes
MPS1000X	220/240 VAC +10%, −15% 50 hertz, 1.5 amperes
Temperature Range	
Operating	0°C to +50°C
Storage	−55°C to +85°C
Approximate Weight	
MPS1000	20 pounds
MPS1000X	25 pounds

TYPES MPS3000 and MPS3000X



- For use with STM103 Translator Module or PIM153 Preset Indexer Module
- STM103 or PIM153 can be mounted on power supply to form a single unit

SLO-SYN Power Supplies types MPS3000 and MPS3000X have voltage and current ratings compatible with the STM103 translator module and PIM153 preset indexer module. The power supplies are of open chassis design and are designed for base mounting. Provisions are made on the chassis for mounting the STM103 or PIM153 unit to form a single unit combining both power supply and motor drive control. If desired, the translator or preset indexer module can be mounted separate from the power supply. The power supply has terminals for all a-c input, d-c output and motor connections.

SPECIFICATIONS

Dimensions	length: 17" (432mm) width: 8" (203mm) height: 8" (203mm)
24VDC Output	24VDC ±10%, up to 10 amperes, maximum ripple: 10% peak-to-peak
5VDC Output	5VDC ±5%, up to 1 ampere maximum ripple: 10% peak-to-peak
Power Input	
MPS3000	120VAC ±10%, 60 hertz, 5 amperes
MPS3000X	220/240VAC +10%, −15% 50 hertz, 3 amperes
Temperature Range	
Operating	0°C to +50°C
Storage	−55°C to +85°C
Approximate Weight	
MPS3000 and MPS3000X	25 pounds