NASA/TM—2005-214092

Shuttle Rudder/Speed Brake Power Drive Unit (PDU) Gear Scuffing Tests With Flight Gears

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December 2005

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Abstract

Scuffing-like damage has been found on the tooth surfaces of gears 5 and 6 of the NASA space shuttle rudder/speed brake power drive unit (PDU) number 2 after the occurrence of a transient backdriving event in flight. Tests were conducted using a pair of unused spare flight gears in a bench test at operating conditions up to 2866 rpm and 1144 in.-lb at the input ring gear and 14,000 rpm and 234 in.-lb at the output pinion gear, corresponding to a power level of 52 hp. This test condition exceeds the maximum estimated conditions expected in a backdriving event thought to produce the scuffing damage. Some wear marks were produced, but they were much less severe than the scuffing damage produced during shuttle flight. Failure to produce scuff damage like that found on the shuttle may be due to geometrical variations between the scuffed gears and the gears tested herein, more severe operating conditions during the flight that produced the scuff than estimated, the order of the test procedures, the use of new hydraulic oil, differences between the dynamic response of the flight gearbox and the bench-test gearbox, or a combination of these. This report documents the test gears, apparatus, and procedures, summarizes the test results, and includes a discussion of the findings, conclusions, and recommendations.

Executive Summary

Scuffing-like damage has been found on the tooth surfaces of gears 5 and 6 of the NASA space shuttle rudder/speed brake power drive unit (PDU) number 2 after the occurrence of a transient backdriving event in flight. Experiments were conducted at NASA Glenn Research Center using a pair of unused spare flight gears for PDU serial number 0405 in a bench test setup to achieve the following objectives:

(1) Recreate scuffing damage similar to that found on the flight gears at conditions expected during backdriving and document conditions that induce scuffing.
(2) Demonstrate that scuffed PDU flight gears can be operated long enough to complete a shuttle mission.
(3) Quantify the scuffing and tooth wear.

Tests were conducted up to 2866 rpm and 1144 in.-lb at the input ring gear and 14,000 rpm and 234 in.-lb at the output pinion gear, which corresponds to a power level of 52 hp. This test condition exceeded the maximum estimated condition of the backdriving event that produced scuffing-like damage in flight.

The scuffing tests performed did not produce scuff marks similar to that produced during shuttle flight. Wear marks were produced on the pinion teeth near the tips and on the ring gear teeth faces during the test Back-3c, which was conducted at an input speed, torque, and power of 2402 rpm, 664 in.-lb, and 25.3 hp. Very light wear marks were generated on side-2 of the pinion gear during the test Score-1 conducted at input speed, torque, and power of 2865 rpm, 1167 in.-lb, and 53 hp.

Failure to produce scuff damage like that found on the shuttle gears may be due to geometrical variations between the scuffed gears and the gears tested herein, more severe operating conditions during the flight that produced the scuff than estimated, the order of the test procedures, the use of new hydraulic oil, differences between the dynamic response of the flight gearbox and the bench-test gearbox, or a combination of these.

Options to consider for resolving the scuffing issue include, but are not limited to:

- Analyze the shuttle power drive unit to determine the inertial loads and transient conditions expected during back drive.
- Examine inspection reports and possibly re-inspect the pinion and ring gears to assess variations in tooth profile, particularly at the edge break at the tips of the teeth and their possible contributions towards scuffing.
- Change the test procedure to attain the most severe test conditions early on in the test matrix.
- Conduct transient scuffing tests.

Also, if a future shuttle flight includes a backdriving event that produces gear scuffing, the GRC bench test rig could be used to assess the remaining life capability of gears that were scuffed in flight. Such an approach provides the most direct assessment method short of system-level testing. However, it does require removal of the PDU unit from service for replacement of the scuffed gears.

Introduction

Gears used in the NASA space shuttle rudder/speed brake power drive units (PDU) have been damaged during transient events termed “backdriving”. The damage occurs to the working surface of the gear teeth. The damage is termed “scuffing”. Scuffing was observed on gears 5 and 6, on one side of the gear teeth, in the tooth-tooth contact area. The damage can be seen in figure 1 (from ref. 1). During back-drive, the outer teeth of the ring gear (gear 6) drive the smaller pinion gear (gear 5). In normal operation the pinion gear drives the ring gear. Motion of the PDU gears is produced by hydraulic motors, and so the backdriving event is torque limited. The maximum speed and power for gear 5, the pinion, during backdriving is estimated to be 50 hp at 14,000 rpm.

Gear scuffing is considered as a failure mode for many applications. The term “scuffing” refers to surfaced distress (material removal) that can occur when load carrying surfaces are in intimate contact and have some amount of relative sliding. Scuffing is of concern for mechanical components such as cams, bearings, and gears. Scuffing refers to a wear mode associated with a complete breakdown of lubrication. Wear rates are high, and a scuffed surface shows scoring-like marks in the direction of sliding. Scuffing is usually associated with some amount of solid-phase welding of asperity-scale features of the surfaces that is accompanied by tearing, material transfer, and galling of the sliding surfaces.

Gear technologists sometimes differentiate between cold-scuffing and hot-scuffing. During hot-scuffing, thermal energy within the lubricated contact assists the breakdown of both lubricant films and chemical boundary lubricating films. The onset of hot-scuffing has been postulated to be a type of thermal stability problem. “Flash temperature” limits were established for concentrated mechanical contacts lubricated with non-reactive mineral oils by classical experiments of Blok (ref. 2). Flash temperature approaches are also commonly used for other types of lubricants.

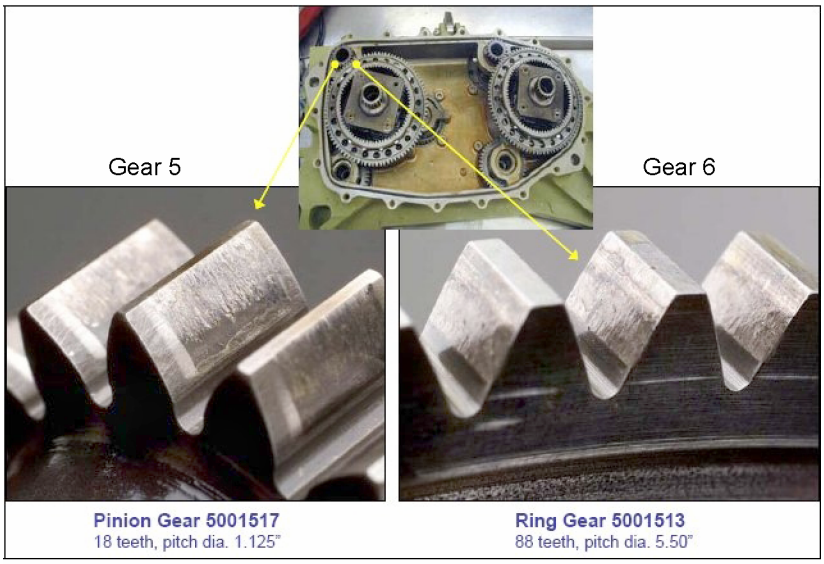


Figure 1.—Damaged gear teeth from shuttle power drive unit 2.

Scuffing can also occur without the "thermal-instability" phenomena as described above, and such scuffing is usually referred to as "cold-scuffing". Calculation methods to predict the probability of scuffing have been developed. The scuffing prediction analyses provide guidance for product design and development, but highly reliable predictions for the onset of scuffing for any particular gear application has remained elusive. Predictions are difficult because many interdependent factors influence the onset of scuffing including geometric accuracy of tooth profile, dynamic load effects, rolling and sliding speeds, surface finish and micro-topography, oil physical properties, and the chemical interactions of the metal alloy and lubricating oil.

Previous to the research reported herein, research was done by Wedeven Associates and Glenn Research Center to better understand the root cause, the severity of damage, and the capability of the gears to continue to operate safely after scuffing damage occurs and the backdriving event is concluded. The following was learned from the previous research (refs. 1 and 3):

- The damage observed on flight gears and bench test specimens are consistent with a cold-scuffing mode. There is no evidence to suggest that hot-scuffing of the gears is likely. These facts are important since cold-scuffing tends to be a self-relieving event while hot-scuffing can cause extensive damage and weaken the gear teeth by tempering the case-carburized gear teeth.
- The damage observed on flight gears and bench test specimens is consistent with gears having insufficient tip relief for the operating torque. The evidence suggests that during back driving the transient torque was sufficiently high to cause gouging of the tips of the meshing gear teeth.

Although the previous research provided insight concerning the scuffing damage, it was desired to better understand the conditions (temperature, speed, torque, rate of change for speed and torque) that produced scuffing during a backdriving event. It was also desired to study the capability of scuffed gears to operate safely and successfully for the remainder of a mission and, perhaps, for multiple missions. Should the scuffed gears fail to carry torque, then proper positioning of the rudder and speedbrake panels for safely controlled flight would not be possible. To better understand the scuffing phenomena and any potential safety implications, experiments were conducted at Glenn Research Center using a pair of flight gears in a bench test setup to achieve the following objectives:

(1) Recreate scuffing damage similar to that found on the flight gears at conditions expected during backdriving and document conditions that induced scuffing.

(2) Demonstrate that scuffed PDU flight gears can be operated long enough to complete a shuttle mission.

(3) Quantify the scuffing and tooth wear.

Previous research results and technical discussions were used to develop the test protocols. The Mechanical Components Branch conducted the tests in the Gear Noise Facility with support from the Engineering and Technical Services Directorate to design and fabricate the test gearbox. Testing began on June 1, 2005 with the bulk of the data obtained prior to launch of STS–114 on July 26, 2005. The final test was conducted on August 9, 2005. This report documents the test gears, apparatus, and test procedures, summarizes the test results, and includes a discussion of the findings, conclusions and recommendations.

Test Gears

The test gears were unused spares from the Rudder Speed Brake Power Drive Unit (RSB PDU), number 2, S/N 0405. Table 1 shows their part and serial numbers and key design parameters. Both of these spur gears are made of AMS 6265 (AISI 9310), a standard aerospace gear steel. For these tests the outer teeth of the ring gear drove the pinion gear. The distance between the test gear centerlines is approximately 3.3125 in.

TABLE 1.—IDENTIFICATION AND KEY DESIGN PARAMETERS OF TEST GEARS

Test gear	Part number	Serial number	Number of teeth	Diametral pitch	Pitch diameter, in.	Tooth width, in.	Pressure angle
Ring (no. 6)	5001513	D5K001	88	16	5.5	0.188	25°
Pinion (no. 5)	5001517	D5G009	18	16	1.125	0.265	25°

To mount the ring and pinion gears to their test shafts some modifications were required. These modifications included removing the inner teeth of the ring gear and cutting off the internal spline of the pinion gear.

Apparatus

Test gearbox

A test gearbox was designed and fabricated specifically for these tests (fig. 2). Design decisions were driven by an extremely tight schedule that initially required both the design and fabrication to be completed in just 5-1/2 weeks.

The welded test gear box is made of 1/2-in.-thick mild steel plate. Endplates which support the ends of the shafts were bolted to the gearbox and location pins installed to assure precision assembly. The ring gear is bolted on a steel hub (fig. 3), which is mounted on a 3/4 in. ground and hardened shaft. The shaft drives the hub with two 1/8 in. rectangular keys. The maximum speed of the input shaft is 2,864 rpm.

The pinion gear is also mounted on a 3/4 in. ground and hardened shaft, which drives the pinion through two 1/8 in. rectangular keys. The maximum speed of this output shaft is 14,000 rpm. The shafts are supported by steel ball bearings rated for a maximum speed of 19,000 rpm. The pinion and ring gears are mounted with collars and/or sleeves to maintain their axial position on the shaft. Once the gears were mounted to the shafts, the shafts were balanced.

Lip seals are used at the shaft ends to contain the hydraulic fluid lubricant. Polymer spacers, metal shims and e-clips are used at each shaft end to hold the axial positions of the shafts so that the gears have

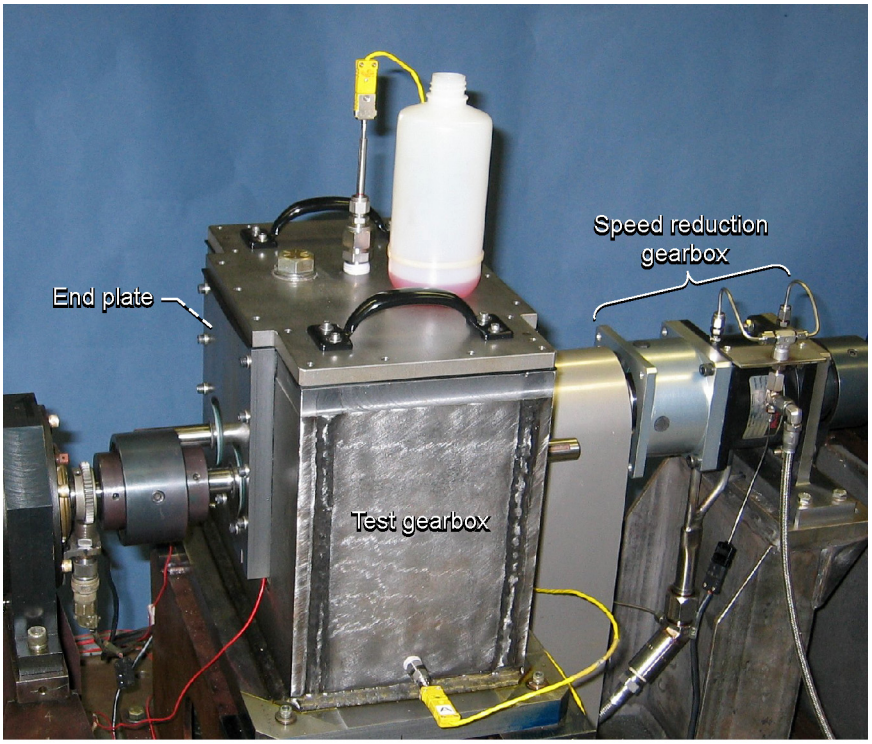


Figure 2.—Test gearbox.

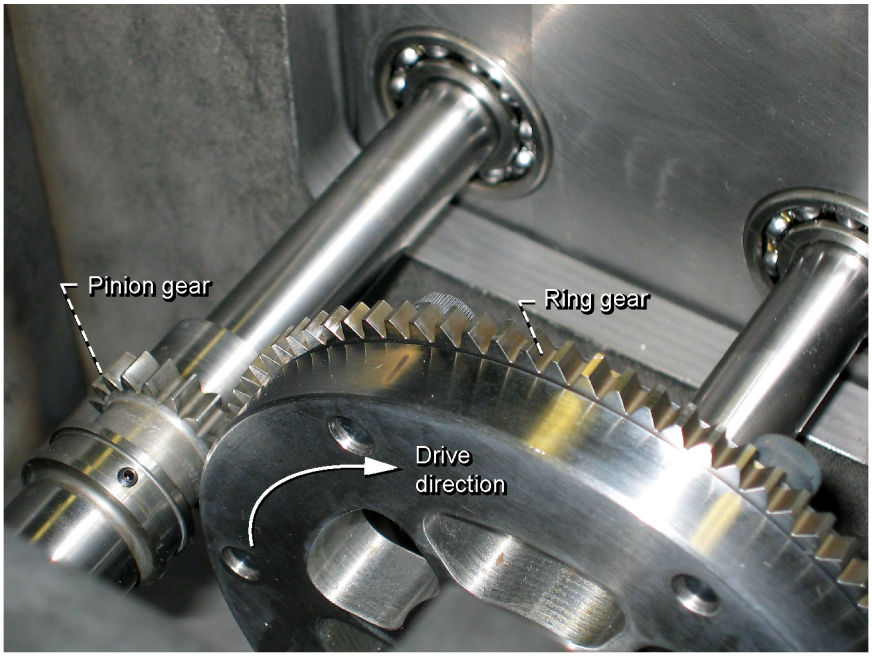


Figure 3.—Pre-test photo of ring and pinion gears installed in the test gearbox for side-1, build-1.

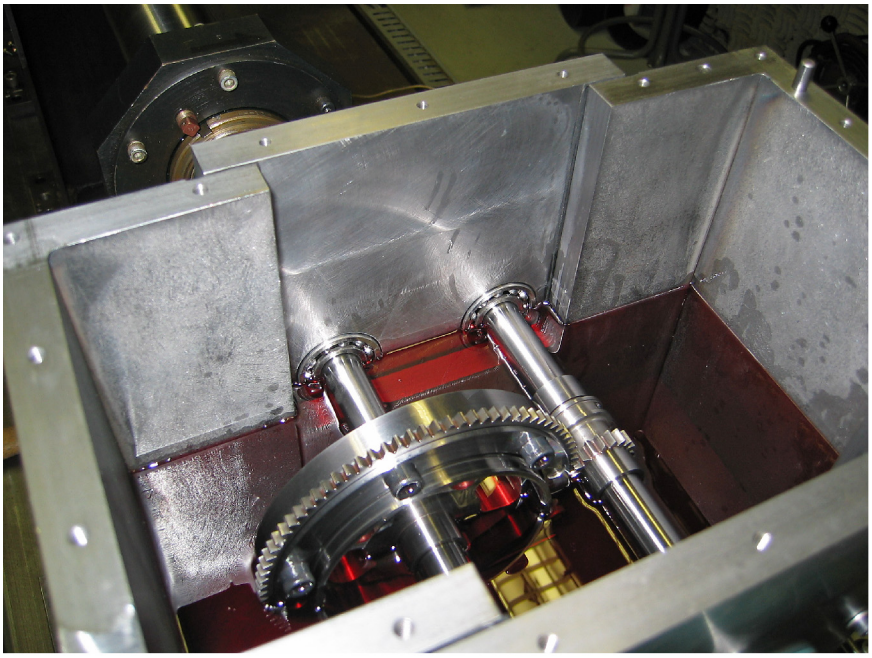


Figure 4.—Test gearbox as assembled for side-1, build-1 is filled to centerline with Brayco Micronic 882 hydraulic fluid.

a centered engagement. A lid is bolted on to the top of the gearbox to contain the lubricant. The lid has handles for easy removal for visual inspections of the test gears. The lid is vented to atmosphere with a tube connected to a plastic bottle to capture any lubricant mist.

There were a total of three builds of the test gearbox. In the order tested, they are referred to as side-1, build-1; side-2, build-1; and side-1, build-2. "Side" refers to the loading side of the gear teeth. Most of the testing was conducted on side-1. Side-2 is the opposite teeth sides of side-1. Testing on side-2 was performed by removing the shafts and flipping the shafts end-for-end with the gears still on them and then reinstalling the shafts in the gearbox.

Lubricant

The test gearbox was filled to the shaft centerlines (fig. 4), with Brayco Micronic 882 hydraulic fluid to splash lubricate the gears and the bearings. New hydraulic fluid was used for each build of the gearbox and the fluid is from the same batch used on the shuttle.

Test facility

The test gearbox was installed in the Gear Noise Test Facility (fig. 5). A 200 hp DC motor powers a pulley-belt system to drive the input shaft. A torque meter on the input shaft measures both the speed and torque of the input ring gear. The maximum input shaft speed was 2864 rpm. The output shaft or pinion gear shaft has a maximum speed of 14,000 rpm and is connected to a 5 to 1 speed reduction gearbox. The speed reduction gearbox, which can be seen in figure 2, is connected to an absorption dynamometer rated for 175 hp and 6000 rpm. This eddy current dynamometer provides load torque for the system.

To accommodate the test gearbox and the speed reduction gearbox, a shorter shaft was made to connect the torque meter to the input shaft to the test gearbox. Also, a pedestal was added to support the speed reduction gearbox. The Gear Noise/Dynamics Rig (with a different test gearbox) is described in more detail in reference 4.

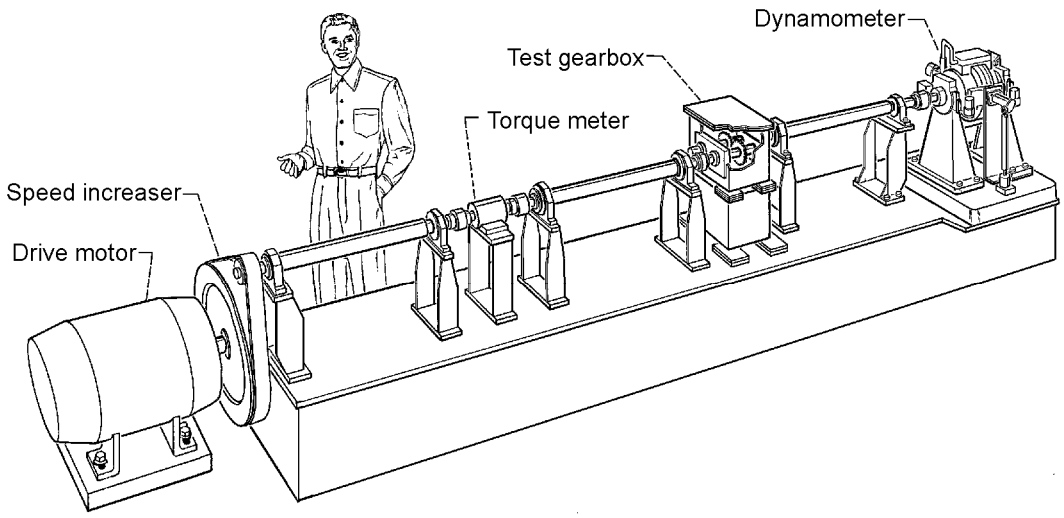


Figure 5.—Gear noise test facility as configured before modifications for gear scuffing experiments.

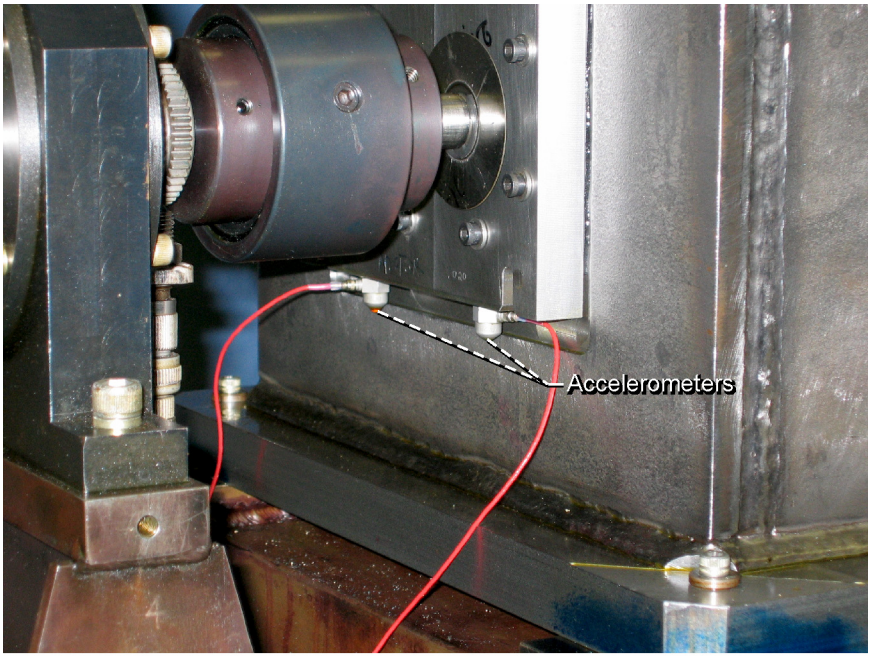


Figure 6.—Accelerometers mounted to input endplate underneath the input and output shafts.

Research Measurements

Type K thermocouples were used to measure the bath temperature of the hydraulic fluid at the bottom of the gear box and the oil fling-off temperature at approximately 1/2 in. above the gear mesh. Accelerometers were installed on the drive-side endplate of the test gear box under each shaft bearing (fig. 6), to measure the vertical vibration in each shaft. It was anticipated that either the fling-off temperature of the hydraulic fluid or the vibration would give some indication if a scuffing event had occurred.

A speed transducer was used to measure the input shaft speed. The torque meter on the input shaft was used to measure the input shaft torque to an accuracy of ±2 rpm. The output torque at the dynamometer was also measured. Note that the dynamometer torque reflects power losses in both the test gearbox and the speed reduction gear box. These measurements along with the rms vibration level, date and time of test initiation and the accumulated time of the test were recorded using a data acquisition system on a personal computer. These data were recorded typically once every second during testing.

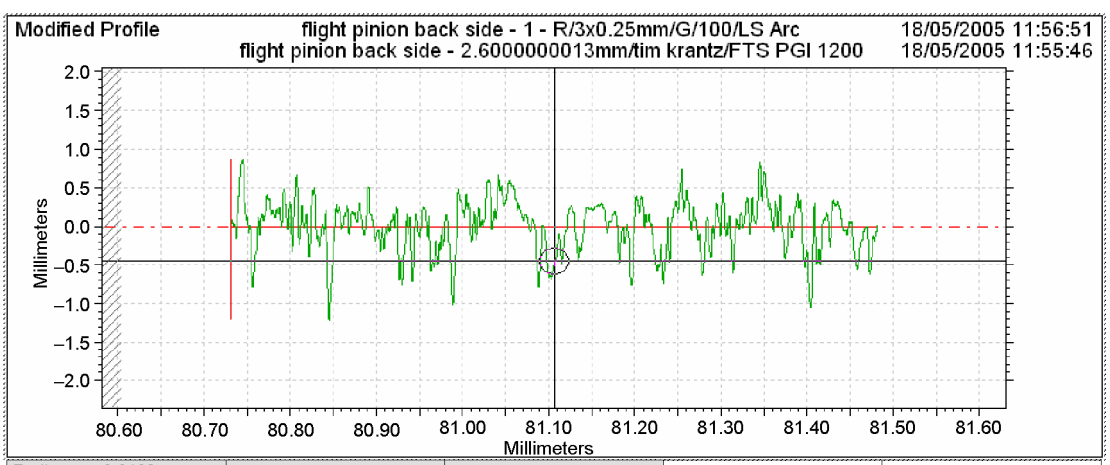
Approximately once every 50 sec, a vibration time record was recorded for spectral analysis. Each vibration record consisted of 8192 readings for each of the two channels. The sample rate was approximately 60,000 samples per second per channel. Alias protection was provided by 26 kHz low pass filters.

Test Procedures

Pre-test Measurements

A profilometer was used to measure the tooth surface roughness of the pinion gear teeth. The ring gear teeth surface roughness was not measured, because the profilometer stylus is too big to get between the teeth. The pre-test profile was measured using a stylus profilometer having a 2 µm radius, and the data was filtered using a 0.25 mm cutoff and 100:1 bandwidth. The roughness average (Ra) of the surface was 0.25 µm (10 µin.). A typical micro-topography of a pinion gear tooth is shown in figure 7.

Once the test gear box was assembled, the backlash between the gears was measured at four positions approximately one quarter turn of the ring gear apart. Backlash is the amount by which the width of a tooth space exceeds the thickness of the engaging tooth measured on the pitch circles (ref. 5). The backlash measurements are shown in table 2. The backlash checks verified that the test gears were suitably mounted to the test gearbox shafts and had appropriately small runout.



Radius	8.9102	mm					
Ra	0.2490	µm	Rq	0.3236	µm		
Rsk	−0.5417					R3y	1.2685 µm
			Rv	1.0846	µm		
			Rt	2.0723	µm		
			Rz	1.8736	µm		

Figure 7.—Typical micro-topography of the pinion gear teeth.

TABLE 2.—MEASURED BACKLASH OF RING AND PINION GEARS IN THE TEST GEAR BOX

Position	Side-1, build-1 5/23/05 in.	Side-2, build-1 6/24/05 in.
1	0.010	0.008
2	.012	.010
3	.010	.010
4	.011	.009
Average	.011	.009

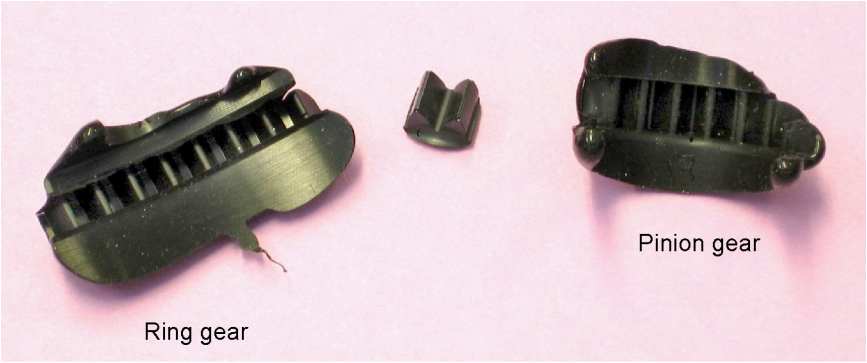


Figure 8.—Pre-test rubber mold of the pinion and ring gear teeth and the hard epoxy replication of the pinion teeth.

A rubber mold of 3 teeth on each of the pinion and ring gears was made prior to any testing. A second set of rubber molds was made on 6/23/05 as a post-test mold for side-1, build-1 and pre-test mold for side-2, build-1. The product Repliset F5 was used and set up in about 20 min at room temperature. It was easily peeled off of the gear teeth. An acid pen mark on the ring gear mounting hub was easily observed in the rubber mold indicating that surface wear marks could be transferred to the rubber mold. A two part epoxy (80 percent epoxy, 20 percent catalyst), Durelco 4525, was then poured into the rubber mold used to make a hard model of two pinion teeth. The epoxy, which cures in 24 hr at room temperature or in 20 min at 160 °F, was oven cured at 120 °F for 1 hr since the rubber mold material has a 150 °F temperature limit. The black rubber mold easily separated from the hard epoxy model of the tooth. The intent was to develop a process to transfer any wear marks to the hard epoxy tooth. If this process worked then it would be a way to examine the ring gear teeth, since the epoxy teeth could be cut apart so they could be measured with the profilometer. No profilometer measurements were made of the hard epoxy teeth to verify the usefulness of this process. This may be worth pursuing if further work is desired. The pre-test rubber mold of the pinion and ring gear teeth and the hard epoxy replications of the pinion teeth are shown in figure 8.

A digital camera with +1, +2, and +4 diopter closeup lenses was used to photograph the pinion and ring gear teeth in the gear box to document their condition throughout the testing. Pre-test photos of the pinion and ring gear teeth are shown in figures 9 and 10, respectively.

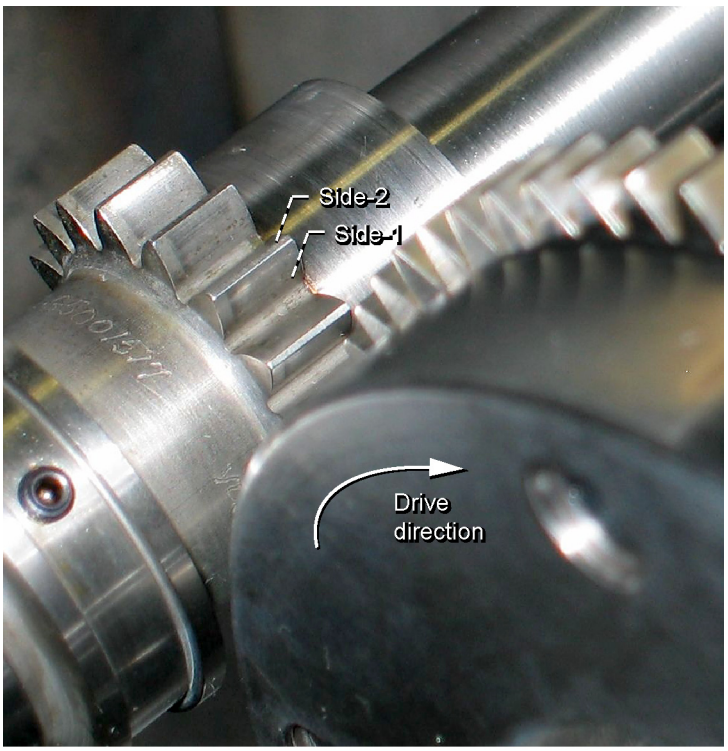


Figure 9.—Pre-test photo of pinion teeth.

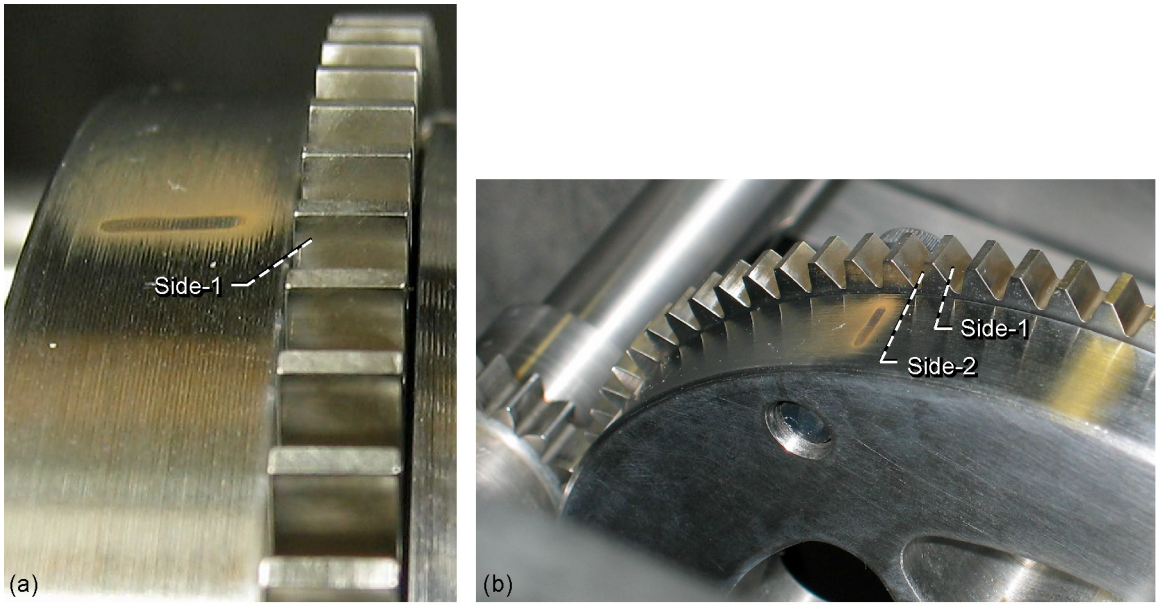


Figure 10.—(a) Pre-test photo of ring gear teeth showing side-1. (b) Pre-test photo showing another view of ring gear teeth, side-1 and side-2.

Tests Conducted

The tests conducted are summarized in tables 3, 4, and 5 for side-1, build-1; side-2, build-1; and side-1, build-2, respectively.

First, with side-1, build-1, a short checkout test to verify operation of the rig and the data system was conducted at an input speed of 500 rpm and torque of 162 in.-lb. Next a speed survey was conducted at a low input torque of approximately 75 to100 in.-lb and the input speed was incrementally increased and decreased between 500 to 1429 rpm. After the speed survey, the test gearbox lid was removed to make a visual inspection and take photographs.

The Run-in test was then conducted at an input speed of approximately 800 rpm while the input torque was increased from 100 to 500 by 100 in.-lb increments. After each steady-state test condition was held for approximately 10 min, the rig was shut down, the lid removed, and the gears visually inspected.

Three back drive simulations were made. The first, “Back-1”, was conducted at 500 in.-lb of input torque and shaft speeds of 1000, 1250, and 1431 rpm. Each condition was held for approximately 5 min before the rig was shutdown and the gears visually inspected and photographed. The second, “Back-2”, was conducted at an input shaft speed of 1432 rpm and the input gear torque set to 500, 700, 900, and 1040 in.-lb. Again each test condition was held for approximately 5 min before the test was terminated and gears visually inspected and photographed. The third back drive simulation, “Back-3”, was intended to be conducted at 1040 in.-lb and speeds of 1432, 1900, 2400, and 2863 rpm, but these conditions could not be obtained due to dynamic instability of the test rig. The actual conditions obtained are shown in table 3. Each test condition was held for approximately 5 min before the test was terminated and gears visually inspected and photographed.

To improve control of the drive train a soft rubber coupling between the drive motor and the torquemeter was replaced with a hard gear coupling. Then tests “Back-3x” and “Back-3y” were conducted. Removing the rubber coupling improved but did not eliminate the instability problem; therefore the desired test conditions of “Back-3” could not be fully attained.

Next, the high speed pulley on the test rig was changed to reduce the speed up ratio of the pulley system from 4.3:1 to 3:1. Also, a heat gun and a heat lamp were used to heat up the hydraulic fluid in the test gear box. Then “Back-3z” tests were conducted attaining the test conditions indicated in table 3. Modifications to the motor control circuit were made and several stability tests (“Stab-test-1” through “Stability-9”) were conducted at the conditions shown in table 3.

TABLE 3.—SUMMARY OF SHUTTLE GEAR SCUFFING TESTS CONDUCTED ON SIDE-1, BUILD-1

Test name	Date	Ring gear input			Pinion output		Oil bath temperature		Oil fling temperature		Time at condition	Total time of rotation	No. of cycles at condition		Visual assessment	
		Speed (rpm)	Torque (in.-lb)	Power (hp)	Speed (rpm)	Torque (in.-lb)	Initial (°F)	Final (°F)	Initial (°F)	Final (°F)	(sec)	(sec)	Ring gear	Pinion gear	Ring gear	Pinion gear
Checkout	06/01/2005	500.0	162.4	1.3	2444.4	33.2	69.3	69.5	68.6	68.9	78.0	98.0	650.0	3177.8	n/a	n/a
SpdSurvey	06/01/2005	498.0	98.8	0.8	2434.7	20.2	63.6	63.8	62.9	63.2	48.0		398.4	1947.7		
		714.0	91.5	1.0	3490.7	18.7	63.8	64.0	63.2	63.4	76.0		904.4	4421.5		
		1000.0	96.7	1.5	4888.9	19.8	64.1	64.4	63.5	63.8	48.0		800.0	3911.1		
		1250.0	95.3	1.9	6111.1	19.5	64.4	65.1	63.9	64.6	64.0		1333.3	6518.5		
		1429.0	92.9	2.1	6986.2	19.0	65.2	67.0	64.8	66.6	154.0		3667.8	17931		
		1248.5	82.7	1.6	6103.8	16.9	67.0	67.9	66.7	67.5	112.0		2330.5	11394		
		998.5	76.9	1.2	4881.6	15.7	68.0	68.6	67.6	68.1	104.0		1730.7	8461.4		
		714.0	98.1	1.1	3490.7	20.1	69.6	69.7	68.9	69.0	64.0		761.6	3723.4		
		495.0	101.0	0.8	2420.0	20.7	69.6	69.7	69.0	69.0	178.0	1256.0	1468.5	7179.3	okay	okay
Run-In-1	06/01/2005	799.0	98.1	1.2	3906.2	20.1	70.1	73.2	69.7	72.7	624.0	850.0	8309.6	40625	okay	okay
Run-In-2	06/02/2005	799.4	198.8	2.5	3908.2	40.7	77.7	81.5	77.2	80.9	657.5	780.0	8760.1	42827	okay	okay
Run-In-3	06/02/2005	798.9	298.9	3.8	3905.7	61.1	79.4	83.2	78.9	82.8	692.0	720.0	9214.0	45046	okay	okay
Run-In-4	06/02/2005	798.8	399.0	5.1	3905.2	81.6	82.8	86.3	82.3	85.8	638.0	702.0	8493.9	41526	okay	okay
Run-In-5	06/02/2005	801.7	497.0	6.3	3919.4	101.7	83.7	84.8	83.4	84.3	142.0	212.0	1897.4	9276		
Run-In-5a	06/02/2005	800.6	497.9	6.3	3914.0	101.8	84.8	88.5	84.4	88.0	698.0	728.0	9313.6	45533	okay	okay
Back-1b	06/02/2005	1000.1	498.0	7.9	4889.4	101.9	87.1	88.9	86.7	88.7	304.0	334.0	5067.2	24773	okay	okay
Back-1c	06/02/2005	1250.0	495.3	9.8	6111.1	101.3	87.7	91.0	87.3	90.8	333.0	371.0	6937.5	33917	okay	okay
Back-1d	06/02/2005	1431.0	500.1	11.4	6996.0	102.3	89.1	92.8	88.8	92.6	332.0	371.0	7918.2	38711	okay	okay
Back-2a	06/03/2005	1432.0	497.2	11.3	7000.9	101.7	80.2	84.9	79.8	84.5	353.0	386.0	8424.9	41189	okay	okay
Back-2b	06/03/2005	1432.0	699.0	15.9	7000.9	143.0	82.8	87.4	82.7	87.2	331.0	384.0	7899.9	38622	okay	okay
Back-2c	06/03/2005	1432.0	898.6	20.4	7000.9	183.8	86.3	91.9	n/a	n/a	317.0	344.0	7565.7	36988	okay	okay
Back-2d	06/03/2005	1431.7	1040.6	23.6	6999.4	212.9	90.4	95.4	90.3	95.4	328.0	365.0	7826.6	38264	okay	okay
Back-3a	06/03/2005	1430.5	1035.6	23.5	6993.6	211.8	89.2	95.4	89.0	95.4	372.0	457.0	8869.1	43360		
Back-3b	06/03/2005	1896.0	905.7	27.2	9269.3	185.3	99.9	107.0	100.1	107.1	370.0	632.0	11692.0	57161	okay	okay
Back-3c	06/03/2005	2401.7	664.5	25.3	11741.6	135.9	109.1	116.8	109.4	117.1	332.0	665.0	13289.4	64970	wear at mid-tooth	thumbnail wear mark at tip on all teeth
Back-3d	06/03/2005	2864.6	390.0	17.7	14004.7	79.8	114.5	125.0	114.8	125.4	416.0	740.0	19861.2	97099	Similar to Back-3c	Similar to Back-3c
Back-3xb	06/07/2005	1898.0	1032.8	31.1	9279.1	211.3	81.1	83.8	80.9	83.5	122.5	355.5	3875.1	18945	no change	no change
Back-3xc	06/07/2005	2393.8	900.0	34.2	11703.0	184.1	72.0	74.5	72.3	74.9	62.0	232.0	2473.6	12093	no change	no change
Back-3yc	06/07/2005	2400.6	920.0	35.0	11736.3	188.2	78.2	88.4	78.3	88.6	337.0	510.0	13483.4	65919	no change	no change[a]
Back-3za	06/08/2005	1433.7	1037.9	23.6	7009.2	212.3	167.9	169.5	168.0	169.4	343.0	443.0	8196.0	40069	no change	no change[b]
Back-3zb	06/08/2005	1900.4	1039.1	31.3	9290.8	212.5	161.9	164.4	161.8	164.5	320.0	431.0	10135.5	49551	no change	no change[c]

TABLE 3.—SUMMARY OF SHUTTLE GEAR SCUFFING TESTS CONDUCTED ON SIDE-1, BUILD-1 (Continued)

Test name	Date	Ring gear input			Pinion output		Oil bath temperature		Oil fling temperature		Time at condition	Total time of rotation	No. of cycles at condition		Visual assessment	
		Speed (rpm)	Torque (in.-lb)	Power (hp)	Speed (rpm)	Torque (in.-lb)	Initial (°F)	Final (°F)	Initial (°F)	Final (°F)	(sec)	(sec)	Ring gear	Pinion gear	Ring gear	Pinion gear
Back-3zc	06/08/2005	2397.7	965.2	36.7	11722.1	197.4	161.8	162.9	162.0	163.2	58.0	456.4	2317.8	11331	no change	no change[d]
Stab-test-1	06/17/2005	925.2	245.9	3.6	4523.2	50.3	74.1	75.4	73.5	74.8	143.5		2212.8	10818	n/a	n/a
	06/17/2005	2403.4	1038.9	39.6	11750.0	212.5	80.2	82.5	80.3	82.6	55.5		2223.1	10869	n/a	n/a
	06/17/2005	2857.1	1033.4	46.8	13968.0	211.4	85.4	88.5	85.8	88.8	72.0	516.8	3428.5	16762	n/a	n/a
Stab-test-2	06/17/2005	2633.8	261.9	10.9	12876.4	53.5	83.9	84.6	83.9	84.6	14.4		632.1	3090.3	n/a	n/a
	06/17/2005	2872.1	267.2	12.2	14041.4	54.7	85.0	86.5	85.0	86.6	33.0	77.5	1579.7	7722.8	n/a	n/a
Stab-test-3	06/17/2005	2676.3	573.2	24.3	13084.3	117.2	86.5	86.6	86.3	86.7	6.0	34.0	267.6	1308.4	n/a	n/a[e]
Stab-test-4	06/17/2005	2628.0	270.6	11.3	12847.8	55.4	86.2	87.0	86.2	87.0	18.5		810.3	3961.4	n/a	n/a
	06/17/2005	2856.6	278.1	12.6	13965.6	56.9	87.1	88.0	87.1	88.1	23.0		1095.0	5353.5	n/a	n/a
	06/17/2005	2875.0	473.5	21.6	14055.7	96.9	88.3	88.9	88.5	89.0	11.0	93.5	527.1	2576.9	n/a	n/a
Stab-test-5	06/17/2005	2861.4	698.7	31.7	13989.3	142.9	90.2	90.8	90.5	91.1	11.5		548.4	2681.3	n/a	n/a
	06/17/2005	2833.1	933.1	41.9	13850.6	190.9	95.3	95.8	95.7	96.2	12.0	307.5	566.6	2770.1	n/a	n/a
Stab-test-6	06/17/2005	2382.2	1041.3	39.4	11646.4	213.0	96.7	100.2	96.9	100.5	109.0	238.0	4327.7	21158	n/a	n/a
Stab-test-7	06/17/2005	2417.5	960.2	36.8	11819.0	196.4	101.4	101.8	101.5	101.8	11.0	181.5	443.2	2166.8	okay	okay
Stability-1	06/20/2005	2864.4	1041.4	47.3	14003.9	213.0	87.8	89.5	88.0	89.8	17.8	233.7	849.8	4154.5	n/a	n/a
Stability-2*	06/20/2005			0.0	0.0	0.0						~20	0.0	0	n/a	n/a[f]
Stability-2	06/20/2005	2855.9	965.3	43.7	13961.9	197.5	96.3	97.4	96.5	97.7	29.6	297.0	1408.9	6887.9	okay	okay
Stability-3	06/20/2005	1430.5	1039.0	23.6	6993.6	212.5	91.2	92.1	90.9	91.8	39.7	132.4	946.5	4627.4	n/a	n/a
Stability-4	06/20/2005	1432.5	1048.1	23.8	7003.3	214.4	91.9	92.8	91.4	92.1	30.8	92.9	735.4	3595	n/a	n/a
Stability-5	06/20/2005	1439.6	1040.9	23.8	7038.1	212.9	92.1	92.5	91.8	92.1	15.4	74.9	369.5	1806.5	n/a	n/a
Stability-6	06/20/2005	1436.2	1045.8	23.8	7021.2	213.9	92.7	92.8	92.3	92.5	8.8	79.7	210.6	1029.8	okay	okay
Stability-7	06/22/2005	2864.6	1146.4	52.1	14004.5	234.5	88.0	90.2	88.3	80.4	44.3	391.4	2115.0	10340	n/a	n/a
Stability-8	06/22/2005	2547.3	1140.7	46.1	12453.5	233.3	90.2	95.6	90.4	95.9	129.2	257.8	5485.2	26817	n/a	n/a[g]
Stability-9	06/22/2005	2409.8	1141.2	43.6	11781.3	233.4	95.8	96.5	96.0	96.7	15.0	122.4	602.5	2945.3	okay	okay[h]

[a]"±85 on input torque"

[b]shaft rotating when file ends

[c]shaft rotating when file ends

[d]See time history

[e]not very stable. Max input torque 1073 in.-lb at 2736 rpm

[f]File deleted

[g]Not very stable.

[h]Max torq 3387 in.-lb at 181.3 rpm

TABLE 4.—SUMMARY OF SHUTTLE GEAR SCUFFING TESTS CONDUCTED ON SIDE-2, BUILD-1

Test name	Date	Ring gear input			Pinion output		Oil bath temperature		Oil fling temperature		Time at condition	Total time of rotation	No. of cycles at condition		Visual assessment	
		Speed (rpm)	Torque (in.-lb)	Power (hp)	Speed (rpm)	Torque (in.-lb)	Initial (°F)	Final (°F)	Initial (°F)	Final (°F)	(sec)	(sec)	Ring gear	Pinion gear	Ring gear	Pinion
Score-1	06/24/2005	2866.5	1143.9	52.0	14014.0	234.0	162.5	162.8	162.9	163.1	6.0	175.5	286.7	1401.4		small scuff
Score-2	06/24/2005	2865.2	1167.0	53.1	14007.5	238.7	162.4	164.8	162.9	165.2	37.5	189.0	1790.7	8754.7	Damaged due to disengagement	Damaged due to disengagement

TABLE 5.—SUMMARY OF SHUTTLE GEAR SCUFFING TESTS CONDUCTED ON SIDE-1, BUILD-2

Test name	Date	Ring gear input			Pinion output		Oil bath temperature		Oil fling temperature		Time at condition	Total time of rotation	No. of cycles at condition		Visual assessment	
		Speed (rpm)	Torque (in.-lb)	Power (hp)	Speed (rpm)	Torque (in.-lb)	Initial (°F)	Final (°F)	Initial (°F)	Final (°F)	(sec)	(sec)	Ring gear	Pinion gear	Ring gear	Pinion
Final-1	08/09/2005	2048.1	1162.1	37.8	10012.8	237.7	80.1	88.9	78.0	87.0	314.0	462.0	10718.2	52400.1	No scuff	No scuff
Final-2	08/09/2005	1981.7	1502.6	47.2	9688.4	307.4	86.1	95.1	84.4	93.4	295.5	442.5	9760.0	47715.6	No scuff	No scuff
Final-3	08/09/2005	1497.6	1796.1	42.7	7321.5	367.4	93.5	98.3	91.7	96.5	256.5	514.0	6402.2	31299.4	No scuff	No scuff
Final-4	08/09/2005	1316.3	2001.1	41.8	6435.2	409.3	96.0	101.4	94.1	99.6	298.5	504.5	6548.6	32015.2	No scuff	No scuff
Final-5	08/09/2005	1055.2	2212.2	37.0	5158.7	452.5	90.7	93.6	88.4	91.9	164.5	270.5	2893.0	14143.5	No scuff	No scuff[a]

[a]Speed is average while being ramped up. Std dev =326 rpm for input speed.

It was then decided to test on the unused face of the gear teeth. The test conditions attained for this side-2, build-1 configuration are shown in table 4. In these tests the rig was brought up to low speed (~200 rpm) and then the full the torque was set. Then the speed was rapidly increased to the test point conditions and held for 5 sec. Then the test was stopped to inspect and photograph the gears. Unfortunately, in the last test an e-clip that restrained the high speed (14,000 rpm) shaft flung off, allowing the gears to move axially out of mesh. This event damaged side-2 of the gear teeth, as well as the spacers and shims that set the axial positions of the gears. Rough burrs were hand filed off of the teeth to allow the gears to be further tested on side-1.

A final set of tests was conducted on the first side of the teeth. See table 5 for the test conditions for side-1, build-2. The intent of this sequence of tests was to see if higher torques would cause scuffing. At a low speed the desired torque was set and then the speed increased to the test condition. The test condition was held for approximately 5 min. Then the test rig was shut down and a visual inspection and photography were performed. During test Final-5 the belts from the drive motor to pulley broke before steady conditions were obtained and testing ended.

Test Results

The only tests that generated any damage beyond normal polishing wear of the gear teeth were Back-3c, Score-1, and Score-2. The Back-3c test was conducted at an input speed, torque, and power of 2402 rpm, 664 in.-lb, and 25.3 hp. A plot of the time history of the speed, input torque, oil fling temperatures, and the pinion vibration levels for Back-3c is shown in figure 11.

It is interesting to note the fling temperature shows a sudden increase at approximately 300 sec. Just prior to this there is a spike in both the pinion and ring gear vibration and an instability in the input torque and speed measurements. This may indicate the time when the wear marks were created.

Visual inspection after the Back-3c test found half-moon-shaped wear marks near the tip of the driven side of all pinion gear teeth (fig. 12). These wear marks were slightly offset from the tooth center towards the drive motor. There were corresponding marks on the driving side of the ring gear teeth near the root (fig. 13). While the wear pattern is similar to the scuffing found on the shuttle flight gears, it is much less severe. The mark had no depth perceptible to touch.

Frequency spectra of the accelerometer located near the pinion shaft taken at 250 and 550 sec are shown in figure 14 (a) and (b), respectively. The spectra show the vibration frequencies for the first four harmonics of gear mesh frequency. If we speculate that the tooth damage observed after this test occurred at 300 sec, when the oil temperature increased, we might expect to see a difference in these vibration traces because of this damage. However, the traces do not show any indirect evidence of a change to the tooth surfaces.

Small wear marks near the tips of the driven side of the pinion teeth (fig. 15), were generated during the Score-1 test on side-2, build-1 conducted at input speed, torque, and power of 2865 rpm, 1167 in.-lb, and 53 hp. No corresponding wear was observed on the ring gear teeth as shown in figure 16. The time histories of input speed, input torque, oil fling temperature, and pinion vibration are shown in figure 17. There is no distinct corroboration of vibration rise and fling temperature rise as in the Back-3c test. There are some high vibration levels in the test however. The drop in oil fling temperature is likely due to turning off the heat gun and heat lamp prior to rotation and some initial cooling due to flinging the oil to cooler surfaces above the oil bath.

As mentioned previously, during the Score-2 test on side-2, build-1 the gear mesh disengaged at high speed. The resulting damage to the pinion and ring gear teeth is shown in figures 18 and 19, respectively. Note that cloth fibers are visible in these photos. The fibers were created by rough burrs on the damaged gears when the teeth were wiped for photographs.

The condition of the pinion and ring gear teeth at the completion of testing (after the Final-5 test) is shown in figures 20 and 21, respectively. The tooth surfaces, including the mild damage created earlier, appear to have been polished.

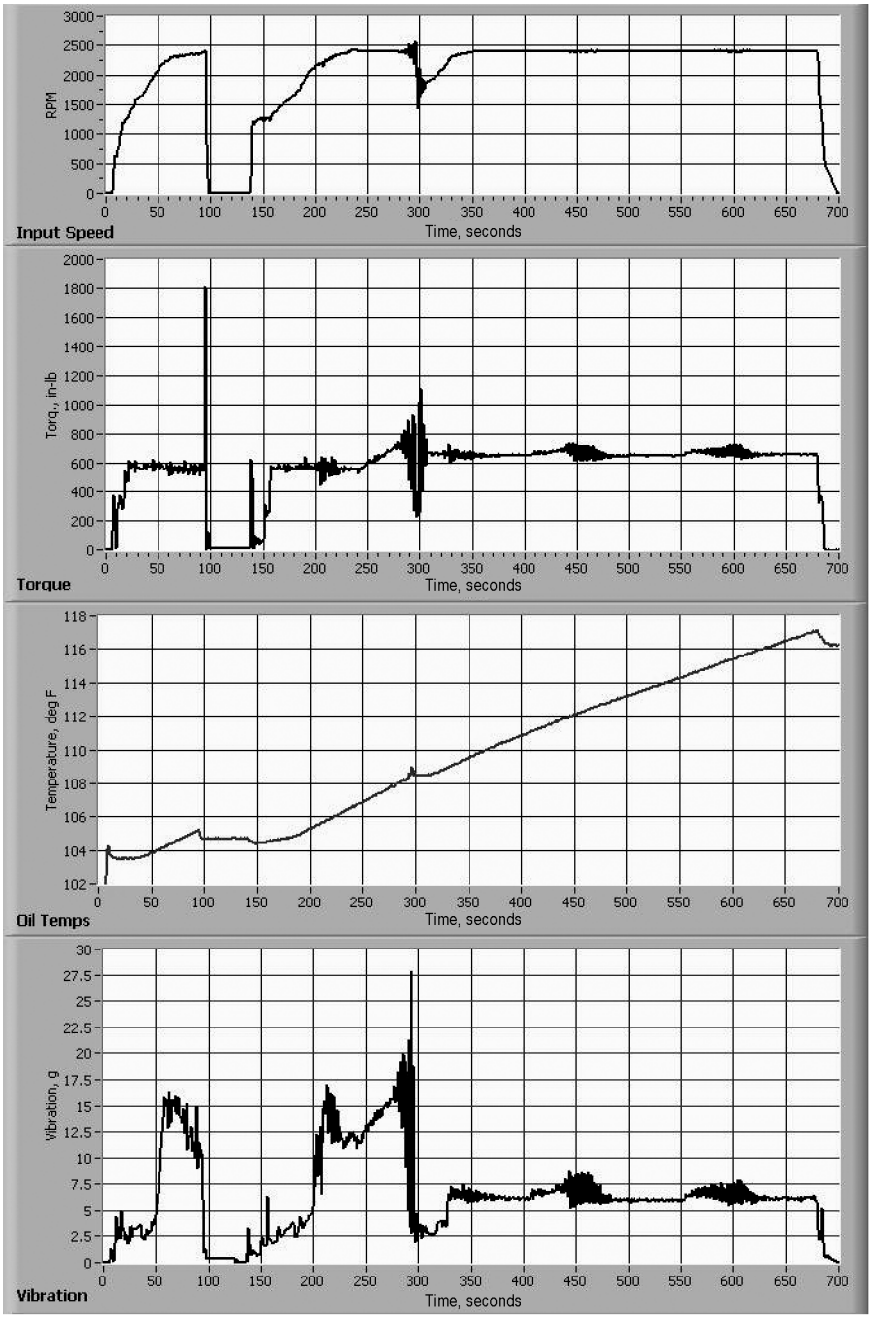


Figure 11.—Time history of test Back-3c with side-1, build-1 showing input ring gear speed and torque, oil fling temperature and vibration data from the accelerometer near the pinion shaft.

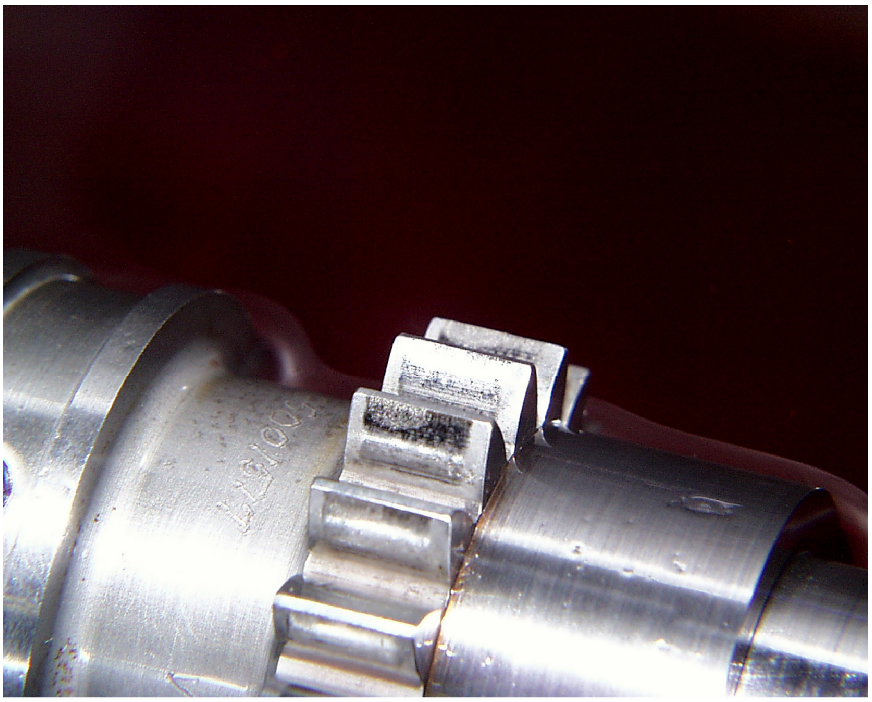


Figure 12.—Wear marks on driven side of pinion gear teeth after Back-3c.

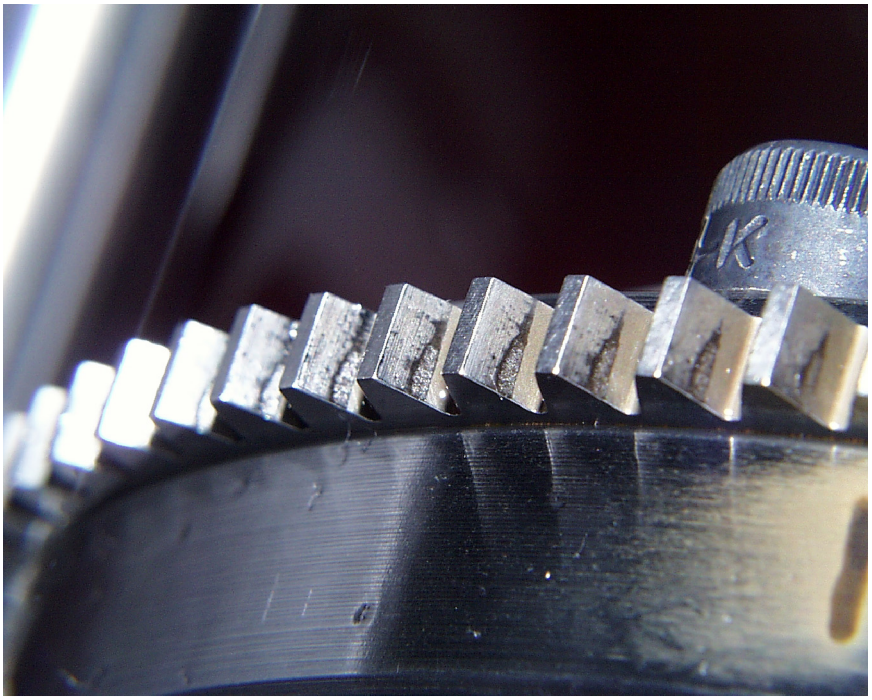


Figure 13.—Wear marks on driving side of ring gear teeth after Back-3c.

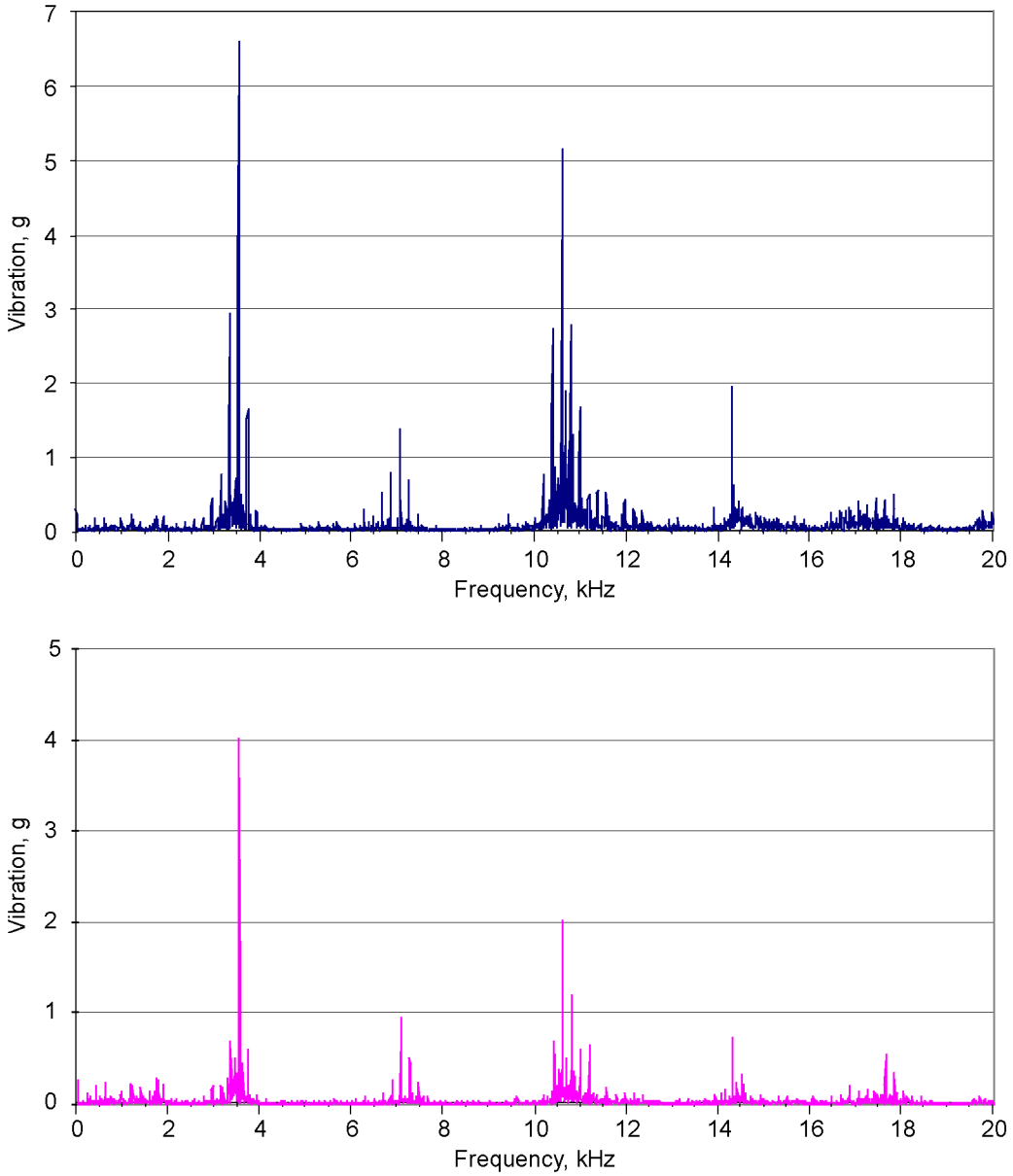


Figure 14.—Frequency spectra from test Back-3c at 250 sec (top) and 550 sec (bottom). The first harmonic of gear mesh frequency occurs at 3523 Hz (2402 rpm x 88 teeth/60 sec/min).

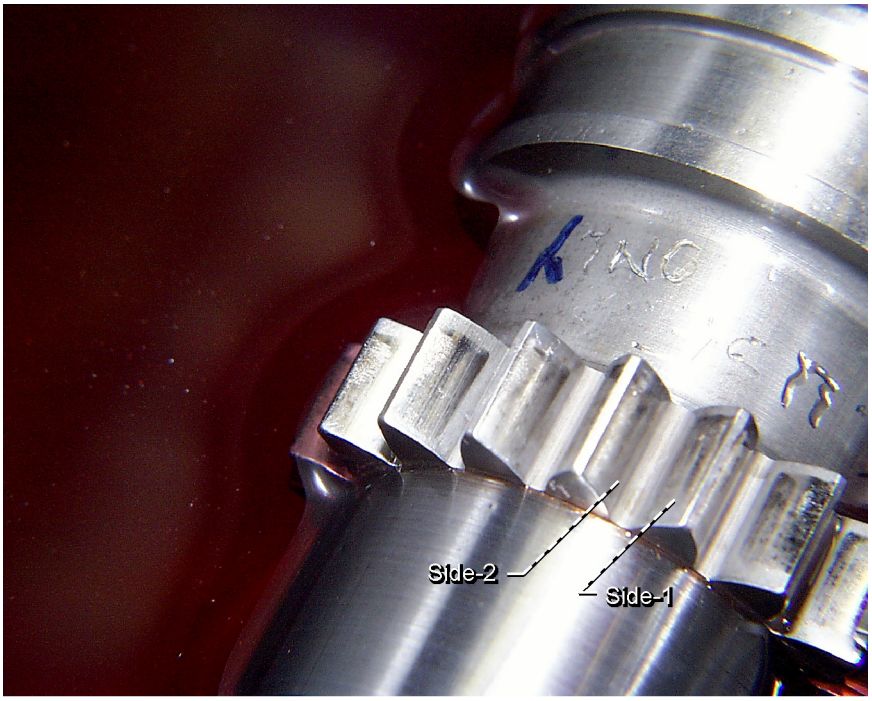


Figure 15.—Wear marks on driven side of pinion gear teeth after Score-1 test on side-2, build-1.

Figure 16.—No visible damage on driving side of ring gear teeth after Score-1 test on side-2, build-1.

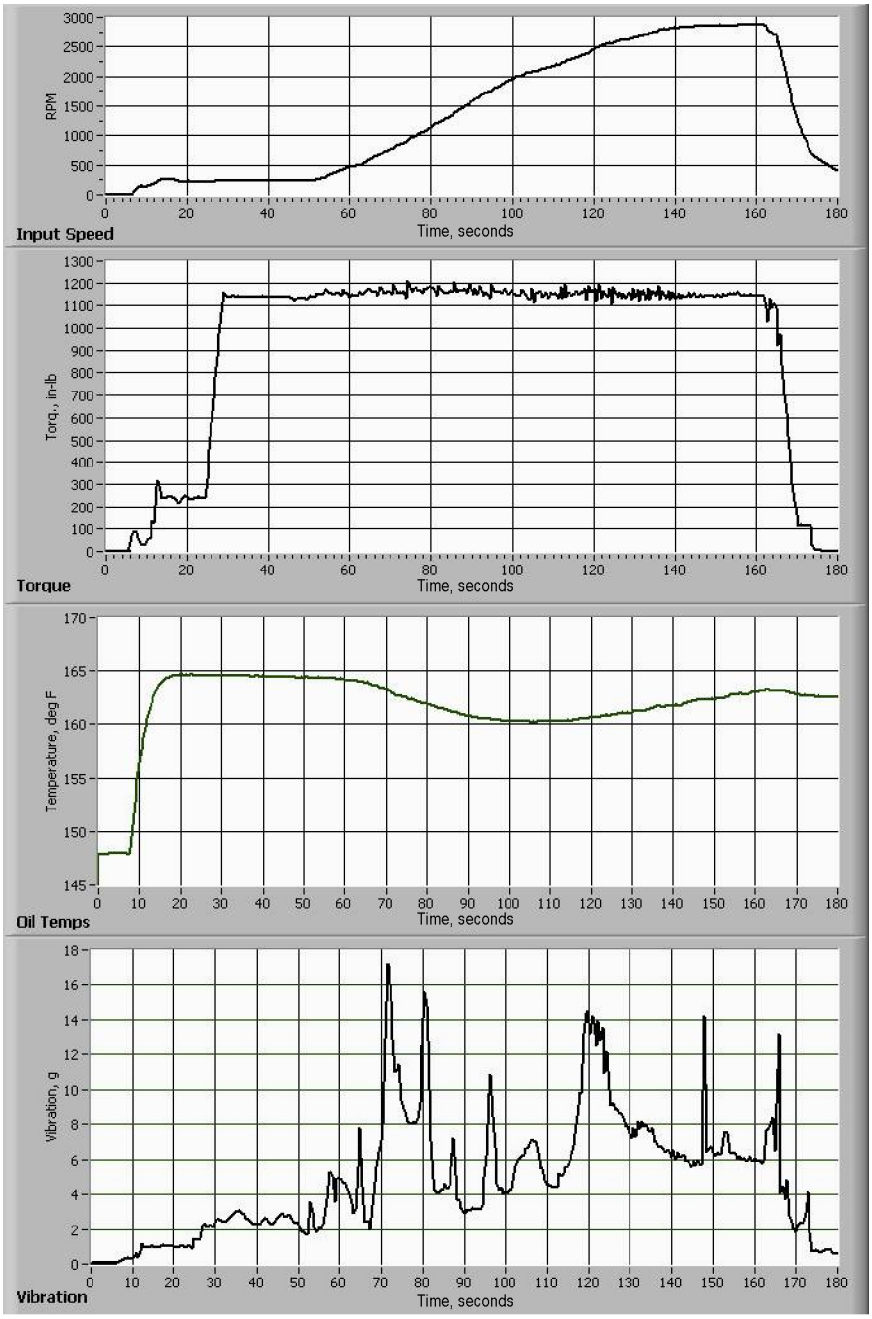


Figure 17.—Time histories of input ring gear speed and torque, oil fling temperature and pinion rms vibration level for Score-1 test on side-2, build-1.

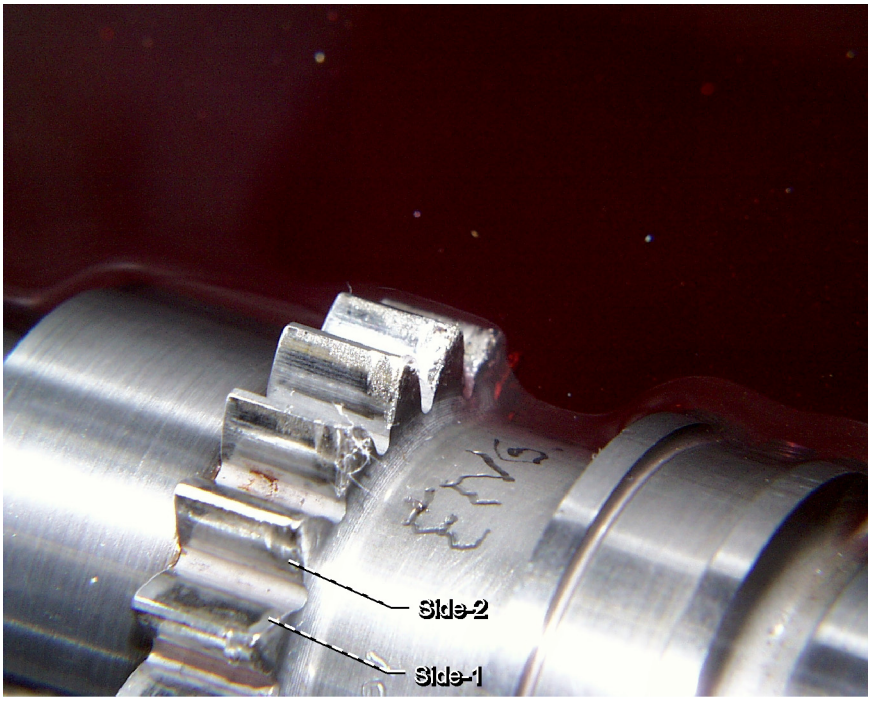


Figure 18.—Damaged teeth of pinion gear after disengagement at 14,000 rpm pinion speed during the Score-2 test on side-2, build-1. White cloth fibers are caught on teeth from wiping oil.

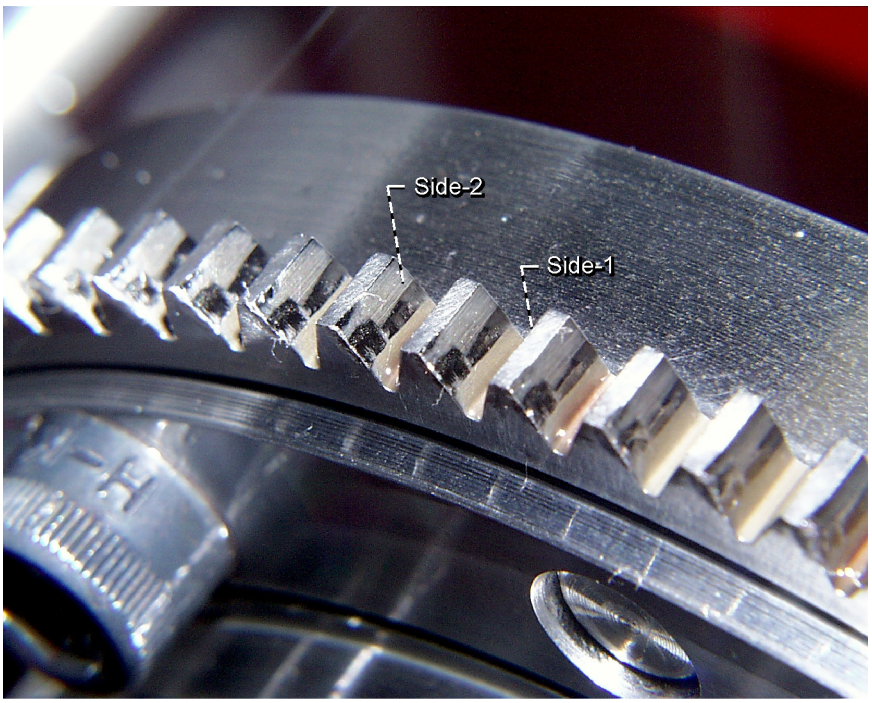


Figure 19.—Damaged teeth of ring gear after disengagement at 14,000 rpm pinion speed during the score-2 test on side-2, build-1. White cloth fibers are caught on teeth from wiping oil.

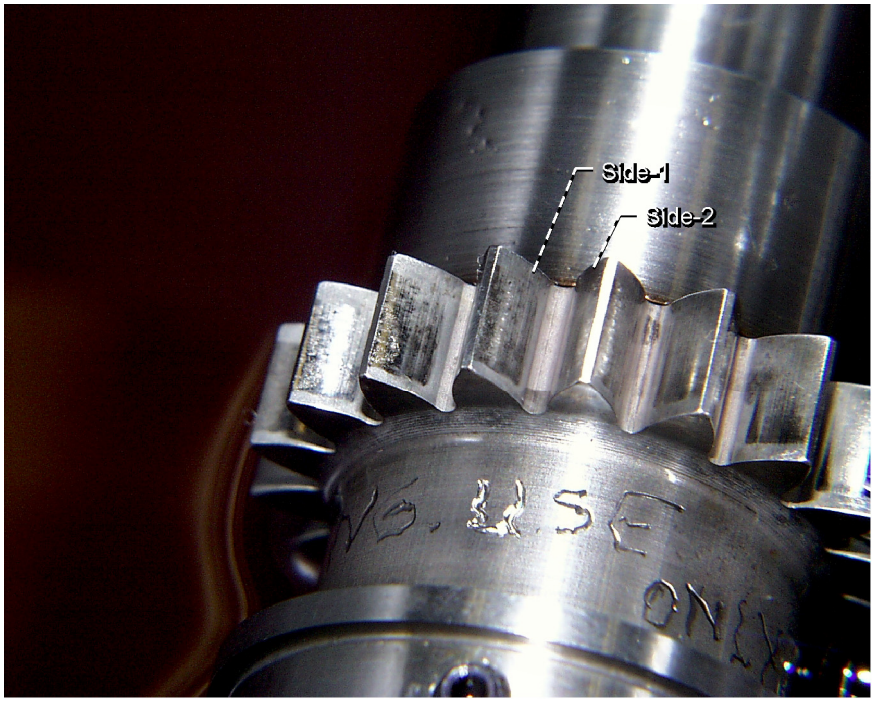


Figure 20.—Driven side of pinion gear teeth after the test Final-5 are still in good condition.

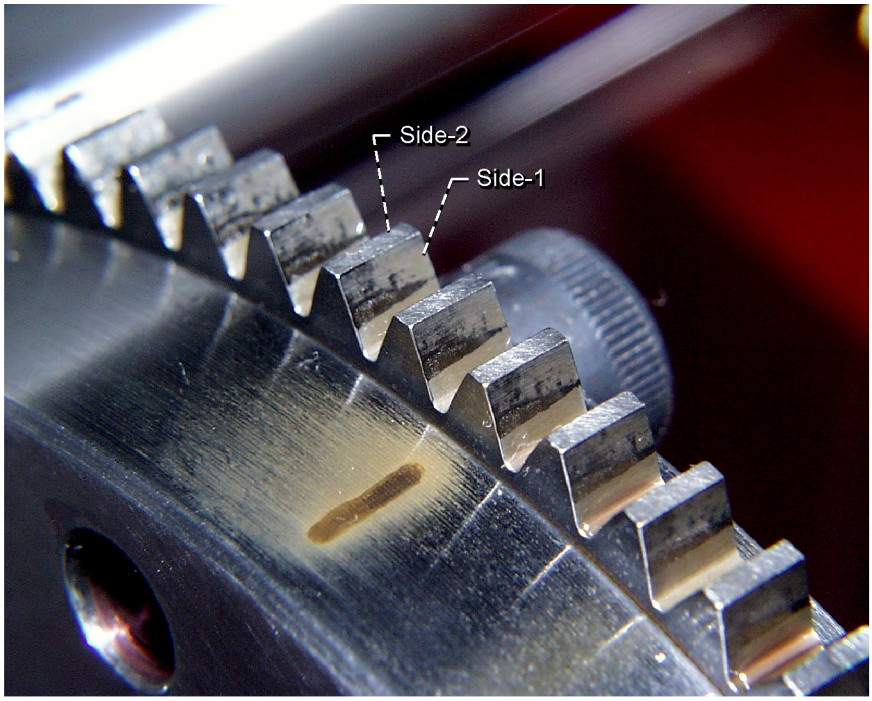


Figure 21.—Driving side of ring gear teeth after the Final-5 are still in good condition.

Discussion

The tests conducted did not create scuff marks similar to those found on the shuttle power drive unit. Possible reasons for this are:

- Geometrical differences between the flight gears that scuffed and the gears used for these tests may be sufficient to cause or prevent scuffing. Even small differences within gear blueprint tolerances provide a plausible explanation.
- The operating conditions during a back drive event, when it is thought that scuffing occurs on the shuttle, may be more severe than estimated.
- The procedure of testing used may have gradually worn away the sharp edge at the gear teeth tips, which may be responsible for the scuffing, prior to testing at operating conditions that would produce scuffing if the tips were new.
- The oil used in the shuttle power drive units was several years old. Thus, the additives in this oil may have been used up. In contrast, these tests were conducted with new oil.
- The flight gear unit and the bench test arrangement have different dynamic responses that could give rise to very different dynamic gear tooth forces and motions.

To help assess the capability of a scuffed gear to operate safely, it may be helpful to note that 18.96 min of operation at pinion speed of 7000 rpm and pinion torque of approximately 212 in.-lb were accumulated on side-1, build-1 of the gears. Of this, 7.29 min were accumulated after the wear mark was generated in the Back-3c test. Further, 30.8 min of operation at input power of at least 23 hp, with a pinion speed 7000 rpm or greater were accumulated after the wear mark was generated in the test Back-3c on side-1, build-1. An additional 14.4 min of operation at input power of 37 hp or higher at pinion speed at least 7000 rpm, and pinion torque at least 237 in.-lb were obtained on side-1, build-2.

The maximum torque applied occurred in the Final-5 test and was 2212 in.-lb at 1660 rpm on the ring gear and 452 in.-lb and 8,115 rpm on the pinion gear. This condition was obtained just prior to failure of the belts on the pulleys and was sustained for about 1 sec.

Options to consider for resolving the scuffing issue include, but are not limited to:

- Analyze the shuttle power drive unit to determine the inertial loads and transient conditions expected during back drive.
- Examine inspection reports and possibly re-inspect the pinion and ring gears to assess variations in tooth profile, particularly at the edge break at the tips of the teeth and their possible contributions towards scuffing.
- Change the test procedure to attain the most severe test conditions early on in the test matrix.
- Conduct transient scuffing tests.

Also, if a future shuttle flight includes a backdriving event that produces gear scuffing, the GRC bench test rig could be used to assess the remaining life capability of gears that were scuffed in flight. Such an approach provides the most direct assessment method short of system-level testing. However, it does require removal of the PDU unit from service for replacement of the scuffed gears.

Conclusions

The scuffing tests performed did not produce scuff marks similar to that produced during shuttle flight. Wear marks were produced on the pinion teeth near the tips and on the ring gear teeth faces during the test Back-3c, which was conducted at an input speed, torque, and power of 2402 rpm, 664 in.-lb, and 25.3 hp. Very light wear marks were generated on side-2 of the pinion gear during the test Score-1 conducted at input speed, torque, and power of 2865 rpm, 1167 in.-lb, and 53 hp.

Failure to produce scuff damage like that found on the shuttle may be due to geometrical variations between the scuffed gears and the gears tested herein, more severe operating conditions during the flight that produced the scuff than estimated, the order of the test procedures, the use of new hydraulic oil, differences between the dynamic response of the flight gearbox and the bench-test gearbox, or a combination of these.

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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.

1. AGENCY USE ONLY (*Leave blank*)

2. REPORT DATE
December 2005

3. REPORT TYPE AND DATES COVERED
Technical Memorandum

4. TITLE AND SUBTITLE
Shuttle Rudder/Speed Brake Power Drive Unit (PDU) Gear Scuffing Tests With Flight Gears

5. FUNDING NUMBERS
WBS–22–376–70–30–08

6. AUTHOR(S)
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7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
John H. Glenn Research Center at Lewis Field
Cleveland, Ohio 44135–3191

8. PERFORMING ORGANIZATION REPORT NUMBER
E–15429

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
Washington, DC 20546–0001

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
NASA TM—2005-214092

11. SUPPLEMENTARY NOTES
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12a. DISTRIBUTION/AVAILABILITY STATEMENT
Unclassified - Unlimited
Subject Category: 15
Available electronically at http://gltrs.grc.nasa.gov
This publication is available from the NASA Center for AeroSpace Information, 301–621–0390.

12b. DISTRIBUTION CODE

13. ABSTRACT ***(Maximum 200 words)***
Scuffing-like damage has been found on the tooth surfaces of gears 5 and 6 of the NASA space shuttle rudder/speed brake power drive unit (PDU) number 2 after the occurrence of a transient backdriving event in flight. Tests were conducted using a pair of unused spare flight gears in a bench test at operating conditions up to 2866 rpm and 1144 in.-lb at the input ring gear and 14,000 rpm and 234 in.-lb at the output pinion gear, corresponding to a power level of 52 hp. This test condition exceeds the maximum estimated conditions expected in a backdriving event thought to produce the scuffing damage. Some wear marks were produced, but they were much less severe than the scuffing damaged produced during shuttle flight. Failure to produce scuff damage like that found on the shuttle may be due to geometrical variations between the scuffed gears and the gears tested herein, more severe operating conditions during the flight that produced the scuff than estimated, the order of the test procedures, the use of new hydraulic oil, differences between the dynamic response of the flight gearbox and the bench-test gearbox, or a combination of these. This report documents the test gears, apparatus, and procedures, summarizes the test results, and includes a discussion of the findings, conclusions, and recommendations.

14. SUBJECT TERMS
Gears; Damage; Rudders; Mechanical drives; Wear

15. NUMBER OF PAGES
30

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT
Unclassified

18. SECURITY CLASSIFICATION OF THIS PAGE
Unclassified

19. SECURITY CLASSIFICATION OF ABSTRACT
Unclassified

20. LIMITATION OF ABSTRACT