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PRACTICAL EXPERIENCES WITH WORM GEARING FOR SPACECRAFT POWER TRANSMISSION APPLICATIONS

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ABSTRACT

Experiences of several organizations using worm gearing for spacecraft power transmission are discussed. Practical aspects and subtleties of using worm gearing in a space environment are covered. An overview of advanced considerations for design and operation is included. Knowledge gained from these applications is analyzed, and guidelines for usage are proposed.

INTRODUCTION

Worm gearing is often specified for spacecraft mechanisms because it offers moderate reduction ratios in a single gear stage with 90-deg shaft orientation, and because it is backdrive resistant. Worm gearing is one of the smallest, lightest gear-reduction methods available, and can also withstand high shock loads. With these advantages, worm gearing seems to be an obvious choice for spacecraft mechanisms.

Worm gearing, however, is not simple in nature. The same attributes that give worm gearing its unique features also act to its disadvantage. By transferring all power through a sliding interface, power transmission efficiency and predictability can be adversely effected by many factors, most of which act through increased sliding friction. Lubrication of this interface is the single most important part of any worm gear system.

Lubrication in the contact interface is sensitive to many design, operational, and environmental factors. The effects of tooth geometry, mounting, materials and finishes, lubrication, loads, rubbing speeds, temperatures, and vacuum, influence gearset output. With so many variables, no two worm system applications tend to be exactly alike. Drive efficiency can be difficult to predict, obtain, and maintain, and often requires a trial-and-error test process to produce acceptable levels.

Spacecraft worm gear systems have the additional challenges of working with compromised lubrication in extreme environments while being required to work at low to stall speeds. Worm gearing has a mixed history of success and failure in spacecraft mechanisms due to demands beyond those of industrial speed reducers. Stock gearing and speed reducers generally rely on copious lubrication, benign environment, non-critical weight, moderate loads and speeds, and maintenance availability. Most successful applications undergo

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interactive development to achieve adequate levels of performance. The purpose of this paper is to help spacecraft mechanism users and designers achieve the advantages inherent in worm gearing by investigating several practical experiences, and by showing the finer points of worm gearing technology.

OPERATIONAL BASICS OF WORM GEARING

Most texts do not describe the complex nature of the worm gear interaction. A review is beneficial before analyzing applications and recommending guidelines for spacecraft use. Single enveloping, 90-deg worm gear systems will be addressed.

The sliding motion between worm and gear forms lines of contact across the faces of the worm thread and gear teeth, as shown in Figure 1. These contact lines continually move and change shape through the engagement of a single thread and tooth. Individual points on these lines have both lateral and radial movement relative to the gear. Lateral movement effects rubbing speed while radial movement changes the shape and position of the contact line. The worm usually contacts the gear on several teeth simultaneously. The shape and movement, or gear action, of the contact lines is controlled by the pressure angle, lead angle, and other geometric constraints.

Lateral sliding works to deplete lubricant from the gear interface. This depletion process is modified by the orientation and shape of the contact line. When there is a substantial radial component of the line shape, a wedge of lubricant tends to be pushed ahead of the laterally advancing contact line.

Standard gearsets feature approach and recess gear action. Approach action occurs during early engagement between the worm and the gear as the line of contact moves from the tip area toward the root of the gear tooth. Recess action follows as the gear tooth recedes from engagement, and movement of the contact line reverses direction, heading back toward the tip of the tooth.

Forces and sliding characteristics can vary greatly between approach and recess phases. When coupled with lateral sliding and grease lubrication, gear action can act as a squeegee to remove lubricant from the face of the gear. This effect can be minimized by control of lubrication, contact stresses, contact forces and directions, gear action, contact line shape, rubbing speeds, and cycle duration.

The relationship between lead and pressure angles and efficiency is not obvious. Despite low angles describing a shallow wedge and increasing mechanical advantage, efficiency is reduced because sliding action increases, resulting in lubricant depletion. Increased lead and pressure angles can reduce this sliding, thus reducing lubrication degradation and increasing drive efficiency.

The coefficient of sliding friction in the thread/tooth interface is a large factor in the mechanical efficiency of a worm gear system. Efficiency prediction is difficult at best for worm gearing. Many efficiency equations are available which do not consider lubricant-starved conditions. Predictability and control of the efficiency mandates good lubrication of this sliding interface. Efficiencies should be verified by test, as worm gearing does not deliver precise outputs, especially for low speed and stall applications.

Adequate lubrication is usually the key to a successful worm gear system. Examination of the action between the tooth and thread shows the harsh environment in which a lubricant must succeed.

PRACTICAL EXAMPLES

A discussion of several different applications provides insight into the behavior of worm gearing in spacecraft mechanisms. Design, detail, and operating requirements for each system are presented in Table 1. Discussion of each example emphasizes operational characteristics, problems encountered and their causes, symptoms, and solutions. A comparison of the characteristics of each system shows the effects of design features and operating conditions on performance.

The following examples are presented:

1. Naval Research Laboratory (NRL)/Sundstrand; two similar worm gear systems in a single ballscrew actuator

2. NASA Goddard; double enveloping worm gear system in latch mechanism

3. Astro Aerospace; worm gear systems used for drive and braking of deployable masts

4. Rexnord Aerospace Mechanisms (RAM); worm gear set in latch drive.

NRL/SUNDSTRAND WORM GEARING IN BALLSCREW ACTUATOR

Requirements and Design

Two similar worm gear systems were used to drive a ballscrew actuator built by Sundstrand Corporation in conjunction with the Naval Research Laboratory for a spacecraft application. The first gearset, referred to as the primary system, had an 86:2 ratio and consisted of a 20.2 mm (0.797 in.) diameter steel worm and beryllium copper gear. There were two of these type worm gear systems in the actuator called the primary and back-up drives. The second type of system, called the emergency system, was on a redundant drive for the first two systems. This gearset consisted of a two-start worm of the same design as the primary system, and a 58-tooth gear cut into a steel ballnut, called the emergency drive. The actuator was required to drive under a constant load for 15 min, generate a sufficient stall load, then reverse its cycle. The emergency system had to drive against constant load for 30 min.

In addition to the requirements of Table 1, another requirement was that neither system could produce more than 580 in.-lb. This maximum output requirement severely limited the amount of torque margin that could be designed into the drive train.

Discussion

The two systems operated as designed in ambient air, ambient vacuum, and hot vacuum testing. All systems demonstrated an unexpected failure mode during cold vacuum qualification testing. The actuator would start a cycle working normally but would gradually slow down during the cycle, indicating increasing torque demand on the drive motor. The emergency and one of the primary systems would actually slow down to the point of stall under a constant load. After much investigative testing it was shown that the efficiency of the worm gearing was dropping over time. The worm gear system efficiency has to drop to approximately 12 percent for the primary drive to stall in these conditions and to 19 percent for the emergency system to stall. This is a very low efficiency as compared to the 40 percent efficiency the systems demonstrated in ambient tests and at the start of each cold vacuum cycle. Design calculations predicted efficiency to be between 47 and 62 percent.

This decay was severe in cold vacuum conditions, minimal in ambient vacuum conditions, and nonexistent in hot vacuum and ambient conditions. The severity of the decay varied for each system and for each drive direction of each system. The cause was shown to be lubrication depletion in the worm gearing. The decay, and therefore the lubrication problem, was not permanent. Whenever the actuator was retested in cold vacuum, it exhibited the same behavior of starting well and then decaying. This decay problem was eliminated by switching from Braycote 601 to Braycote 608 grease for the worm gear lubrication. This fix was demonstrated only on the emergency system, although it is expected to succeed on the primary systems also.

The decay phenomenon was attributed to a gradual wiping away of the grease, with the poor efficiency demonstrating a weakness in the boundary lubrication regime. The MoS_2 bonded dry-film lubricant applied to the gear teeth wore off the driving surfaces during run-in, and provided no lubrication during operation. The manner in which the 608 grease solved the problem is not fully understood, because it has two major differences from 601 grease. The 608 grease has MoS_2 added, which could be improving the boundary lubrication. The 608 grease also has much higher oil content, which could help the healing process of lubricant after it has been wiped away. It has not been determined whether the problem was solved by either one or both of these changes.

The decay was strongly affected by temperature and load. In cold vacuum, the actuator did not slow down under a moderate load (approximately 1/3 of the maximum required load). However, the stall load generated at the end of this cycle was unacceptably low. Decay could not be detected during no-load, cold vacuum operation of the actuator and the stall load generated at the end of this cycle was normal. Decay in ambient vacuum was minimal to nonexistent, depending on the system tested.

An interesting discovery was the healing ability of the worm gear system lubrication. The primary systems would show normal efficiency when restarted after they had been turned off for a 20 min period after decaying to stall. A graph of the typical speed-versus-time characteristic in cold vacuum testing is shown in Figure 2. The figure covers two cycles showing the healing effect.

After disassembly and reassembly of the worm gear system, with no change to the grease other than slight smearing during disassembly, the actuator's performance was much improved, but only temporarily. After two cycles the performance had returned to its normal problems. This demonstrates a high sensitivity to lubrication in harsh operating conditions.

All of these symptoms show that worm gearing efficiency can be very sensitive to small factors when used in harsh conditions. Lubrication with Braycote 601 grease was found to be ineffective only in cold vacuum conditions, while Braycote 608 was always successful. The non-permanent decay observed was the significant symptom of worm gear problems in this application.

NASA-GODDARD CONE DRIVE SYSTEM

Requirements and Design

At the Goddard Space Flight Center, a 50:1 cone drive (double enveloping) worm gear system was used to drive an over center latch for a Shuttle payload capture mechanism. The worm gear drives for approximately 10 sec against a torque that increases to a peak at the 6 deg before center position. The worm is driven by a motor with a peak torque at stall of 27.5 Nm (250 in.-lb), and has a requirement to produce a minimum 339 Nm (3000 in.-lb) peak output at the gear. The system must operate from -70^{o}C to +70^{o}C in a vacuum environment.

The reduction ratio was changed from 50:2 to 50:1, after galling and poor efficiency were observed in cold vacuum testing of a development motor/worm gear system. The development system was lubricated with Braycote 601, which was changed to a mixture of 50 percent Braycote 802EP grease and 50 percent Braycote 815Z oil for the final system. The 802EP grease is different from the 601 in that it contains a molybdenum disulfide based compound, and it is based on a different oil than the 601, which is based on 815Z oil. The system was designed to operate properly with a worm gear efficiency of 40 percent.

Discussion

The final system operated as designed between -50°C and +70°C in thermal vacuum testing. Below -50°C, however, the worm gear efficiency was significantly lower, dropping as low as 21 percent at -70°C. Gear efficiencies in test were from 40 to 50 percent at ambient and hot vacuum conditions. With the system's ample torque margin, it barely passed its -70°C vacuum operation requirement. At this writing, the system has not yet been disassembled and examined for galling or other degradation.

Tests on the development system showed generally poor efficiency during operation below -10°C. The efficiency was anywhere from 5 to 50 percent lower than efficiencies measured at higher temperatures. The original system failed during these cold vacuum tests, having wiped bronze from the gear onto the worm. Data on torque versus speed at high and low temperatures showed that at low speed, high torque conditions, the efficiency was significantly lower and more inconsistent in the cold case. Data taken at low torque, higher speed conditions showed equal performance in hot or cold conditions.

Some important worm gear performance characteristics were demonstrated by this system. At extreme low temperature conditions, the worm gear efficiency dropped from normal efficiencies of 40 to 50 percent to 21 percent. The system was highly successful at temperatures above -50°C. As a result of development testing, the performance of the system was significantly improved by the switch to a wetter grease that contained MoS_2.

ASTRO WORM GEAR SYSTEM

Astro Aerospace has successfully used two worm gear systems as drives and governors in deployable masts. The worm gear systems are used as a drive to retract the mast and as a brake/governor when the mast deploys under its own spring energy. This paper will discuss the systems' characteristics only when used as a drive. Two systems used in this capacity are being examined. One system, detailed in Table 1, was a 30:1 ratio gear set with a 25.4 mm (1.000 in.) worm and 63.5 mm (2.500 in.) gear. The other system will not be discussed in detail. However, lubrication failed completely allowing massive gear tooth wear when a dry film lubricant was the sole lubricant. Following a switch to grease lubrication, the system was successful.

The first system mentioned had to produce an output torque of 4.8 Nm (42 in.-lb) for several minutes, after briefly producing a torque of 25 Nm (225 in.-lb). The system had to operate in vacuum at temperatures from -85°C to 70°C.

One of the most important aspects of this design is the grease lubrication and its application. A thin coat of Braycote 601 grease is used as the only lubricant for the worm gear set. The grease is applied before run-in, and then cleaned off, first using freon, and then toluene to remove freon residue after the run-in is finished. A thin film of grease is then applied in the final assembly.

This system performed successfully with no difficulties encountered. A critical factor in the success of this design is the ample torque margin of the drive motor at nominal loads. At nominal loads, the motors had greater than 6 to 1 torque margin, although there was only a 10 percent margin at peak output. It is important that the system succeeded at extremely cold temperatures as low as -85^{o}C.

REXNORD AEROSPACE MECHANISMS WORM-GEAR DRIVEN LATCH SYSTEM

Requirements and Design

A worm gear system is used in a rollerscrew latch used to clamp a connector system together. The gearset features a 40:1 ratio consisting of a 15.9 mm (0.625 in.) diameter steel worm, and an aluminum-bronze gear of 63.5 mm (2.500 in.) diameter. This system undergoes minimal loads for latch extension and engagement, then is driven under power to stall as the screw and nut tighten.

This system operates in vacuum at ambient temperatures, with a peak torque output of 12 Nm (107 in.-lb) with a maximum input torque of 2.0 Nm (18 in.-lb) available. Output load variance using governed motor power was limited to 10 percent in a life cycle test of 20 full actuations. Sliding velocities run from as great as 1.52 m/sec (60 in./sec) down to stall, going from high to low extremes in as little as 3 sec. Design details are listed in Table 1. Braycote 601 grease is applied to lubricate this system. Tungsten disulfide dry film is applied and is worn away during break-in.

Discussion

The drive system demonstrated a load degradation after 10 full load cycles, decreasing steadily to a 60 percent level at 20 cycles. Gear lubrication was found to be at fault, as re-lubrication brought back initial loads. A wiper system was installed to force grease back onto the gear teeth, eliminating the load decay, and providing successful operation.

Stall conditions under peak loading aggravated the tendency of the worm to wipe grease from the gear teeth. A healing effect was evident, but produced output loads of only 80 percent at best from previous, well lubricated runs.

COMPARISON OF EXAMPLES

NOTE: The system(s) demonstrating a characteristic are referenced by number.

1. NRL/-Sundstrand
2. NASA Goddard
3. Astro
4. Rexnord

All worm gearing problems encountered by the examined systems were caused by inadequate lubrication. Three of the systems (1,3,4) showed that Braycote 601 would do a fine job of lubricating when it was present in the tooth interface. The NRL system worked at the start of each cycle, the Astro system always worked, and the Rexnord system worked well with the addition of a wiper to force grease into the teeth. A switch to wetter greases containing moly-disulfide resulted in satisfactory lubrication in two examples (1,2).

In three instances (1,3,4), dry film lubricants were completely wiped off the worm and gear teeth. Two of the organizations (1,2) had problems only under cold, vacuum conditions. The symptoms of efficiency decaying over time, and healing of worm gear systems were observed on two of the examples cited (1,4), and also in one other system not discussed elsewhere in this paper.

In most cases, the mechanisms would have survived low efficiencies with motors having larger torque margins. Limitations on the output force often limited this option. The Goddard system benefitted from a motor and worm gear subsystem development test.

ADVANCED CONSIDERATIONS FOR WORM GEARING DESIGN

Beyond general guidelines (Table 2), worm gearing for spacecraft can benefit if additional aspects are considered. The optimization of gear interface lubrication is of primary importance to the function of the gearset. Secondary functions include techniques to augment this lubrication. The following areas of importance in worm gear design will be briefly discussed.

1. System Design

2. Lubrication

3. Actuation

4. Design, Analysis, and Geometry

5. Mounting

6. Materials and Finishes

7. Break-in and Development

8. Qualification Test and Flight.

Several of the topics to be presented require great expertise to implement. The authors do not possess this expertise and have therefore identified experts known to them in the field of the paper.

Systems Design

Before choosing worm gears for an application, their suitability must be assessed. Worm gearing does not lend itself well to precise outputs, low input power margins, very low speeds, redundant systems, high cycle life, and long duty cycles. Motor sizing should be able to accommodate low worm gear efficiencies, even as low as 10 percent. Component strength must accommodate high efficiencies, even as high as 95 percent. Worm gear systems can be very weight efficient, but if motor and component sizes must be oversized to accommodate uncertain efficiencies, the weight benefit quickly disappears. Development and good design are the keys to extracting all of the potential advantages of worm gearing.

Lubrication

The key element in worm gearing is interface lubrication. Most worm gearing failures reflect back to lubrication problems. The worm gear interface operates in boundary layer conditions. The choice of a lubrication scheme for worm gearing benefits greatly from development work.

Wet lubrication is almost always necessary for these harsh contacts, as dry film lubricants are typically worn away very quickly. The addition of moly-disulfide to the wet lubricant helps reduce friction in the boundary lubrication regimes present. Lubricant replenishment systems, such as wipers, are very helpful by replenishing the oil or grease scraped away by the rubbing contact. High oil content greases may be beneficial in cold operating environments. Tests are currently underway on lubricants specifically for spacecraft worm gearing by John Christian of Aerospace Lubricants, Inc., and Rick Scott of NASA-Goddard.

Actuation

Successful worm gearing becomes harder to attain when used in harsh duty cycles. Actuations should, if possible, be planned to overcome peak loads early in each cycle before lubrication has been worn down. High cycle life should be avoided, as well as long durations and very high and low rubbing speeds. Stalling at peak load should also be avoided, especially if it occurs in the same worm gear position on each cycle. This can lead to localized wear similar to a notching effect. Under repeated cycling, expect lubrication degradation to occur unless a relubrication system is employed.

Design, Analysis, and Geometry

Initial system design can be done with handbook formulas and catalog ratings if significant derating factors are used. This initial derating does not allow for reduced lubrication, but rather provides adequate envelope for later design changes.

Several approaches are used to design worm gearing for lubrication-critical applications. All of these use derating relative to terrestrial applications. These factors are somewhat empirical relative to the gear geometry approach used. Three methods found include: (1) standard geometry with high derating factors, (2) optimized recess action geometry, and (3) optimized contact stress reduction.

Standard geometry worm gearsets can benefit from high derating factors if rubbing duration is low, speeds are kept moderate, and lubrication is present. Factors of 2.5 for peak torque loads and 10 for nominal torque loads relative to commercial ratings have worked for short-term applications. Empirical values must be developed in test to establish derating values suitable to individual applications. This is a "brute force" approach that does not critically address weight or lubricant degradation.

Recess action geometry is a method favored by a number of experts including Eliot Buckingham of Buckingham Associates. A computer program and texts are available which aid in altering worm and gear geometry to put the entire contact interface into recess action, where friction is reduced and contact lines do not reverse direction. Speed reducer data indicates this to be a valid approach, but no examples were found for review in this paper.

Contact stress reduction between worm and gear extends life and can aid lubricant survivability. This method is proposed by Henry Minaisian of Grant Gear Company. A computer program is available on a consulting basis which predicts contact stresses on the tooth face of the gear. Using iteration, contact stress is lowered by increasing the contact area of the worm and gear, lowering relative curvatures between teeth, and modifying approach and recess action. An example of the results of this analysis is shown in Figure 3. Again, no spacecraft applications of this technique were available for review.

Other programs and consulting services are available from Ken Gitchel of Universal Technical Systems and consultant Henry Ryffel, Gear Section editor for Machinery's Handbook.

Mounting

Worm, gear, shaft, bearing, and housing stiffness must be adequate to preserve proper interface contact under load. Any deflection in the system that moves the contact interface away from the previously established contact zone will drive contact stresses up and degrade lubrication. The mounting should be very accurate to maintain the geometry specified by design and manufacture. A means for adjusting the location of the contact region during assembly and break-in should be provided.

Materials

Materials choice can be very difficult. While steel worms and bronze gears are most common, stainless steel worms and gears have been used in space, as well as steel, beryllium copper, and aluminum gears. Testing and experience are important to evaluate a material's suitability to each application.

Most spacecraft worm systems use steel worms and bronze gears with a hardness differential of 50 to 80 Brinnell points, so that the gear will wear in to conform to the worm. All worms should be of fine finish, preferably polished, before break-in.

Gear materials can vary widely depending on their application. Bronze gears are chosen because their wear and failure characteristics are generally more gradual than that of other materials. As a result of extensive testing, Robert Campbell, of Mueller Brass Company, recommends the proprietary Dynalloy 603 manganese bronze in a forged and heat-treated condition. Cast tin and nickel-tin bronzes also exhibit good properties in test.

As of this writing no data has been found on worm gear materials for vacuum use. It is assumed that terrestrial data is somewhat applicable in that grease lubricants are used. Leaded and molybdenum disulfide-impregnated bronzes have been tried but were found to have gear wear rates under moderate loads.

Break-in and Development Test

Break-in is considered the final machining operation for a worm gearset. Break-in should be run with abundant lubrication, starting at low loads and gradually progressing to a flight-like scenario. Break-in should always be run in final component form. Debris generation will occur during this phase, and must be removed prior to use. Care must be used to clean and reassemble exactly as the gearset was broken in.

The gearset should be set up to produce an even wear pattern on the leaving side of the gear tooth. This pattern will gradually progress across the face of the gear to include the entering side.

Separate gearset testing will determine the ability of the worm gear system to transmit adequate power. This testing should be run informally to resolve any difficulties before the design has been finalized.

Flight and Use

Characteristics of the gearset should be well known at this time. Despite this, problems may yet occur. As with many other complex devices, worm gearing benefits from practical experience, empirical knowledge, and plenty of backup test data. Recognize that eventually worm gears will degrade to the level of failure, but with good technique that point should be well beyond the life of the spacecraft.

CONCLUSIONS

Several key points should be understood by everyone involved with a worm gear application in a spacecraft mechanism.

1. Worm gearing is not simple. Knowledge, experience, and testing is necessary for superior performance.

2. Lubrication is a key factor.

3. The requirements typical of spacecraft mechanisms are often difficult for worm gearing to meet.

4. Proper design is necessary for good performance.

5. Worm gearing benefits from and often necessitates development testing and tuning to achieve predictable advantages.

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TABLE 1. SUMMARY OF DESIGN DETAILS AND REQUIREMENTS

DESIGN | REQUIREMENTS

SYSTEM TITLE	PITCH DIAMETER "Worm" Gear mm (in.)	NUMBER OF TEETH "Worm" Gear	DIAMETRAL PITCH in.(-1)	MATERIAL "Worm" Gear	SURFACE HARDNESS "Worm" Gear (Rock-well)	SURFACE FINISH "Worm" Gear micron (micro-in)	LUBRICANTS "Trade Name"	LEAD ANGLE Degrees -Minutes'	PRESSURE ANGLE Degrees	OUTPUT TORQUE PEAK Nm (in-lb)	OUTPUT TORQUE NOMINAL Nm (in-lb)	INPUT TORQUE PEAK Nm (in-lb)	RUBBING SPEED m/s (IN/SEC)	TEMP LOW/HIGH CELSIUS	DESIGN EFFICIENCY ESTIMATE (%)
NRL/SUND-STRAND PRIMARY	*20.2* 91.5 *(.797)* (3.603)	*2* 86	24	*9310 STL* BERYL COPPER per AMS 4650	*Rc 60* Rc36	*0.8* 1.6 *(32)* (63)	"Sandstrom LC 300" Dry Film "Bray 601"	6	20	9.5 (84) (full cycle) **15 minute cycle	2.8 (25) (full cycle)	1.8 (16)	.16 Max (6.3) 0 Min	-29 / 65	40 - 60
NRL/SUND-STRAND EMERGENCY	*20.2* 61.7 *(.797)* (2.43)	*2* 58	24	*9310 STL* 9310 STL	*Rc 60* Rc 60	*0.8* 0.8 *(32)* (32)	"Sandstrom LC 300" Dry Film "Bray 601" "Bray 608"	6	20	28 (244) (full cycle) **30 minute cycle	2.8 (25) (full cycle)	5.1 (45)	.051 Max (2.0) 0 Min	-25 / 65	40 - 60
ASTRO	*25.4* 63.5 *(1.000)* (2.5)	*1* 30	12	*AISI C1117* PHOS. BRONZE	*Rc 62*	*Grd&Pol* Machined	"Bray 601"	4-46'	14.5	25 (225) (Briefly at start) **10 Minute cycle	4.8 (42) (full Cycle)	28 (250) stall @	.19 Max (7.5)	-85 / 70	
REXNORD	*15.9* 63.5 *(.625)* (2.500)	*1* 40	16	*1045 STL BRONZE per AMS 4640	*Rc 59* Rb 97	*0.4* 0.8 *(16)* (32)	"Dicronite" WS2 dry film "Bray 601" Wiper	5-43'	14.5	12 (107) (@stall) **1 Minute cycle	No-Load (97% of cycle)	2.0 (18)	.41 Max (16) 0 Min	Ambient	
GODDARD CONE DRIVE	*42.2* 161.0 *(1.660)* (6.340)	*1* 50	8	*4150 STL* CAST BRONZE	*Rc 60* Rc 35	*0.8* 1.6 *(32)* (63)	50% "Bray 802EP" 50% "Bray 815Z"	3-49'	22.23	339 (3000) **10 Second cycle	N/A - load varies	28 (250)	.11 Max (4.5) .09 Avg	$\pm$ 70	40

TABLE 2. GENERAL GUIDELINES

A list of general guidelines is useful for the initial design. These guidelines apply to most worm gear systems and are taken from worm gear specific texts.

GUIDELINE	REASON
1. Make the hob as nearly identical to the worm as possible. Use slightly larger center distance for hobbing.	1. Optimize contact prior to break-in
2. Make face-width a maximum of 50 percent of worm diameter	2. Avoid high-contact load on outer edges of gear teeth
3. Avoid low pressure angles on low-tooth-count gears	3. Avoid under cutting
4. Total tooth count (worm + gear) should be a minimum of 40	4. Avoid geometric interference
5. Avoid low speeds and stall	5. Low speed promotes severe boundary lubrication
6. Grease lube may require special techniques to maintain performance	6. Oil film benefits from replenishment such as in oil bath
7. Use fine surface finishes	7. Improves lube and wear
8. Set the gearset up so that initial contact pattern is on the leaving side of the gear	8. Provide oil reservoir on the entering side. Pattern will grow to cover entire width over life
9. Break in gradually with light loads and abundant lubrication	9. Break-in greatly increases life

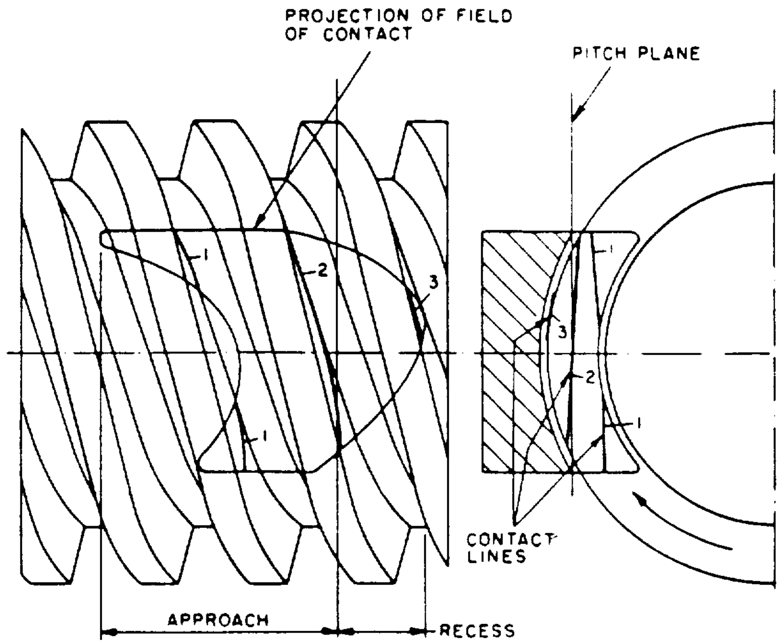

Figure 1. Tooth contact lines.

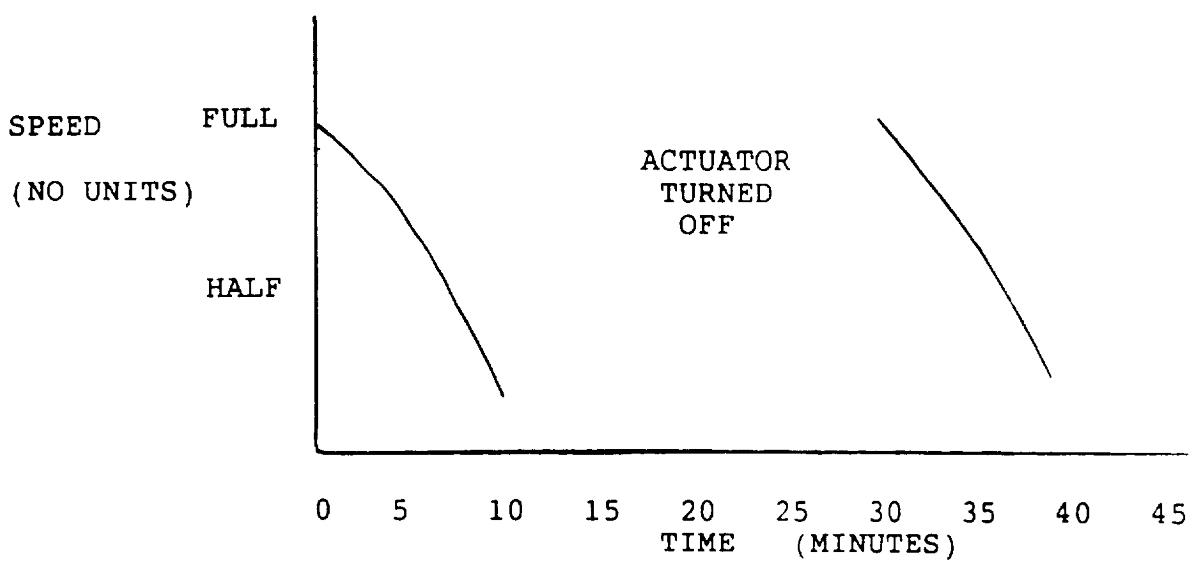

Figure 2. NRL actuation speed versus time.

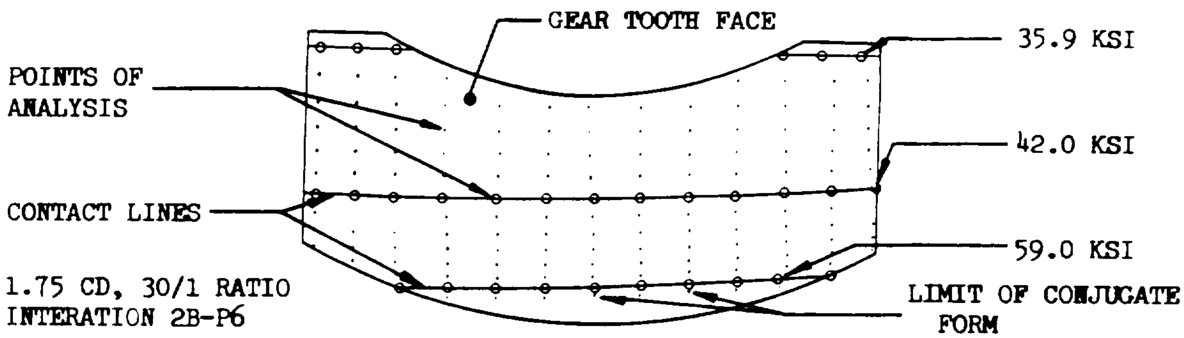

Figure 3. Contact stresses for ASTRO system.