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Gear and Transmission Research at NASA Lewis Research Center

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Abstract

This paper is a review of some of the research work of the NASA Lewis Research Center Mechanical Components Branch. It includes a brief review of the NASA Lewis Research Center and the Mechanical Components Branch. The research topics discussed are crack propagation of gear teeth, gear noise of spiral bevel and other gears, design optimization methods, methods we have investigated for transmission diagnostics, the analytical and experimental study of gear thermal conditions, the analytical and experimental study of split torque systems, the evaluation of several new advanced gear steels and transmission lubricants and the evaluation of various aircraft transmissions. The area of research needs for gearing and transmissions is also discussed.

NASA Lewis Research Center

The NASA Lewis Research Center (LeRC) fig. 1. is located in Cleveland Ohio in the Midwestern U.S.. We are one of 11 major NASA installations and are the center for power systems NASA, meaning our research and development efforts are concerned with power systems such as jet engines, space power and other power sources. LeRC is currently spending most of it's resources for the development of aeronautic systems. We currently have approximately 2500 employees with about 50% scientist and engineers. We currently have research efforts for aircraft engines and related components such as compressors, combustors, turbines, inlets and nozzles for both sub-sonic, super-sonic and hyper-sonic aircraft and some-space related activity such as microgravity and space power .

There are several large research facilities located at LeRC, which include an 8ft × 6ft and 10ft × 10ft supersonic wind tunnel, two jet engine altitude test facilities, a 400 foot drop tower, a large high temperature air facility, an aircraft icing facility, a space power facility and numerous other smaller research facilities.

The Mechanical Components Branch has the responsibility for conducting research on transmissions and gearing for rotorcraft and other aerospace applications fig. 2. Our primary goals are to reduce the weight and noise and increase the life and reliability of transmissions and gearing. We therefore have a variety of research and development programs designed to help us accomplish our goals. We are conducting research on advance transmission concepts, transmission diagnostics, advanced gear materials, advanced gear lubricants, gear vibration and noise, gear thermal analysis and analytical optimization programs for improved transmissions design methods.

Crack Propagation

Gear tooth crack propagation can have a disastrous effect on a transmission. We have conducted analytical and experimental studies on how the rim thickness affects the propagation of gear tooth bending fatigue cracks ref. 1. These experimental and finite element analytical studies show that there is a minimum rim thickness required to prevent rim failure when a gear tooth is subjected to tooth breakage. These results are shown in fig. 3, where a rim thickness to tooth height (t/h) of 1.0 or more would prevent a rim failure.

Noise

Spiral bevel gears are used in most rotorcraft transmissions and have been shown to produce high vibration and noise in some cases. The OH-58 input spiral bevel pinion had high vibration and noise levels that were much higher than other gears in the transmission. A study was conducted where the OH-58 spiral bevel pinion geometry and machine settings were redesigned by Prof. Litvin at the University of Illinois to produce less transmission error and noise ref. 2. There was only a very small change required in the gear tooth geometry. Tests results using this new low noise design are shown in fig. 4, ref. 3 and indicate substantial reductions in noise, vibration and bending stress.

Noise fluctuations in transmissions are caused by the dynamic load on the gear teeth as a result of tooth deflection and profile errors. We have analytical and experimental programs to study the effects of gear design and profile modifications on gear tooth dynamic loads and gearbox noise. Figure 5, ref. 4 is a plot of measured and predicted dynamic loads at various speeds and loads for gears with different tooth profile modifications. As can be seen the dynamic loads were reduce about 30% at the high loads with this tooth profile modification. Also the gears with the profile modification had higher dynamic loads at very light loads which shows that they are over modified for this condition.

Design Optimization

Transmission design should be optimized to provide maximum power at the lowest weight and longest life. Many transmissions have not been designed for this condition. Transmission design optimization programs can provide insight into possible methods to improve the transmission design. NASA LeRC has been conducting research on various optimization methods to provide ways to improve transmission design. Figure 6 shows how the use of an optimization program can show the affect on transmission life for different number of planets and planetary ratios ref. 5. The life increases for increased number of planets, as a result of reduced bearing and gear loads, and also increased with increased planetary ratio except for the 3 planet drive above a ratio of 4. The planetary drive can therefore be optimized for lower weight and longer life.

Diagnostics

In recent years transmission diagnostics has gained importance as a method to reduce maintenance costs and improve the overall efficiency of transmissions. Transmission diagnostics is a very important tool to predict when failures are about to occur and may eventually be used to determine the remaining life of a transmission by predicting when the failure is in the final stages. We have a continuing research effort in transmission diagnostics which includes vibration diagnostics and debris monitoring methods. We have developed some new vibration diagnostic methods, NA4 and NA4* ref. 6, which modifies the FM4 method of Stewart and produces a more robust signal as shown in fig. 7. Here the FM4 signal remains fairly constant while both the NA4 and NA4* signals show a definite indication of failure in the spiral bevel gear. We have also looked at existing diagnostic systems for monitoring and debris monitoring.

We are also developing a numerically simulated method using the joint time frequency domain and the Wigner-Ville distribution method for predicting the surface fatigue failure of gears. Figure 8, ref. 7 shows the results of the Wigner-Ville distribution method for vibration diagnostics for the same spiral bevel gear failure shown in fig. 7. Here the numerically simulated Wigner-Ville vibration signature is compared to an experimental Wigner-Ville vibration signal for the pitted gears. The numerically simulated signal provides a close match of the experimental signal. Using this method we hope to provide a system that would read the Wigner-Ville patterns and recognize an impending failure.

The goal of the diagnostic research is to develop programs to allow longer operating time between overhaul to reduce the maintenance cost and predict the amount of time remaining in the useful life of the transmission before maintenance is required as shown in fig. 9.

Gear Thermal Analysis

We are conducting research programs to better evaluate the gear tooth surface temperature under various operating conditions. The standard scoring programs are not very accurate at predicting the scoring failure of gears therefore a reliable method is needed to predict under what conditions scoring will occur. We have therefore conducted research efforts at calculating the temperature of gears and measuring the operating temperature of gears at various operating conditions. Figure 10, ref. 8 is an analytical plot of gear tooth differential temperatures between the oil jet and gear tooth at different oil jet impingement depths. The larger impingement depth provides much better gear tooth cooling. Figure 11 is the measured gear tooth temperatures for several loads and oil jet pressures. Increased oil jet pressure increases the impingement depth and provides lower operating temperature. We are presently working on new and better thermal analysis methods to improve the accuracy and reduce the computer time for predicting gear tooth temperatures.

We have also developed a finite element method for predicting temperatures in spiral bevel gears. Figure 12(a) ref. 9 shows the transient temperature map of a spiral bevel gear tooth. This program can generate a series of temperature plots showing the gear in motion with changing temperature maps of the gear tooth. Figure 12(b) shows the experimentally measured temperature of the spiral bevel gears.

Split Torque and Face Gears

As part of the Advance Rotorcraft Transmission (ART) program the McDonnell Douglas company proposed a split torque transmission using a face gear drive as shown in fig. 13, ref. 10. The face gear pinion is floating to balance the load between the two face gears. The face gear design is shown in fig. 14 and uses a standard involute pinion running with a specially cut face gear. The first set of face gears that we evaluated could only be cut with Hobbs and therefore could not be hardened to the desired hardness for heavily loaded gears. The initial testing with the unhardened face gears gave early fatigue failures as shown in fig. 15. We therefore had to develop a method fig. 16, to produce a face gear with a hardened and ground teeth that would provide much longer fatigue life. Professor F. L. Litvin ref. 11 developed the necessary geometry and machine settings to allow the manufacturer to grind the hardened face gears. After some initial problems with grinding methods the manufacturer was able to produce a hardened and ground face gear that provides a reasonable fatigue life.

Since split torque methods can provide a weight reduction for rotorcraft transmissions. We have been developing methods for designing balanced split torque transmissions. In split torque transmissions it is desirable to have equal torque split between the different torque paths. Testing with various torque split methods have revealed some variation in the torque to each path ref. 12. An analytical program was developed ref. 13 to analyze split torque systems and provide a method to balance the torque. This program was used to analyze and modify the ART Sikorsky split torque transmission and resulted in balanced torque on the four final drive pinions as shown in figs. 17 from ref. 13.

Gear Materials and Lubricants

As part of the program to improve transmission weight, and reliability we have been testing and evaluating gear materials and lubricants for several years for the purpose of improving the surface fatigue life and the operating temperature limit of gears. One method of improving the surface fatigue life of gears is to shot peen the gear flanks to increase the subsurface residual compressive stress. The increased fatigue life can be calculated using the change in the subsurface residual stress. Two groups of hardened standard test gears were shot peened at different intensities and endurance tested to determine the effect of the shot peening on the gear life. Figure 18 ref. 14 and 15 is a plot of the measured subsurface compressive residual stress of the two shot peened groups compared with the gears without shot peening. As shown in fig. 18 the higher shot peening intensity produces higher and deeper compressive residual stresses in the gears. Figure 19 shows the 10 percent surface fatigue life for a group of 20 fatigue tests for each shot peened condition. The gears with a shot peened intensity of 7.5 had a fatigue life improvement of over 50 percent while the gears with a shot peened intensity of 16 had a surface fatigue life improvement of over four times the standard ground gears.

We have evaluated several gear materials over the past thirty years with many materials showing improvements over that for the standard AISI 9310 aircraft gear material refs. 16 to 20. Figure 20 shows the 10 percent lives of 13 of the materials we have evaluated. Nine of these materials had a surface fatigue life that was more than two times the life of 9310 while four of the materials test had lives that were several times the life of the standard gears. The life of the M50-NiL gears were more than ten times the life of the standard gears.

NASA has been working with the U. S. Navy to develop advanced lubricants for gear transmissions. We have evaluated several lubricants and lubricant additives to determine what effect the lubricant and additives have on the surface fatigue life of standard test gears. Table 1 is a list of seven of several lubricant that have been evaluated in our gear test facility ref. 21. Figure 21 is a Weibull plot of the surface fatigue life of the seven lubricants and shows the fatigue life in millions of stress cycles versus the percent of specimens failed. The fatigue life of the gears was dependent on both the additive and the lubricant viscosity such that a lubricant with a higher viscosity but without a good additive would produce a lower fatigue life than a lubricant with a lower viscosity. Lubricant C had the same fatigue life as lubricant A which had a higher viscosity but no boundary additive package. Lubricant F and G had the same viscosity but lubricant F did not have a good boundary additive package.

If we plot the relative 10 percent life of the gears with the lubricants versus the specific film thickness L the results is the curve shown in fig. 22 where the life for the 5 centistoke lubricant was taken as 1. From this figure, the advantage of having a specific film thickness greater than one is clearly evident.

Transmissions

We have two helicopter transmission research facilities we use to conduct various transmission research programs with transmissions. Figure 23 is a view of our 500HP transmission facility which we have utilized to conduct several transmission research programs. These include evaluation of vibration, efficiency, noise, gear tooth strain, transmission diagnostics and gear tooth crack propagation studies ref. 22. We also have a 3000 HP transmission test facility, fig. 24 that can evaluate the Sikorsky comanche twin engine input transmission. We have conducted tests with this transmission in the past to look at efficiency, noise, vibration and gear and bearing temperatures ref. 23.

NASA was involved in a high efficiency turboprop program a few years ago to develop a fuel efficient aircraft transport program. Figure 25 is a cross section of the contra-rotating gearbox ref. 24, developed for NASA by the Allison Engine Co. This was a 13000 HP transmission that drove a high speed contra-rotating propeller. The system was developed and tested and provided a very fuel efficient system. The program was not continued because of the low cost for fuel and the high cost of developing a new aircraft.

Future Research Needs for Gearing and Transmissions

There is a requirement for improved gear dynamic and noise codes for helical and spiral bevel gears that would aid the transmission designer in the design of low noise gear boxes. These codes need to address the problems of misalignment, optimum profile modifications shaft deflections and other related dynamic conditions.

Wear and scoring prediction in gearing has never been developed to the point that would accurately predict the effect of various parameters on this type of gear failure. A through understanding of the scoring phenomenon is difficult and requires an in-depth knowledge of several scientific disciplines. Blocks temperature method has been in use for many years but is not very accurate and does not consider some of the variables necessary for best results.

The methods used by most people for gear lubrication and cooling does not provide the optimum efficiency and gear cooling that can be obtained with a more precise theory or method. We have all seen transmissions that are operating at less than optimum simply because the lubrication and cooling method is not properly design. I have found that most gear people provide excessive amounts of lubricant and usually in the wrong position for best results. High speed gearing is especially sensitive to improper lubrication schemes.

Transmission diagnostics is developing into a requirement for many transmissions, especially for aircraft where the transmission reliability is of prime importance. Recent developments in diagnostics have made it possible to detect some failures before they become catastrophic. This is a very important area of research that can provide measurable benefits for the gear and transmission and aircraft industry.

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Table 1.—Lubricant Properties of Seven Lubricants

NASA identification	Lubricant						
	A	B	C	D	E	F	G
Kinematic viscosity							
311 K (100 °F)	21.0	29.7	12.2	27.6	34.7	60.54	52.4
372 K (210 °F)	4.31	5.39	3.2	5.18	7.37	8.84	8.98
Flash point, K (°F)	516(470)	539(510)	489(420)	544(520)	519(475)	519(475)	561(550)
Pour point, K (°F)	200(-100	217(-70)	—	211(-80)	214(-75)	228(-49)	213(-76)
Specific gravity at 289 K (60 °F)	1.00	1.00	-	0.995	0.947	0.96	0.986
Total acid number (tan) Mg Koh/g oil	0.07	0.03	0.15	0.40	0.06	0.00	1.01
EHL film thickness							
h mm (min)	0.43(17)	0.52(20)	0.34(13)	0.50(20)	0.66(26)	0.76(30)	0.76(30)
L ratio (h/σ)	0.75	0.90	0.58	0.87	1.15	1.33	1.33
Specification	none b. stock	Mil-L-23699	Mil-L-7808J	DOD-L-85734	DERD-2487	none	none

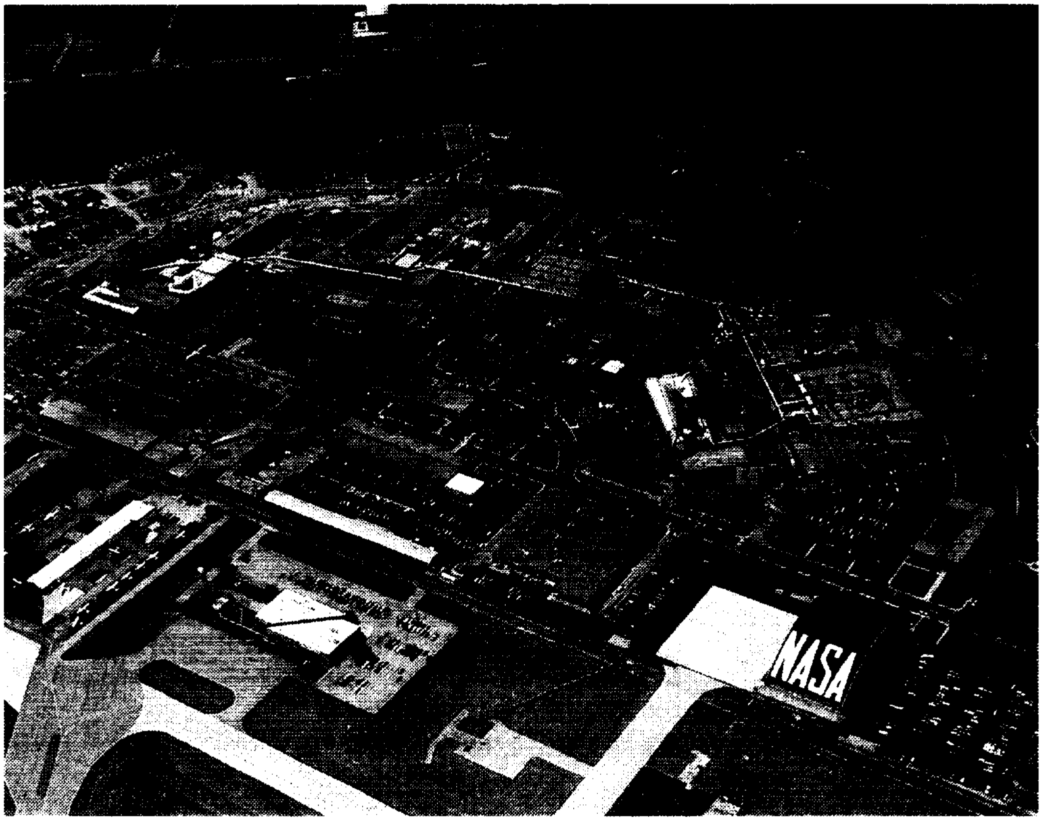


Figure 1.—NASA Lewis Research Center.

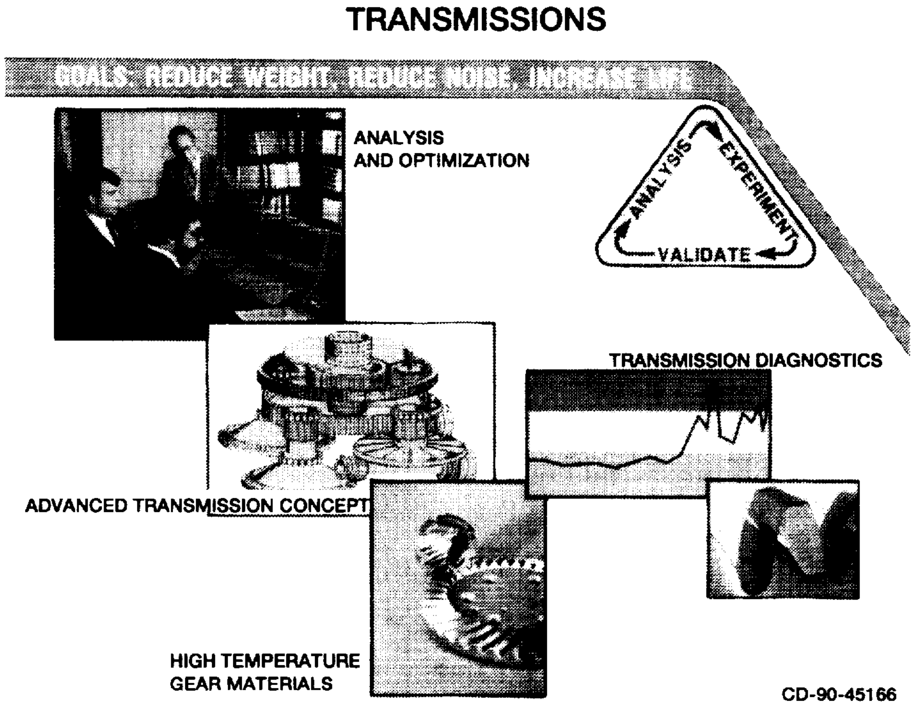


Figure 2.—Mechanical components branch.

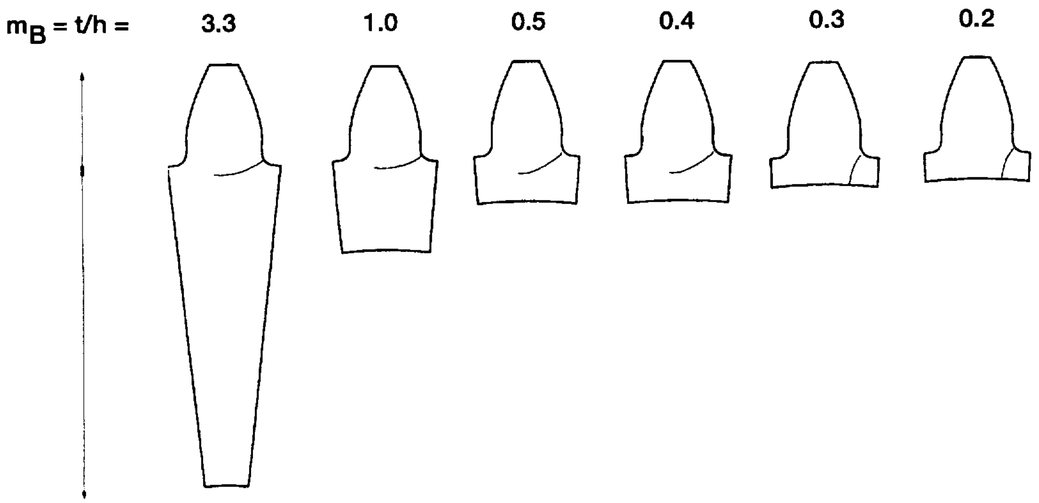


Figure 3.—Effect of rim thickness on crack propagation direction ref. 1.

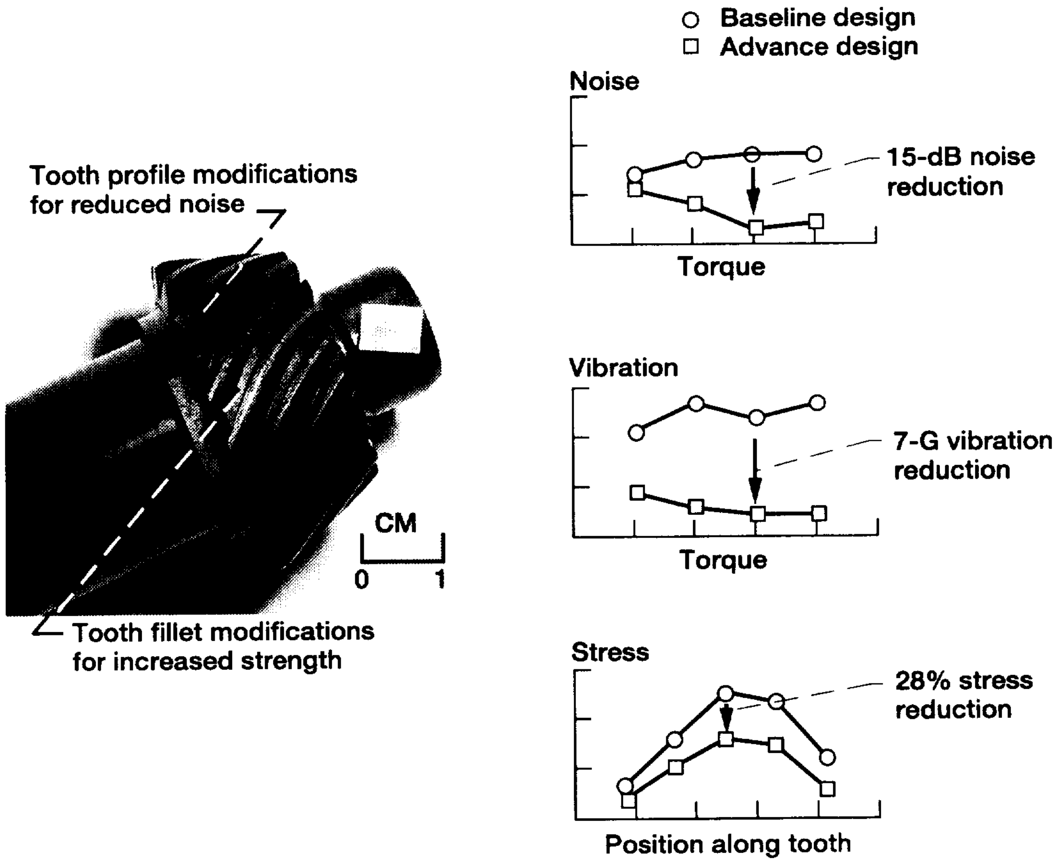
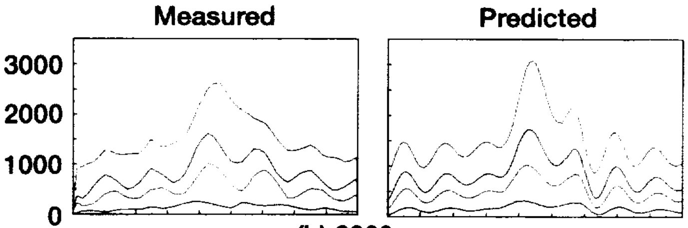
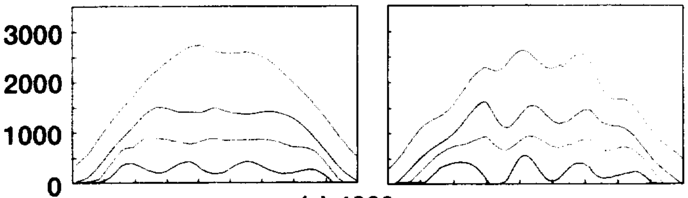


Figure 4.—Results of advanced low noise spiral bevel gear design ref. 3.

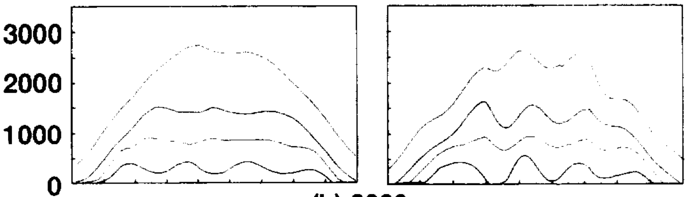


(b) 2000 rpm

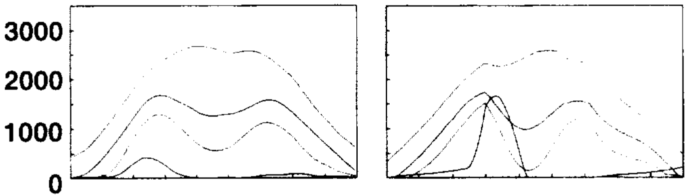


(c) 4000 rpm

Measured and predicted dynamic loads, test gear set A, no relief



(b) 2000 rpm



(c) 4000 rpm

Measured and predicted dynamic loads, test gear set D, intermediate relief

Figure 5.—Measured and predicted dynamic load on spur gears ref. 4.

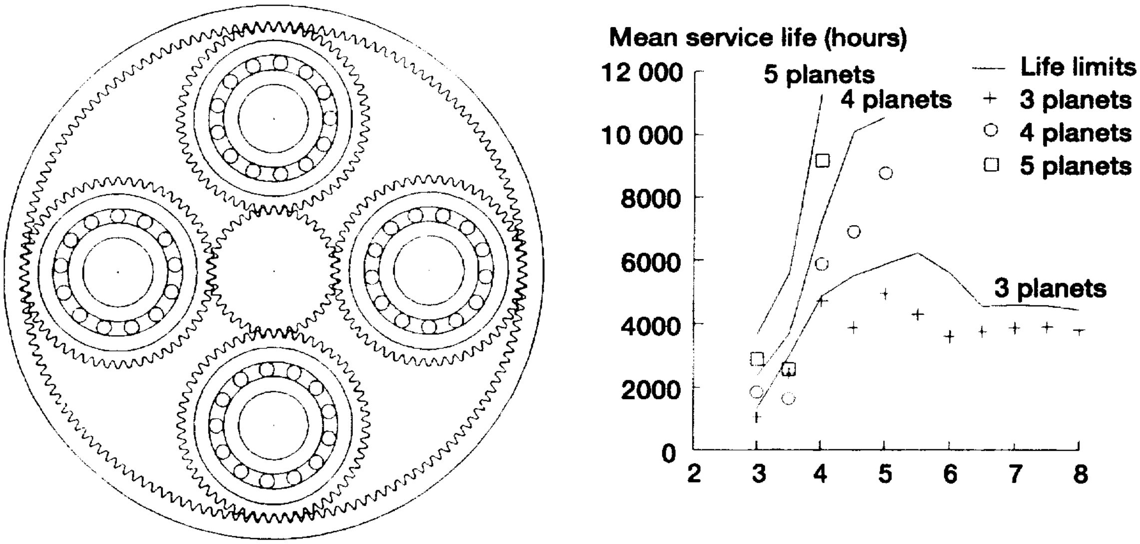


Figure 6.—Mean transmission service life versus speed reduction ratio with constant input speed and torque ref. 5.

Pictures of the damaged pinion teeth. (a) 5.5 hr. (b) 12 hr. (c) 17.8 hr.

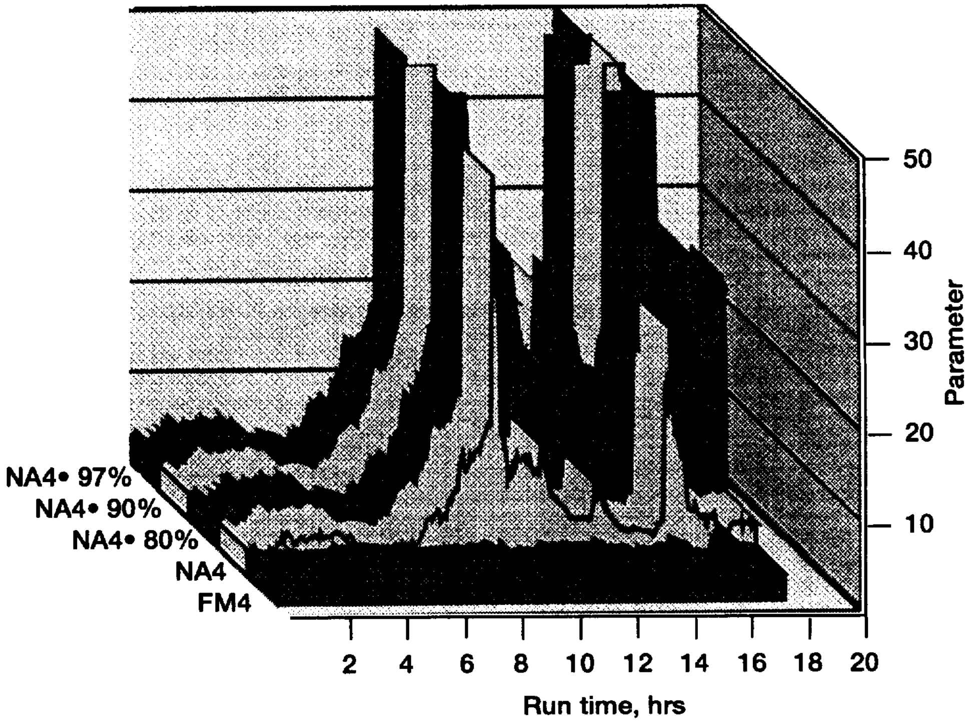
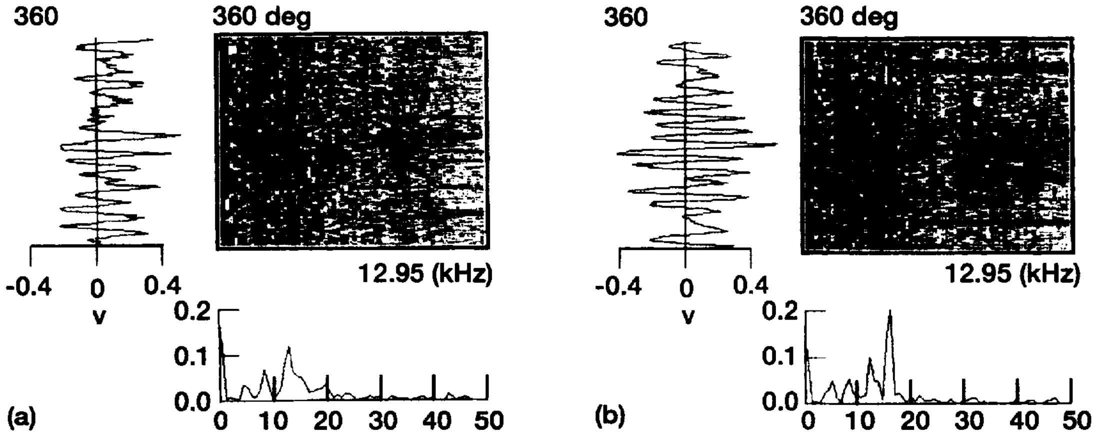
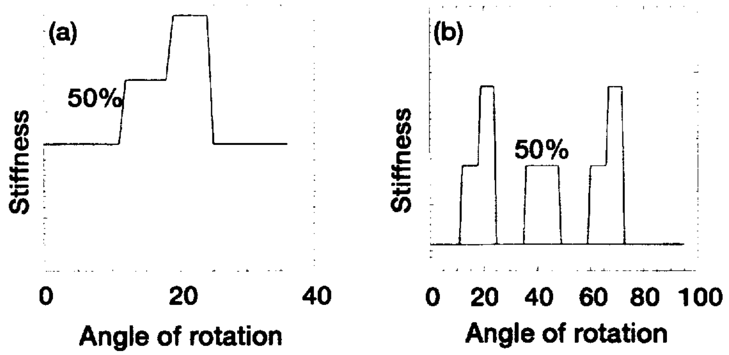


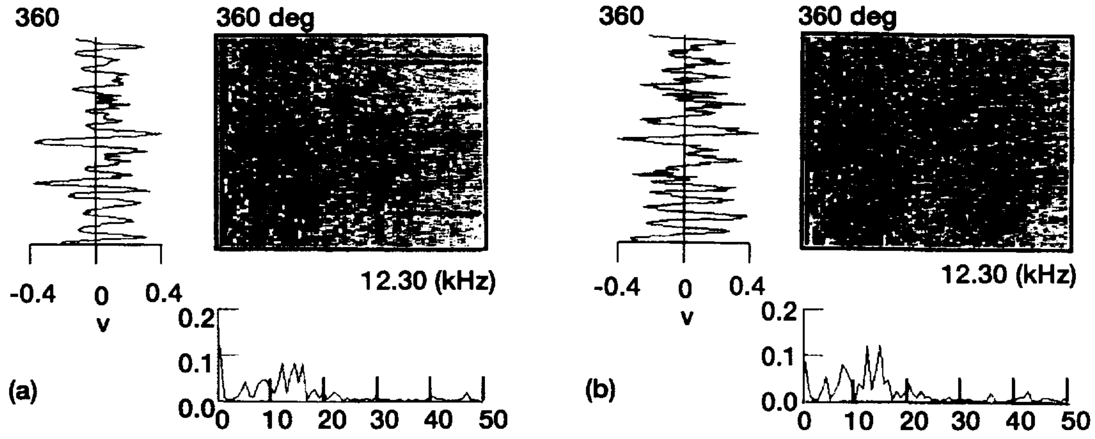
Figure 7.—NA4 results for predicting fatigue damage of spiral bevel gears ref. 6.



Experimental pinion vibration signature due to damage on pinion teeth due to wear and pitting. (a) Single tooth, (12 hr) (b) Three teeth, (17.8 hr).



Gear mesh stiffness model to simulate damages in pinion gear teeth.



Numerically simulated pinion vibration signature due to damage on pinion teeth due to wear and pitting. (a) Single tooth (b) Three teeth.

Figure 8.—Experimental and analytical Wigner-Ville signals for fatigue damage of spiral bevel gear ref. 7.

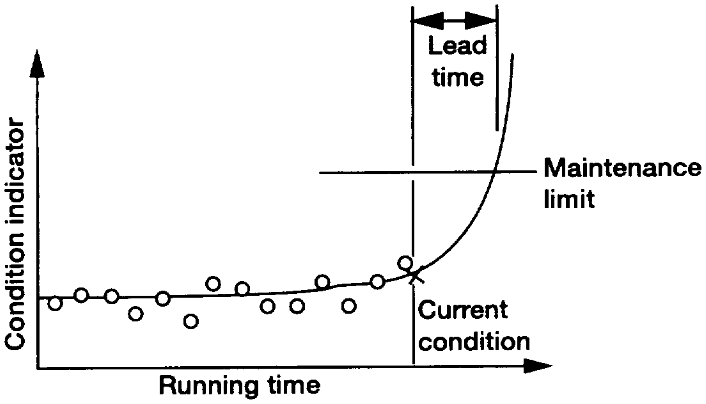


Figure 9.—Diagnostics/prognostics permits lead time for required maintenance.

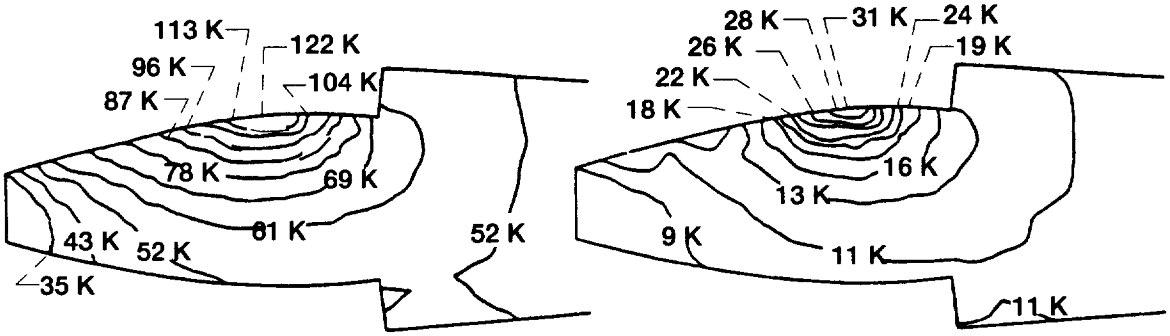


Figure 10.—Calculated gear tooth differential temperature ref. 8.

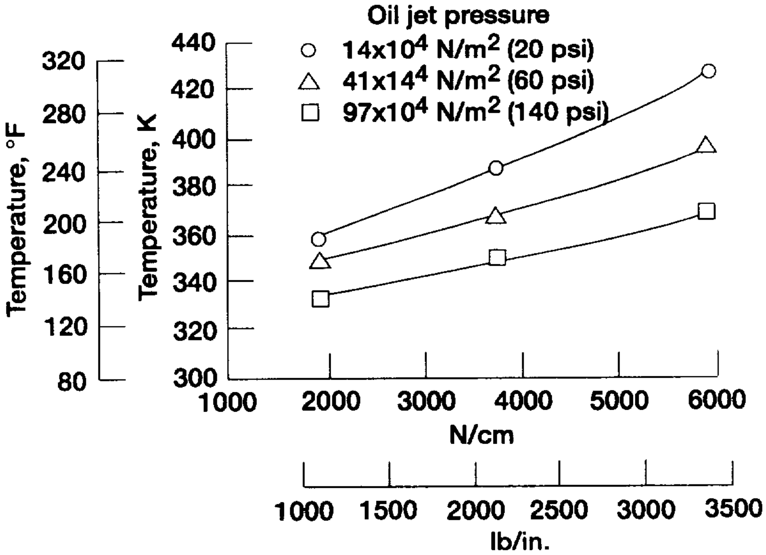


Figure 11.—Measured gear tooth temperature with infra-red microscope.

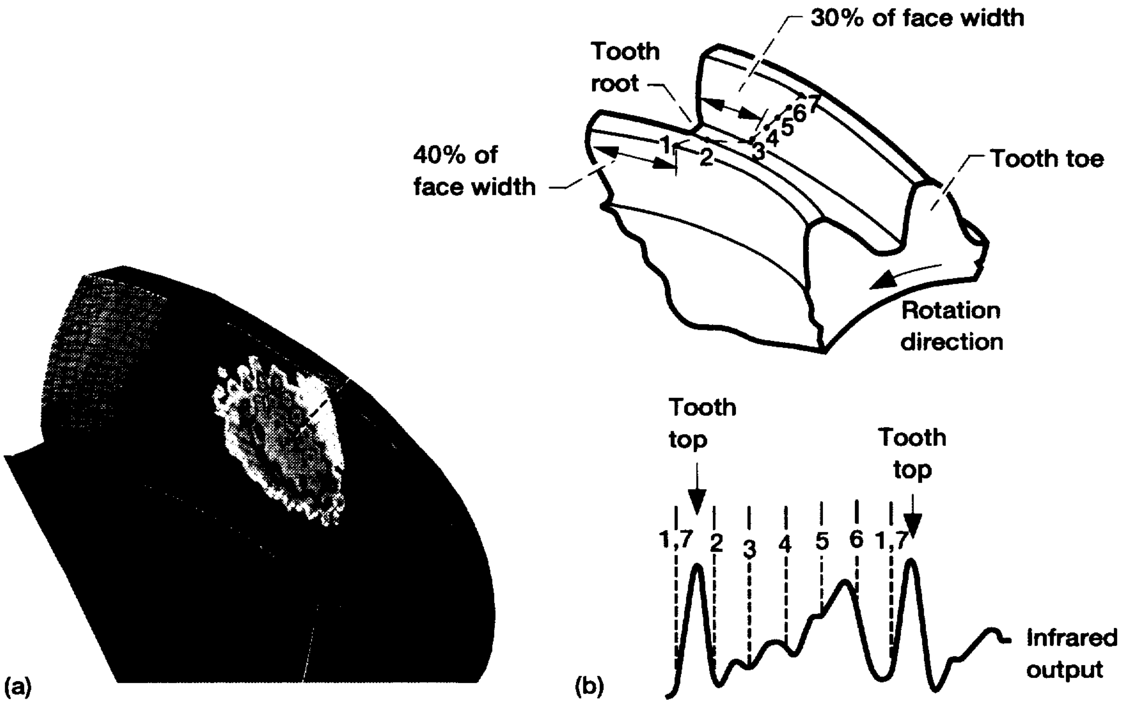
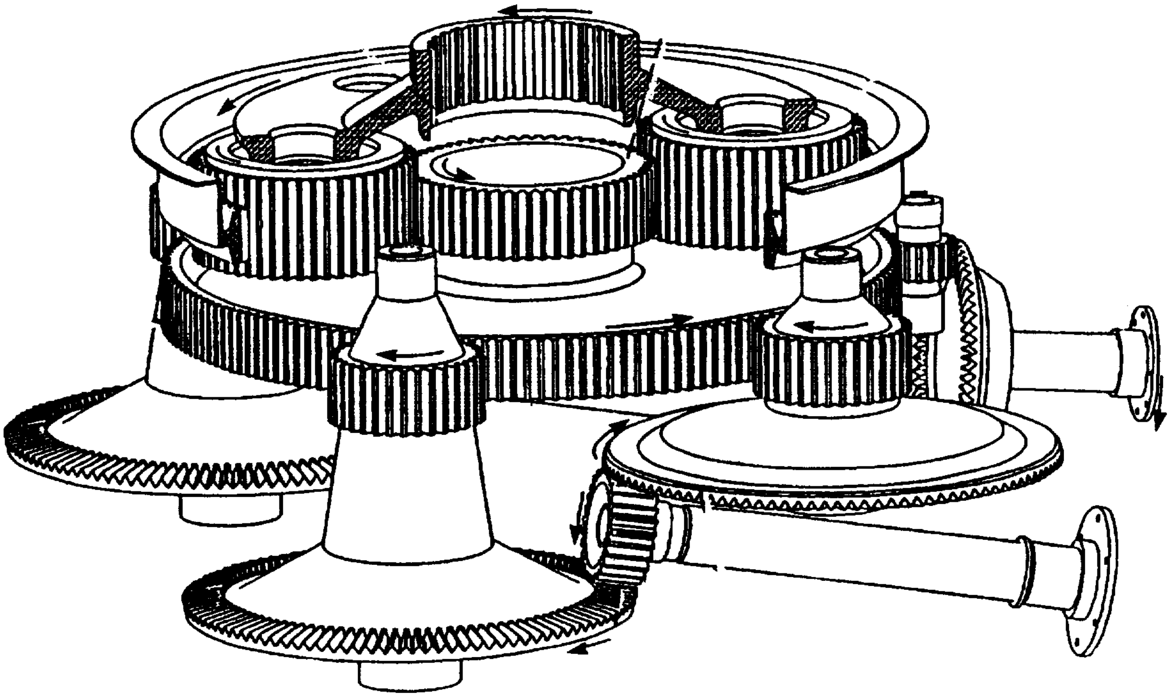


Figure 12.—Calculated and measured sprial bevel gear tooth temperatures ref. 9.



- 40-percent weight reduction
- 9.6 dB noise reduction
- 6270 hours MTBR

Figure 13.—MDHS/Lucas advanced rotorcraft transmission ref. 10.

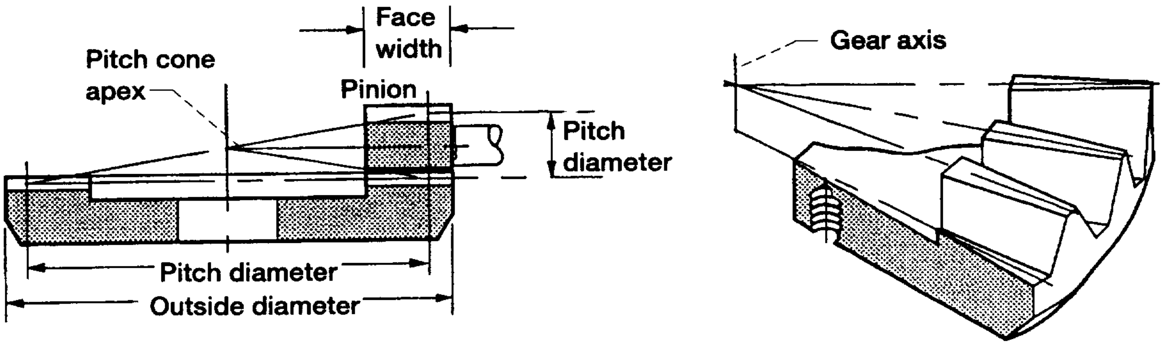


Figure 14.—Face gear terminology ref. 10.

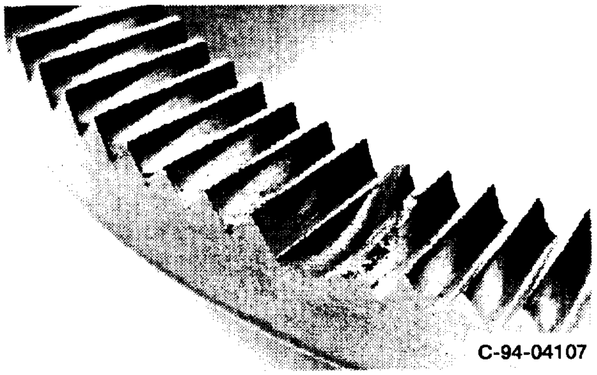


Figure 15.—Face gear tooth damage at end of test run ref. 16.

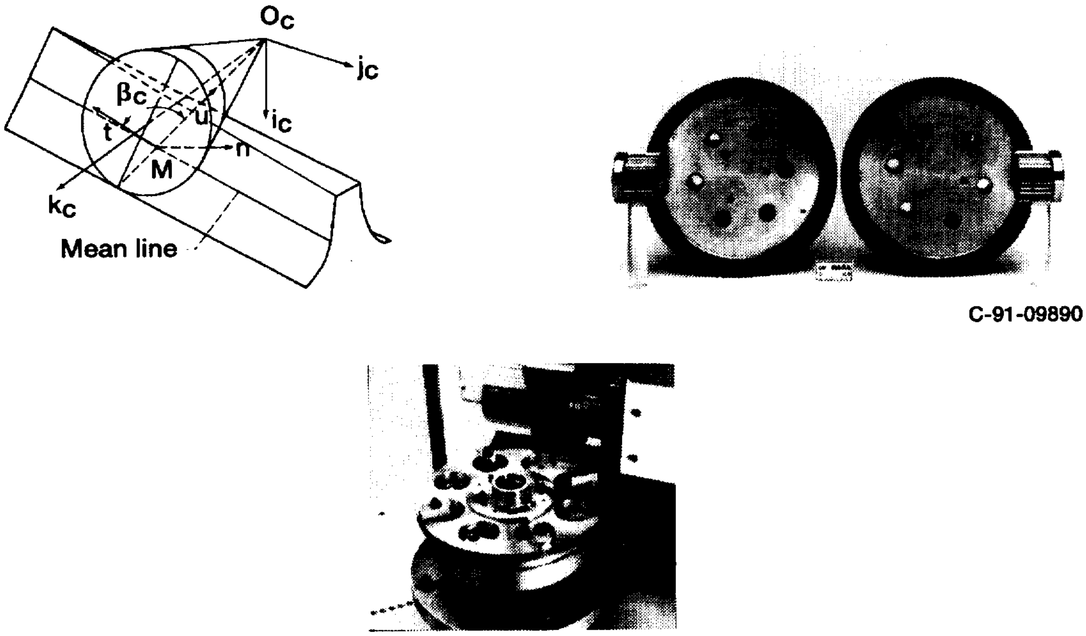


Figure 16.—Grinding of face gears ref. 11.

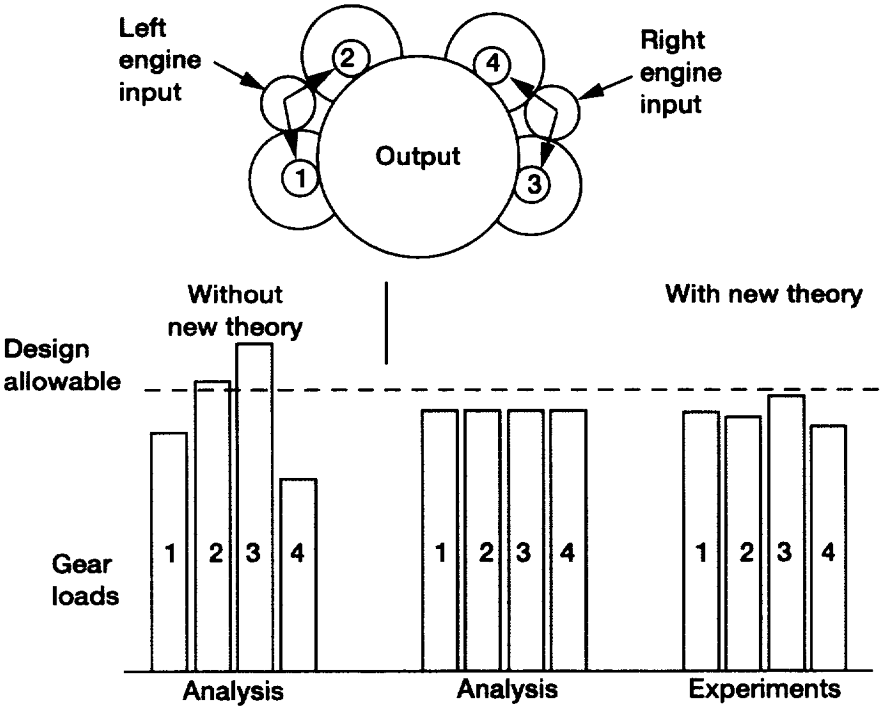
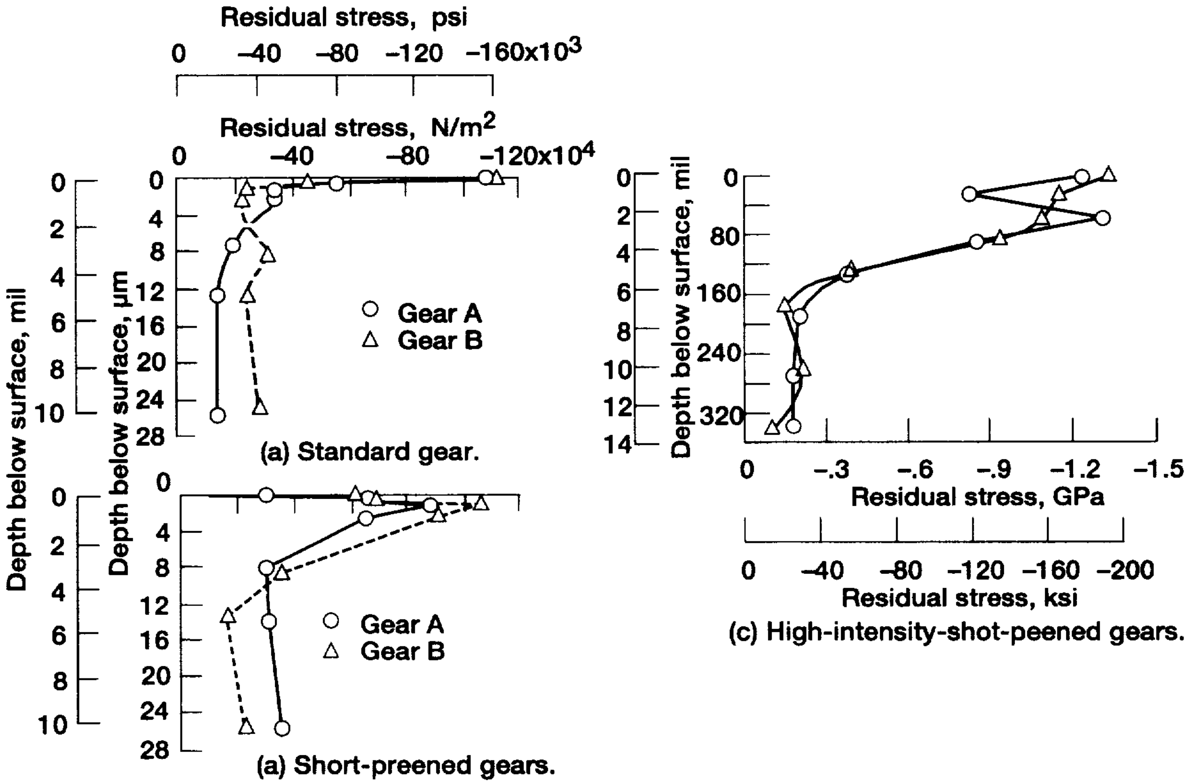


Figure 17.—Effect of appling the new theory to optimize the loads on the final drive gears of theComanche Split Torque Gearbox ref. 13.



(a) Standard gear.

(a) Short-preened gears.

(c) High-intensity-shot-peened gears.

Figure 18.—Measured subsurface residual stress of gear teeth ref. 14&15.

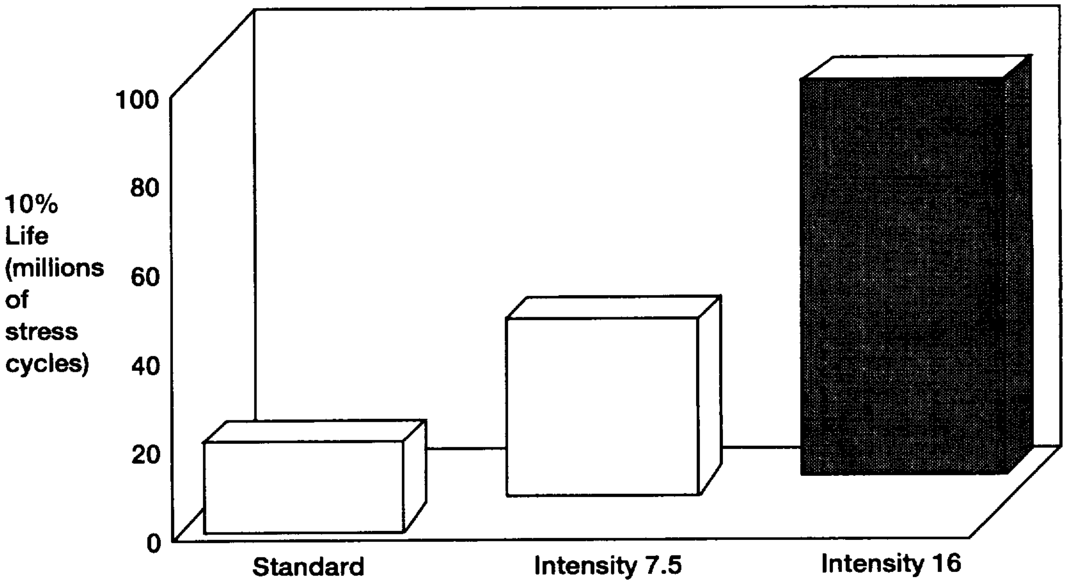


Figure 19.—Life of shot peened gears at different shot peened intensities.

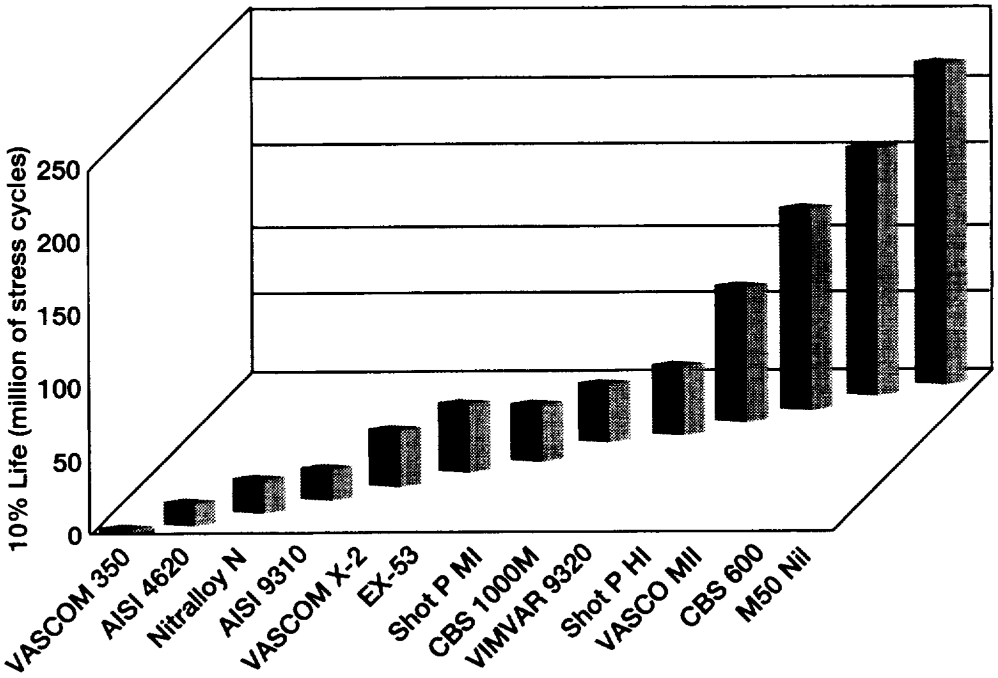


Figure 20.—Surface fatigue life at 248 Ksi hertz stress.

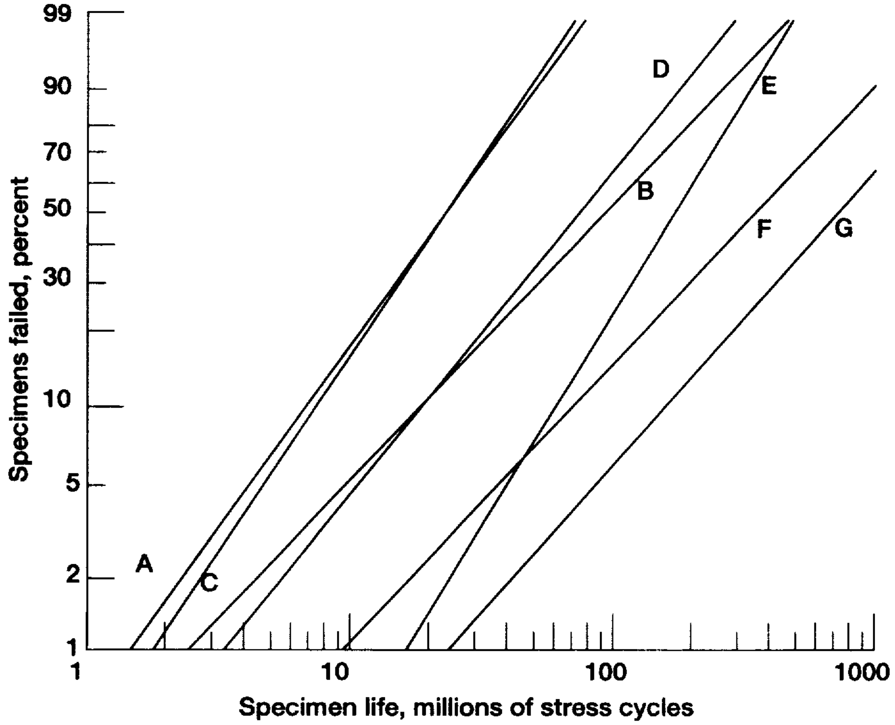


Figure 21.—Weibullplot of surface pitting fatigue life of AISI 9310 spur gears run with seven different lubricants ref. 21.

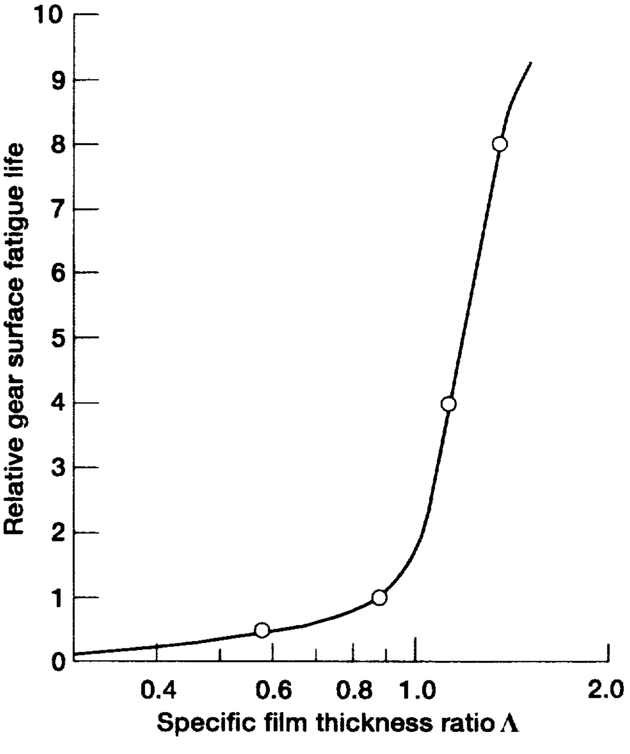


Figure 22.—Relative gear surface fatigue life versus specific film thickness ratio Λ ref. 21.

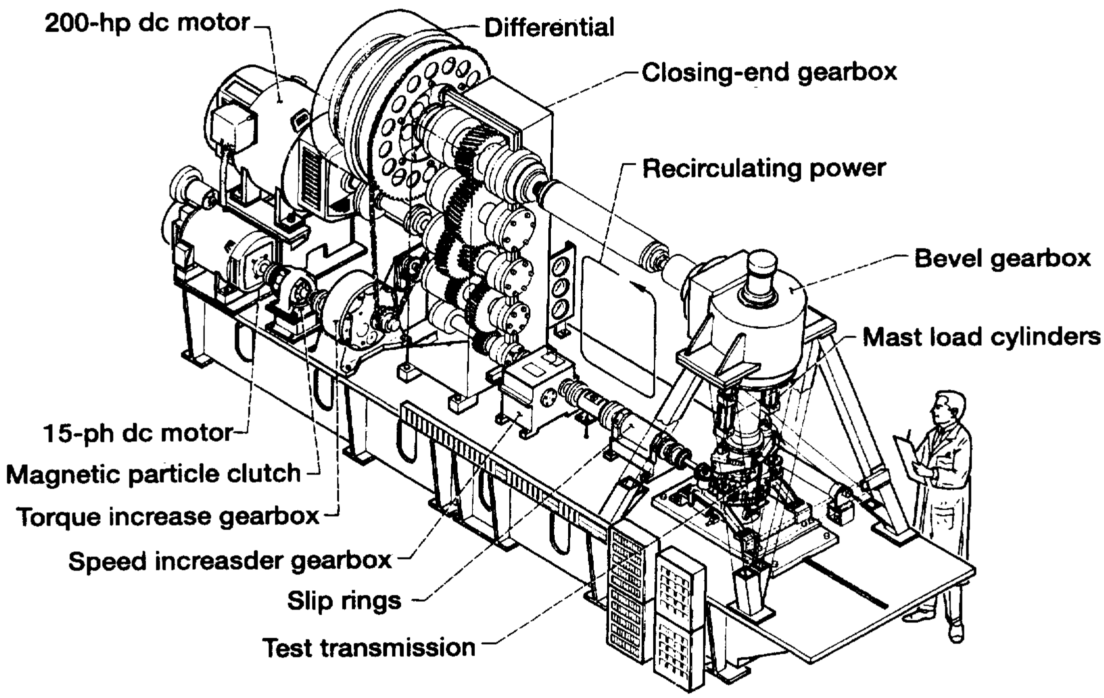


Figure 23.—NASA Lewis 500-hp helicopter transmission test stand ref. 22.

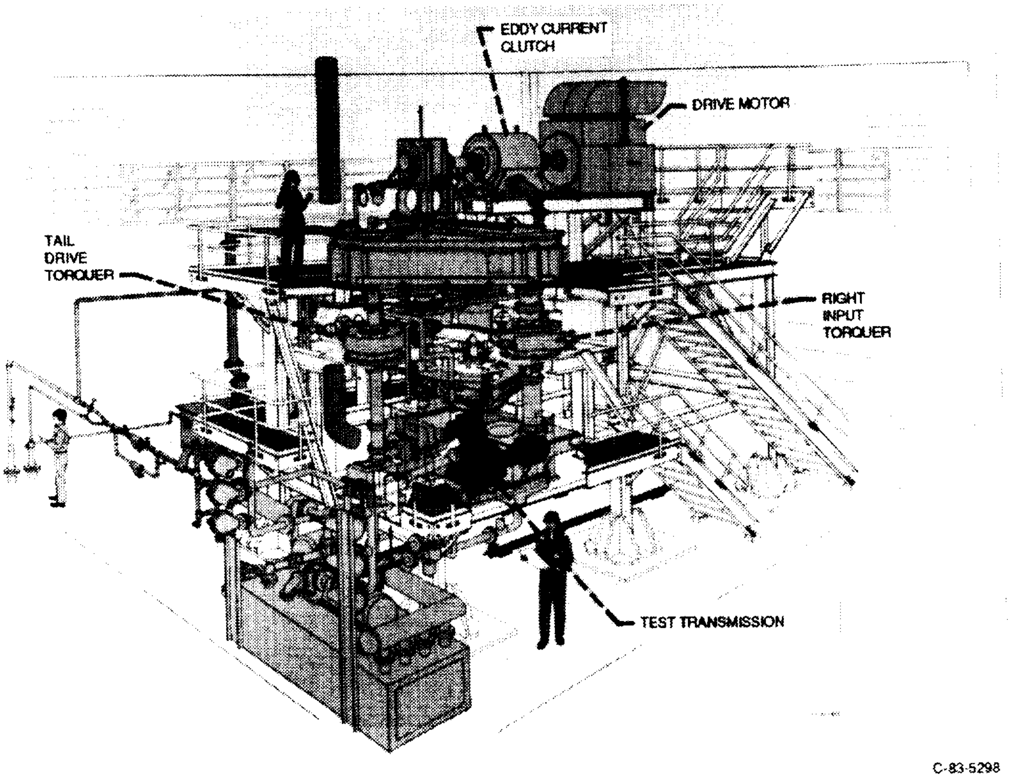


Figure 24.—NASA Lewis 3000-hp helicopter transmission test stand. ref. 23.

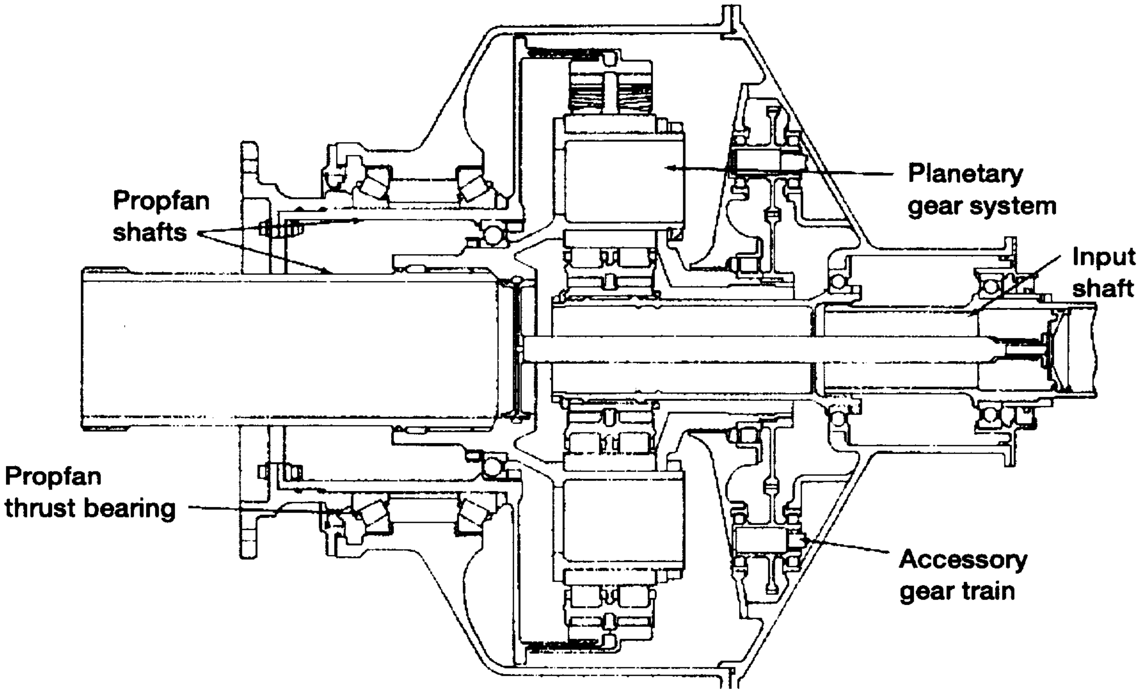


Figure 25.—Contrarotating prop-fan gear arrangement from allison gas turbine ref. 24.

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13. ABSTRACT ***(Maximum 200 words)***

This paper is a review of some of the research work of the NASA Lewis Research Center Mechanical Components Branch. It includes a brief review of the NASA Lewis Research Center and the Mechanical Components Branch. The research topics discussed are crack propagation of gear teeth, gear noise of spiral bevel and other gears, design optimization methods, methods we have investigated for transmission diagnostics, the analytical and experimental study of gear thermal conditions, the analytical and experimental study of split torque systems, the evaluation of several new advanced gear steels and transmission lubricants and the evaluation of various aircraft transmissions. The area of research needs for gearing and transmissions is also discussed.

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