COMPARISON TEST OF DOUBLE CIRCULAR ARC AND INVOLUTE GEARS

INTRODUCTION

The main component of an oil well pumping unit is the gear reducer. During the developmental stages of the soft tooth flank involute gear reducer in the 1950's, the service life was deemed to be low primarily from tip wear of the gear teeth. In the 1960's, the single circular arc gear was developed as a replacement for the involute gear. This solved the tip wear problem, but contributed to low bending strength resulting in large, heavy gear boxes. In the early 1980's, after ongoing development, the double circular arc gear was used as a replacement for the single circular arc and involute gear. The double circular arc gearboxes showed good results and were then manufactured domestically and abroad in increased quantities.

At that time China's oil industry was producing involute gearboxes with medium hard and hard tooth flanks to reduce the tooth wear and improve the load capacity. Presently the double circular arc reducers have replaced the single circular arc and involute reducers with soft gear teeth and made these earlier designs obsolete.

There is contrasting test data for single and double circular arc gears both in China and abroad. Therefore it was decided to conduct a comparison test between a double circular arc gear reducer with soft tooth flanks and an involute gear reducer with medium hard tooth flanks. The purpose of the test was to compare the load capacity, type of failure, noise, and vibration of the two reducers with the same material, size, and test condition.

PURPOSE AND SIGNIFICANCE OF TESTS

Purpose

a. Verify the load capacity for double circular arc and involute gear reducers.

b. Determine reason of failure of the two types of gear reducers.

c. Determine the vibration, noise, and temperature rise at each load condition.

d. Compare the analytical load capacity with the test results of the double circular arc reducer and use the results to design improved lower cost pumping unit reducers.

Significance

a. Provide actual load capacity comparison between the two types of gear reducers as well as to provide data for conducting destructive tests on reducers.

b. Verify the actual load limit capacity and accuracy of the analytical formulas used for designing future reducers.

c. Institute additional steps to improve the technology of pumping unit gear reducers.

d. Improve technology to allow reduced center distance designs that meet the same technical specifications while saving large amounts of material.

e. Examine the actual load allowance for a double circular arc reducer under existing design conditions for future consideration of modification of the design parameters and machining technology. i.e., lower gear hardness can give higher gear cutting speeds and improved machining efficiency.

f. Provide a elevated understanding of the double circular arc gear and its range of potential applications.

TEST PROCEDURE AND GEAR REDUCER DATA

Test Procedure

There are two basic types of test setups that could be used, the open loop and closed loop or back to back tests. The open loop requires more power and is less economical to run for a long duration test. The closed loop test method circulates the power through the loop of the two gear reducers, with the output and the input shafts of each reducer connected to each other (see Figure 1). A method of applying torque is placed in one of the connecting shafts, usually the high speed or lower torque shaft. The complete set up of the two reducers is driven by an external drive. This method is responsible for supplying only the losses of the system, usually about one tenth or less of the circulating power of the closed loop.

The test setup was composed of one double circular arc reducer and one involute reducer connected at the output shafts by a rigid shaft and couplings. The input shafts were connected with shaft, couplings, torque loader, and torque meter. A 13.4 HP motor and belt drive was used to supply power to the closed loop test system.

Each torque load was set by the torque unit in a static condition. After one hour of operation the torque level had decreased slightly, remaining fairly constant and was recorded as the dynamic torque.

Instrumentation consisted of torque meter, thermocouple for temperature, vibration and noise measurement equipment and strain gauges for torque. The test set up is shown in Figure 1 and the reducer parameters are given in Table 1.

Standard Used To Determine Failures.

1. A gear is considered failed when it has pitting or wear over 80% of the contact surfaces.

2. A gear is considered failed if cracks are found at the gear tooth root using a magnifier.

Procedure For Double Circular Arc Gear Loading Tests

Prior to the start of the load tests, the gears are run for 10 hours at no load and 20 hours at 480 in-lb. From this test the dual contact lines can be checked for correct contact at the pitch line. If the contact is proper the test is continued.

The gear material is a steel with a hardness of HB = 300

Its basic cycle time is:

$$N = \frac{1.5 \times (HB - 30) \times 10^6}{50 - .04HB}$$

$$N = \frac{1.5 \times (300 - 30) \times 10^6}{50 - .04 \times 300} = 1 \times 10^7 \text{ cycles}$$

Therefore the time needed for one basic cycle time is:

$$T = \frac{N}{60n} = \frac{1 \times 107}{60 \times 335} = 498 \text{ hours}$$

$$n = \text{pinion RPM} = 335$$

Tests were performed according to the test program up to the safe loading parameters determined from calculations and investigations of production units (see Table 2). Since the double circular arc reducer had a very high loading capacity, the first two loading steps were run for 20 and 25 hours respectively. After 70 hours at 2070 in-lb load, a few small surface pits were observed. However, these small surface pits disappeared after 193 hours at the 3341 in-lb load condition. This wear in phenomenon indicated that the surface pits were caused by some defects in heat treatment. After the final test of 130 hours at 4113 in-lb which was two times the design load and the limit load for the connecting shaft, the gears showed no signs of surface distress, pitting or cracks in the tooth root.

Eight points were considered for noise measurement. However, only four were chosen because of the interference noise from the drive motor (see Figure 1). The distance from the top surface of the gearbox to the sound pickup is one meter. The frequency spectrum of the main noise value at the highest load was 124 hz. This frequency is caused by the gear mesh frequency. The integral average noise of the double circular arc reducer was 68.1 dB(A) and the maximum single measured noise level was 73 dB(A) (see Table 3).

Reducer vibration levels were measured in three directions, the x, y, and z planes for both reducers. The vibration levels in the x direction were heavier than the y and z directions.

The vibration levels of the double circular arc reducer were slightly higher than the involute reducer but the values were generally very low with a maximum value of 2.1 microns. (see Table 4).

Procedure For Involute Gear Loading Tests

The gear material is a medium hard tooth with a hardness of HB = 345.

Its basic cycle time is:

$$N = \frac{1.5 \times (HB\ 30) \times 10^{6}}{50 - .04HB}$$

$$N = \frac{1.5 \times (345 - 30) \times 10^{6}}{50 - .04 \times 345} = 1.3 \times 10^{7}$$

The time required for one basic cycle time is:

$$T = \frac{N}{60n} = \frac{1.3 \times 10^{7}}{60 \times 335} = 646 \text{ hours}$$

The involute gears used in this test were medium hard and they meet both AGMA and Chinese standards. They have a low safety coefficient and a history of surface distress or micropitting.

The loading tests were performed for the designed torque (see Table 5). The first two loading steps were completed without problems. On the third load test after 200 hours, some surface distress or micropitting was observed. After 200 hours at the fourth load test of 2445 in-lb, heavy surface distress was observed on 80% of the gear teeth covering an area of 30% to 40% of the tooth surface. According to the failure standard, this gear reducer is considered to be failed.

The method used to measure the noise level was the same for both gear reducers and the distance of the microphones from the gear case was the same in both tests. The average value of the noise for the involute reducer was 67 dB(A) with a maximum value of 68 dB(A), which was slightly less than the double circular arc gear reducer (see Table 6).

CONCLUSIONS

Loading Capacity

The double circular arc reducer completed six step loading tests for a total time of 599 hours. The fourth step was 45% overload for 193 hours. The fifth step was 82% overload for 161 hours. The sixth step was 107% overload for 130 hours. The double circular arc reducer completed a total of 484 hours at the 145% to 207% load condition without failure. **It is concluded that the double circular arc gear reducer has at least a 150% over design capacity.**

The involute gear reducer completed four load steps for a total test time of 652 hours. Surface distress and micropitting began to occur at 80% of the design capacity of the reducer and the reducer was destroyed at 200 hours at 106% of the design load capacity. **It is concluded that the involute reducer has a load capacity of only 80% of its design capacity.**

Noise And Vibration Of Two Types Of Reducers

The double circular arc gear reducer measured slightly greater noise levels than the involute reducer of only two dB's. The vibration of the double circular arc reducer measured slightly greater vibration than the involute reducer; however both results were extremely low with a maximum of only 81.5 μin (2.1 μm).

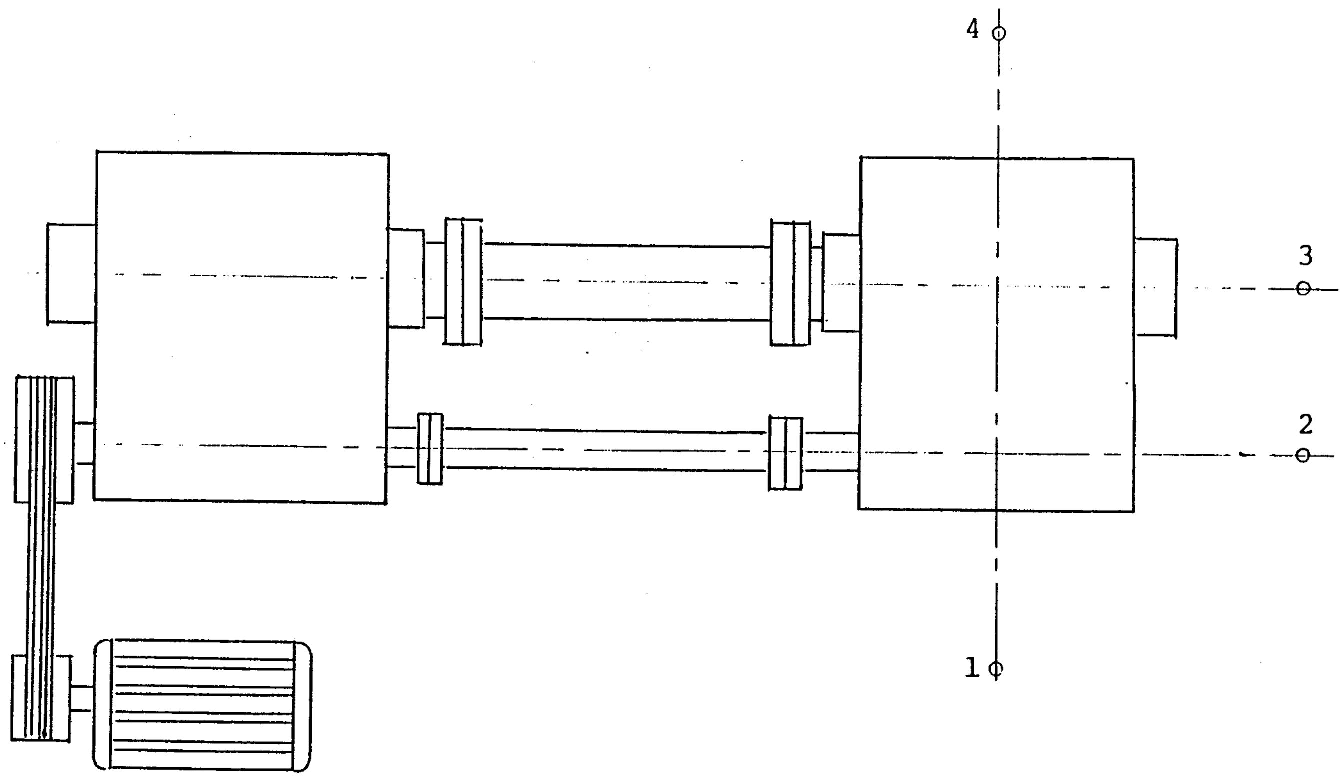

Figure 1. Closed loop test setup showing location of noise measurements

Table 1. Technical Data for Test Gear Reducers

		Involute gear with medium hard tooth flank	Double circular arc gear
Center distance	A	500mm 19.685in	500mm 19.685in
Gear ratio	i	31.73	31.73
Output torque	M_{out}	700 kg-M 60,768 lb-in	700 kg-M 60,768 lb-in
Driving shaft	M_{in}	22 kg-M 1,910 lb-in	22 kg-M 1,910 lb-in
Pressure angle	αn	20^0	24^0
Tooth number	Z1/Z2 Z3/Z4	18/102 22/112	18/102 22/112
Helix angle	$\beta 1$ $\beta 3$	$25^0 50'31"$ $28^0 21'27"$	$25^0 50'31"$ $28^0 21'27"$
Module	Mn1,2 Mn3,4	3mm/8.47dp 4mm/6.35dp	3mm/8.47dp 4mm/6.75dp
Face width	B1,3 B3,4	45mm/1.77in 50mm/2.36in	45mm/1.77in 60mm/2.36in
Material	Z1.Z3 Z2,Z4	40CrNiMoA 35SiMn	40CrNiMoA 35SiMn
Lubricant		320# extreme pressure industrial gear oil	250# extreme pressure industrial gear oil
Heat treatment Hardness	Z1,Z3 Z2,Z4	HB340-375 HB285-320	HB280-310 HB240-270
Machining		Gear Hobbing	Gear Hobbing

Table 2. Loading Condition of Dual Circular Arc Gear Boxes

	Loading Number						
	1	2	3	4	5	6	Total
Input Static Torque Kg-m lb-in	12.15 1055	17.8 1545	23.84 2070	34.48 2993	41.91 3639	47.38 4113	
Input Dynamic Torque kg-m lb-in	10.66 7925	16.71 1451	20.1 1745	31.93 2772	40.12 3483	45.51 3951	
Percentage of Full Load %	48%	76%	91%	145%	182%	207%	
Cycles	$4x10^5$	$5x10^5$	$1.4x10^6$	$3.8x10^6$	$3.2x10^6$	$2.6x10^6$	
Operating time (hour)	20	25	70	193	161	130	599
Condition of tooth Surface	Two Contact Bands	Bright Normal	Normal	Normal	Normal	Normal	

Table 3. Record of Noise Measurement for Double Circular Arc Gear Reducer
Unit dB(A)

	Measuring Point					
Load	1	2	3	4	Average	Background Noise
12.15 kg-m 1055 lb-in	68.5	68	67	66.5	67.5	
23.84 kg-m 2070 lb-in	64	64	64	64	64	53
34.48 kg-m 2993 lb-in	71	66.5	66.5	65.5	68.1	51
41.92 kg-m 3639 lb-in	73	68	68	57.4	66.6	56
47.38 kg-m 4113 lb-in	70.5	67.5	65.5	61	67.3	50

Note: The background noise modifications have been made for the data of each point in Table 4.

Table 4. Record of Vibration Measurement Units (μ m)

Vibration of double circular arc gear reducer				Vibration of involute gear reducer			
Load	Z	X	Y	Load	Z	X	Y
23.84 kgf-m 2070 lb-in	1.47	0.63	0.84	16.72 kgf-m 1452 lb-in	0.84	0.7	0.98
34.48 kgf-m 2993 lb-in	1.4	1.82	1.26	21.63 lgf-m 1878 lb-in	0.56	0.28	0.42
41.92 kgf-m 3639 lb-in	0.91	1.47	1.19	28.17 kgf-m 2445 lb-in	0.42	0.28	0.42
47.38 kgf-m	1.33	2.1	1.4				

Table 5. Loading State of Involute Gear Reducer

	Loading Number				Total
	1st	2nd	3rd	4th	
Static Torque kg-m lb-in	13.19 1145	16.72 1452	21.63 1878	28.17 2446	
Dynamic Torque kg-m lb-in	9.5 825	14.62 1269	18.75 1628	23.24 2018	
Percentage of full load	43%	66%	80%	106%	
Operating time (hour)	92	160	200	200	652
Cycles	$1.84x10^6$	$3.2x10^6$	$4x10^6$	$4x10^6$	
Condition of Tooth Surface	Smaller Contact Area	Bright Tooth face Little Wear	Some Surface Distress	Considerable Surface Distress	

Table 6. Record of Noise Measurement for Involute Gear Reducer Unit dB(A)

Load	Measuring Point				Average	Background Noise
	1st	2nd	3rd	4th		
16.72 kg-m 1406 lb-in	65	62	60	60	62.2	50
21.63 kg-m 1878 lb-in	64.5	61.5	60.5	60	62	48
28.17 kg-m 2446 lb-in	66	62	60.5	60	62.8	52

Note: The background noise modifications were made for the data of each point in Table 4.