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A New High-Speed, High-Cycle, Gear-Tooth Bending Fatigue Test Capability

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Abstract

A new high-speed test capability for determining the high-cycle bending-fatigue characteristics of gear teeth has been developed. Experiments were performed in the test facility using a standard spur gear test specimens designed for use in NASA Glenn's drive system test facilities. These tests varied in load condition and cycle-rate. The cycle-rate varied from 50 to 1000 Hz. The loads varied from high-stress, low-cycle loads to near infinite life conditions. Over 100 tests were conducted using AISI 9310 steel spur gear specimen. These results were then compared to previous data in the literature for correlation. Additionally, a cycle-rate sensitivity analysis was conducted by grouping the results according to cycle-rate and comparing the data sets. Methods used to study and verify load-path and facility dynamics are also discussed.

Introduction

The helicopter community's shift toward a Condition-Based Maintenance (CBM) strategy seeks to extend the useful life of gears and bearings in order to increase the overall affordability of the aircraft. Fatigue failures, to include gear-tooth bending fatigue, take on considerable importance as the number of cycles increases. Fatigue data historically has only extended to the 10^6 to 10^7 cycle range. With the emphasis on longer useful life, gear technology continues to reach further into the infinite life area of the s-n curve, a region that is still largely unknown. The time required to acquire data in this region has been considerable and to date, out of reach. The required enabler is a high-speed test apparatus that will allow the accumulation of 10^8 to 10^9 cycles in a reasonable amount of time. The only way to repeatedly achieve these high-cycle accumulations is to develop and validate a high-speed test rig that can operate at or near 1000 Hz. At this cycle rate, a facility can achieve 10^8 cycles in 27.8 hr, and 10^9 cycles in 11.6 days.

Background

The fatigue life of gears has been studied extensively over the past five decades (Refs. 1 to 14). Gear-tooth bending fatigue is a key characteristic of the gear itself and varies with geometry, material, residual stress, surface finish, and hardness, among other variables. It is a highly variable and stochastic failure property. The primary goal of fatigue testing is to optimize gear design by studying the effects of these variables on the fatigue characteristics of the gear. The Society of Automotive Engineers has developed a standard for conducting single gear-tooth bending fatigue experiments (Ref. 15), with testing established at low-frequency cycle rates of 10 to 20 Hz.

Many tooth-bending test facilities have been established around the world (Refs. 16 to 19). However, none of these existing facilities has the capability to achieve the high cycle rates required for infinite-life testing. Furthermore, most of these test facilities require the removal of gear teeth for mounting in the test apparatus. Therefore, after crack initiation, specimens are unusable in other rotating mesh test facilities. In many cases, it might be desirable to operate the failed specimen in another test apparatus in order to characterize post-failure gear performance in support of health or vibration monitoring initiatives. The destructive removal of specimen gear teeth for use in bending fatigue facilities prohibits such a capability.

Apparatus

NASA Glenn Research Center and the Army Research Laboratory (ARL) teamed together to develop the high-speed Single Gear-Tooth Bending Test Facility. The centerpiece of the facility is the 1000 Hz High-Cycle Fatigue Test System produced by MTS Systems Corporation. The servo-hydraulic system is capable of maintaining high waveform fidelity at high frequency. It has a static load capacity of ±5500 lb force and maximum displacement capability of ±1 in. at an operating frequency of 1000 Hz, the gear tooth is experiencing the bending equivalent to a gear rotating at a speed of 60,000 rpm.

A layout of the test apparatus is provided in Figure 1. A loading arm enters the top of the gearbox through a bushing and rests on the test gear-tooth at the highest point of single-tooth contact. The oscillating load applicator of the load frame contacts the loading arm and transmits the load to the test tooth. A reaction tooth rests on an anvil, maintaining the gear in a stationary position. The test tooth and reaction tooth are separated by an intermediate gear-tooth. The reaction anvil is connected to the reaction arm, which runs through the floor of the gearbox and transfers the load to a load cell. Though the gear itself is keyed, it is mounted on a keyless shaft such that all of the reaction force is provided by the reaction tooth. The reaction tooth rests on the anvil contacting at the root of the tooth to ensure that the test tooth experiences higher bending stress than the reaction tooth. During testing, the applicator, loading arm, test specimen, and reaction interfaces are always in contact with a small nominal load in order to maintain the test and reaction teeth in constant compression and prevent impact of the loading arm on the test tooth. Instrumentation measures load, displacement, and acceleration.

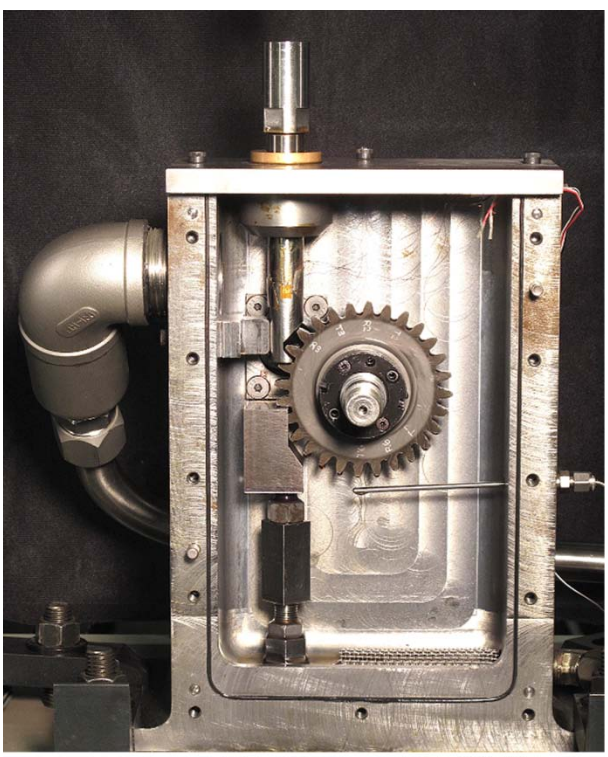

Figure 1.—NASA/ARL single gear-tooth bending test facility.

A circulating oil bath of MIL-PRF 23699 aviation turbine oil is contained in the gearbox and conditions the test specimen. The bath allows the operator to control the temperature of the test condition through an oil heater. The temperature ranges from approximately 50 to 300 °F, although this functionality has yet to be fully implemented.

The spur-gear test specimens for this study are manufactured from AISI 9310 steel. The specimen design has been documented and used extensively in many NASA/ARL studies over the past four decades for a variety of experiments oriented toward bending fatigue, contact fatigue, wear, crack propagation, and health monitoring (Refs. 5, 20 to 21). The gears are case-carburized and heat-treated, with a case hardness of Rockwell C60, a case depth of 0.038 in., and a core hardness of Rockwell C38. Depending upon the specimen, gear tolerances meet the standards for AGMA Quality Class 11 to Class 13 gears. Table 1 lists the design parameters of the specimens.

TABLE 1.—TEST SPECIMEN DESIGN PARAMETERS

Number of teeth	28
Diametral pitch (1/in.)	8
Circular pitch (in.)	0.3927
Whole depth (in.)	0.3000
Addendum (in.)	0.125
Chordal tooth thickness ref (in.)	0.191
Pressure angle (deg)	20
Pitch diameter (in.)	3.500
Outside diameter (in.)	3.750
Root fillet (in.)	0.040 to 0.060
Measurement over pins (in.)	3.7867 to 3.7915
Pin diameter (in.)	0.216
Backlash reference (in.)	0.010
Tip relief (in.)	0.010 to 0.015

Each specimen can be used for multiple tests. One bending experiment consumes four teeth. The first is the test tooth, followed by an intermediate gear-tooth. The third is the reaction tooth, followed by a second intermediate tooth. Continuing this pattern around the gear results in seven test sections per specimen. The intermediate gear-teeth are not tested due to the unknown bending stress interaction effects from the adjacent test and reaction gear-teeth.

Test Methodology

Table 2 lists the user-defined test parameters. The cycle rate and maximum number of cycles are user-defined. The no-load stroke, x_o, defines the baseline displacement for measuring the relative displacement during a test. The no-load stroke is measured by applying a nominal static load of 2 lbf on the gear-tooth.

TABLE 2.—TEST MACHINE SOFTWARE PRE-LOAD PARAMETERS

Parameter	Symbol	Value
Cycle rate	f	User-defined
Maximum number of cycles	n	User-defined
No-load stroke (2 lbf)	x_o	Measured
Minimum cyclic load	F_{min}	200 lbf
Maximum cyclic load	F_{max}	User-defined
Maximum cyclic load stroke	x_{max}	Measured
Crack initiation stroke	x_{crack}	$1.02(x_{max} - x_o)$
Maximum load limit	F_{lim}	5.5 kips
Maximum stroke limit	x_{lim}	User-defined
Data sample rate	n/a	6144 Hz (maximum)

The minimum cyclic load, F_{min}, is pre-defined at 200 lbf. The maximum cyclic load, F_{max}, is the load corresponding to the maximum bending stress desired during the test. The minimum cyclic load is established to ensure that the components in the load path are in constant contact with adjacent components and to eliminate the possibility of damage to the gear teeth or failure due to impact between components.

The maximum cyclic load stroke, x_{max}, is the displacement corresponding to F_{max}. The maximum cyclic load stroke determines the displacement associated with crack initiation, x_{crack}. Based upon previous work (Ref. 5), crack initiation is assumed to occur when the displacement increases by 2 percent of the maximum load stroke, or, in this case, a change of approximately 0.0002 in. The test is allowed to continue until the stroke increases an additional 0.0075 in., which is defined as the maximum stroke limit, x_{lim}. At this limit, the crack is clearly visible and extends from 25 to 50 percent of the tooth thickness at the root. Upon exceeding this limit, the rig automatically terminates the test.

The test matrix incorporated loading conditions comparable to existing data points in the literature. The loads were chosen to avoid the infinite life region of the s-n curve and achieve fatigue failures in less than 10^6 cycles. The test matrix follows in Table 3. This matrix is repeated for cycle rates of 50, 100, 200, 400, 600, 800, and 1000 Hz.

Using the raw data to determine the actual tooth loading conditions, the bending stress and the unit load can be calculated. The bending stress, σ_b, is calculated using the American Gear Manufacturer's Association (AGMA) stress equation for Imperial units, provided in Equation (1). The AGMA parameters are defined in Table 4 (Refs. 22 and 23), along with the values used in this study.

$$\sigma_b = W_t \frac{P}{FJ} K_v K_o K_m K_s K_B \tag{1}$$

TABLE 3.—SINGLE GEAR-TOOTH BENDING TEST MATRIX

Tooth	Nominal load, lbf	Approximate bending stress, ksi
1	4015	389
2	3825	370
3	3060	296
4	2675	259
5	2485	241
6	2295	222
7	3440	333

TABLE 4.—AGMA BENDING STRESS PARAMETERS

	Definition	Value
W_t	Tangential load	$W_t = W\cos(\alpha)$
P	Diametral pitch	8
F	Face width	0.251
J	AGMA geometry factor	0.36
K_v	Dynamic factor	1.0
K_o	Overload factor	1.0
K_m	Mounting factor	1.1
K_s	Size factor	1.052
K_B	Rim thickness factor	1.0

The unit load, σ_{unit}, is defined as the original Lewis equation minus the Lewis form factor. It has been used as a "geometrically dimensionless" stress parameter for comparing the bending fatigue characteristics of gears of differing size and shape (Ref. 1). Rather than the conventional stress units of kips per square inch (ksi), the unit load notation is given in kips-per-inch per-inch (kips/in./in.). The unit load in this effort is used in order to provide consistent units for validating ARL/NASA bending fatigue results against a sizable amount of AISI 9310 fatigue data from the literature. The unit load equation is given in Equation (2), with the parameters having the same definition and value as in Table 4.

$$\sigma_{unit} = \frac{W_t P}{F} \tag{2}$$

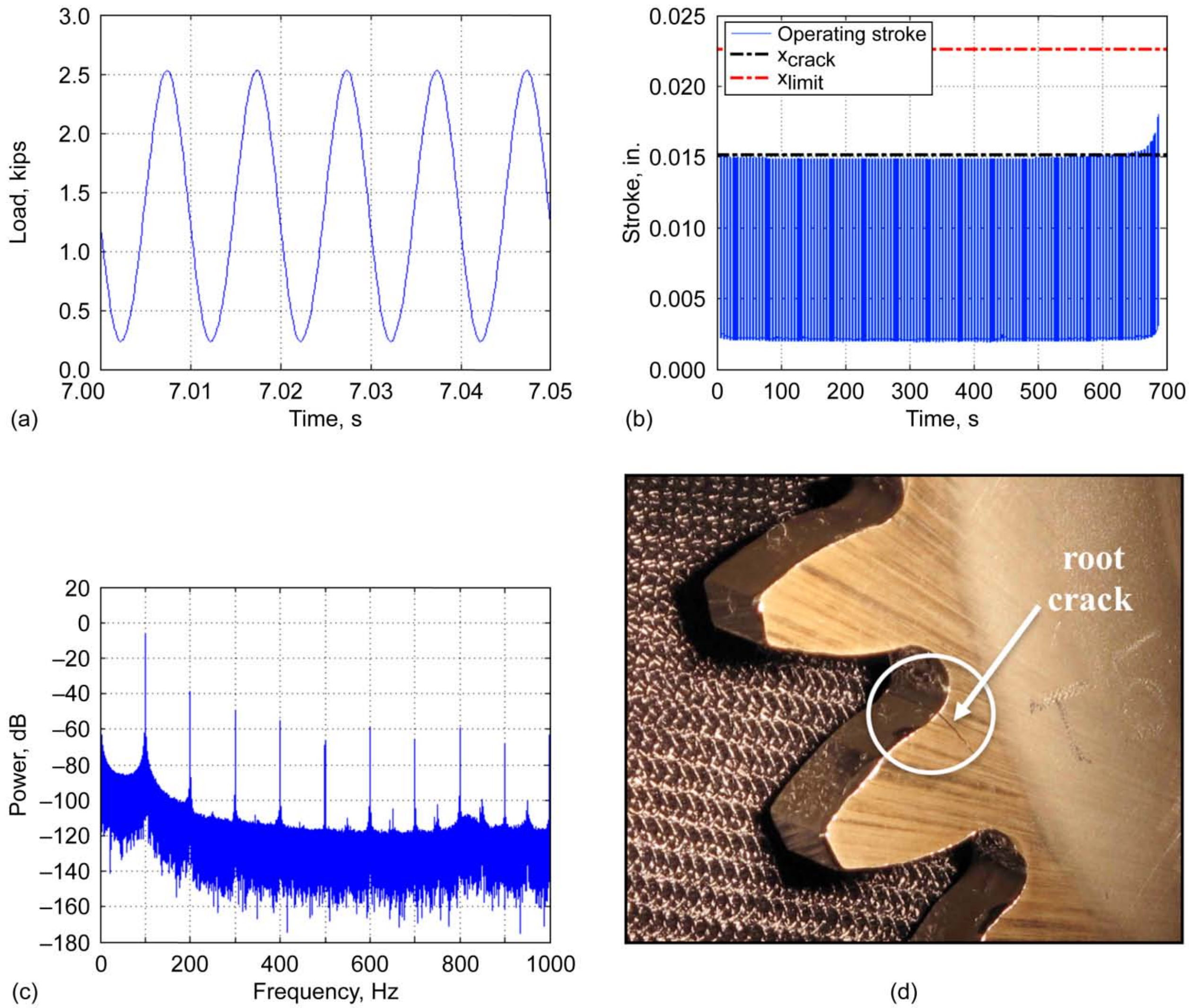

Figure 2.—Sample bending fatigue output, tooth 5, test specimen 0046. (a) Sinusoidal load signal, 100 Hz. (b) Stroke (displacement) signal, 100 Hz. (c) Frequency content of load signal, 100 Hz. (d) Bending fatigue fracture, 100 Hz.

Results and Discussion

Figure 2 displays results representative of each fatigue experiment. Figure 2(a) and (b) provide the load signal and stroke data for operation at 100 Hz, respectively. Figure 2(b) also displays the crack initiation and maximum displacement limits. To reduce data file size at lower cycle rates, data was acquired at periodic increments during the test. Test termination subsequently occurred between data acquisitions, resulting in an absence of recorded data where the stroke exceeded the limit. Figure 2(c) displays the frequency content of the load signal. The data at 100 Hz depicts a clean trace with peaks at 100 Hz and its harmonics. Figure 2(d) depicts a post-test image of the test specimen with the fatigue crack clearly visible at the base of the tooth.

The raw data at each load and cycle rate was screened for abnormalities in transient behavior and frequency content. The data different cycle rates exhibited differences in amplitudes, transient conditions, and frequency content in the applied load signals. When analyzed together, the observed differences create a map of preferred cycle rates for test facility operation. For operation at 50, 100, and 200 Hz, the loading and displacement curves display constant amplitude and a negligible transient state. Although not included here, the frequency domains also show clean traces with defined peaks at the harmonic frequencies. These characteristics define good testing conditions.

At a test frequency of 400 Hz, the data begins to show different characteristics, as depicted in Figure 3. At 400 Hz, (Fig. 3(a)), the loading and displacement amplitudes are no longer constant, but slightly decreasing until failure. A larger transient period also exists. Additionally, frequency contributions from non-harmonic frequencies become apparent. Perhaps the most radical dynamic characteristics

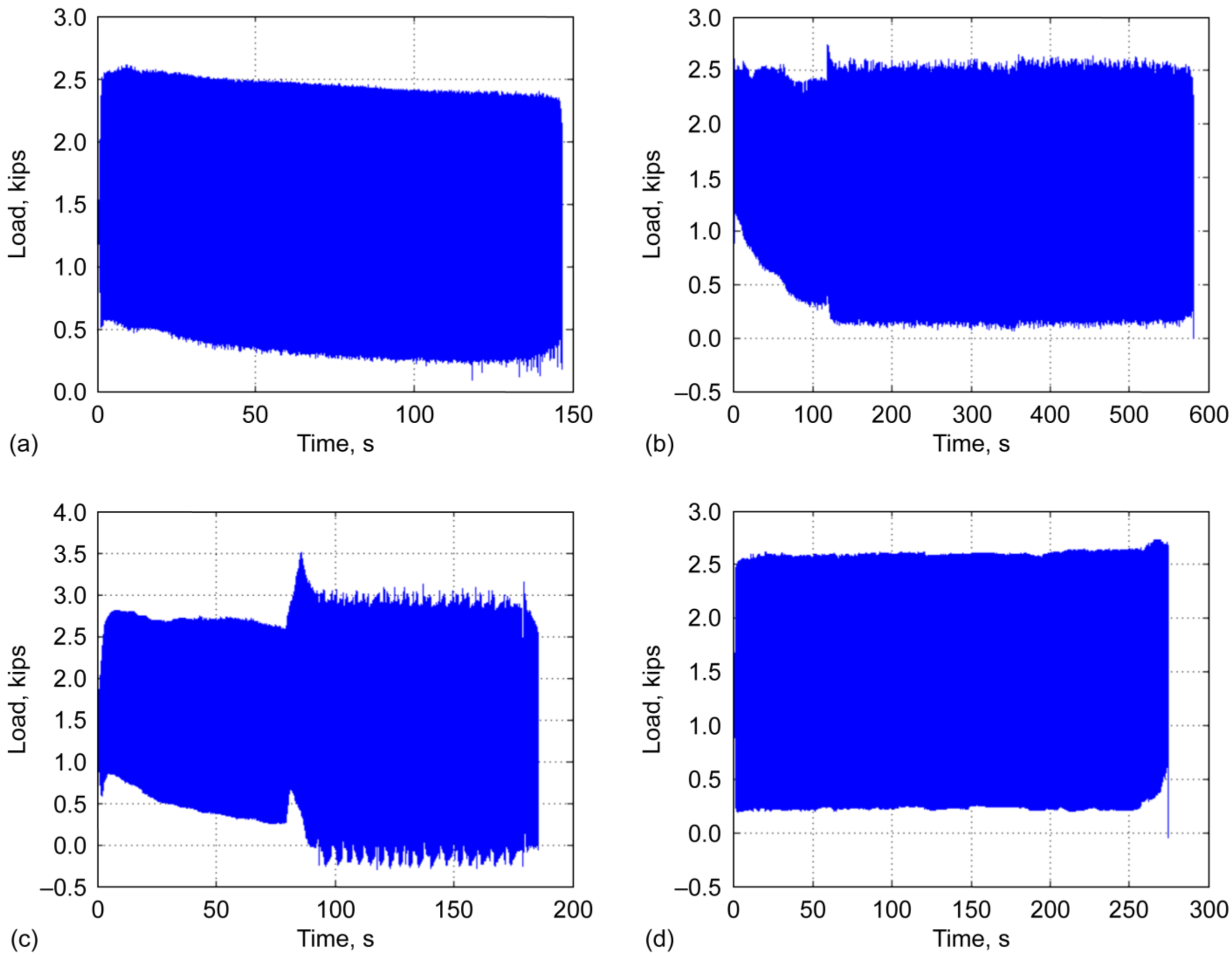

Figure 3.—Load signals for 400, 600, 800, 1000 Hz, tooth 5 loading condition. (a) Load signal, 400 Hz. (b) Load signal, 600 Hz. (c) Load signal, 800 Hz. (d) Load signal, 1000 Hz.

occur at 600 and 800 Hz, Figures 3(b) and (c), respectively. Figure 3(b) shows a large transient period greater than 100 sec at 600 Hz. The frequency domain also shows significant frequency content symmetrically placed around 600 Hz as illustrated in Figure 4. The loading and displacement data for 800 Hz, Figure 3(c), displays the most extreme characteristics. These include significant amplitude spikes, following a lengthy transient period of approximately 90 sec. The frequency content shows corresponding variations (not depicted). These two conditions clearly illustrate that testing at 600 and 800 Hz should be avoided. It is unclear whether the dynamic characteristics of this regime are a result of mechanical dynamic influence, controller algorithm influences, or a combination of both.

At 1000 Hz, the characteristics display similar conditions as at 50, 100, and 200 Hz (Fig. 3(d)). The frequency domain does, however, show significant frequency content, although at a lower power distribution than at 600 and 800 Hz. The relatively benign effects at this cycle rate indicate that operation at 1000 Hz is feasible and valid.

The effects of cycle rate are best shown in Figure 5, which compares the cycle-rate effects on the loading conditions of Table 3, grouped by test tooth. Each tooth was tested at a different nominal bending stress, represented by the first bar in each series. This is the load requested by the test software. The remaining bars in each series are the measured bending stresses at each operational cycle-rate. From this comparison, it is apparent that facility operation between 400 and 800 Hz is not recommended for any loading condition.

Recommended operation at 1000 Hz is also dependent upon the loading condition. At bending stress loads less than 300 ksi, 1000-Hz operating conditions compare closely with the results from cycle-rates between 50 and 200 Hz,. Since the loads of interest in the high-cycle (infinite life) fatigue region are on the order of 150 ksi, operation within this loading region is not expected to cause deleterious effects at 1000 Hz.

The fatigue data collected from the test rig used in this study was compared against other data from two sources. The first is a set of low-cycle bending fatigue tests conducted at the NASA Glenn Research Center on a fatigue tester capable of

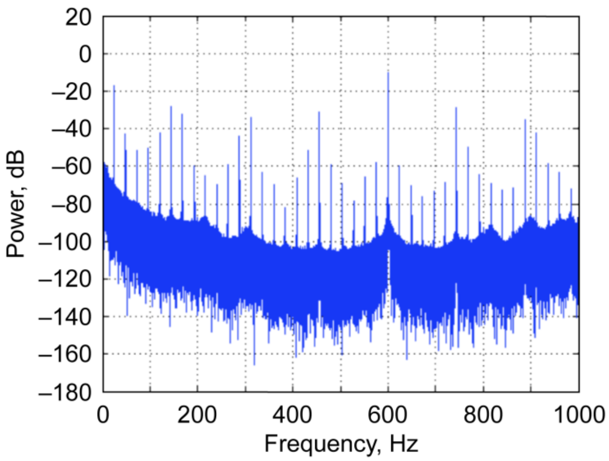

Figure 4.—Frequency content of load signal, 600 Hz.

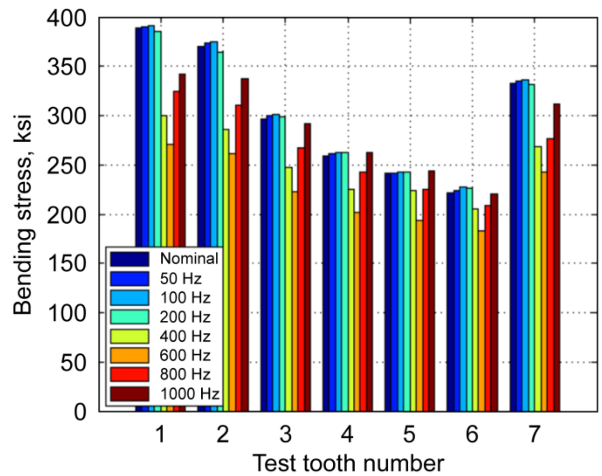

Figure 5.—Loading condition—cycle-rate comparison.

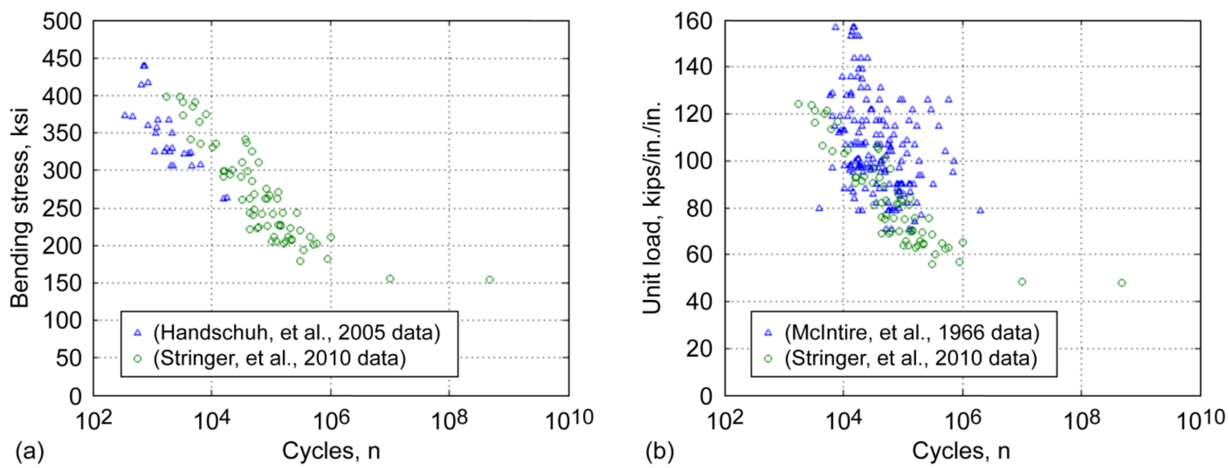

Figure 6.—Bending fatigue data comparison. (a) Data comparison with NASA low-cycle testing. (b) Data comparison with General Motors low-cycle testing.

operating at a maximum cycle-rate of 50 Hz (Ref. 5). The second is a comprehensive fatigue study conducted by General Motors Corporation in the late 1960s (Ref. 1). Figure 6 depicts how well data from the current work compares to those two studies.

Load-Path Verification

Due to the facility's varied behavior at different cycle rates, several methods were used to ensure proper load-path between the load applicator and the load cell. Such tests included load-cell validation, strain-gage measurement, finite element modeling, and three-dimensional optical strain measurement.

After several million cycles, the loading arm showed fretting damage, an indicator of friction between the loading arm and the bushing through which the arm passes into the gearbox. It exhibited this damage even though the loading arm-bushing interface was lubricated prior to each test. This created a concern that the test apparatus was transferring energy to the load-cell via other dynamic mechanical paths, rather than the required loading path. Figure 7 shows the loading bar with minor fretting damage.

Three experiments were conducted to determine the bushing's static effects on load-cell output. The first experiment was a static load of nominal weight, placed on the gearbox, but not in contact with the loading rod. The load display was monitored to see if the load reading changed. There were no noticeable load changes due to added weight on the gearbox. The second experiment used a dial indicator to detect any horizontal motion of the loading arm. As the load steadily increased, the dial indicator was monitored for any increases in horizontal displacement. No significant readings were observed.

The third experiment consisted of a static loading test using a 500-lbf load-cell. The load-cell was placed inside the gearbox between the loading arm and reaction arm. Load was applied in approximately 50-lbf increments from 0 to 500 lbf. The 500-lbf load-cell consistently read the same values as the load frame within the measurement uncertainty.

Figure 7.—Minor fretting on loading arm.

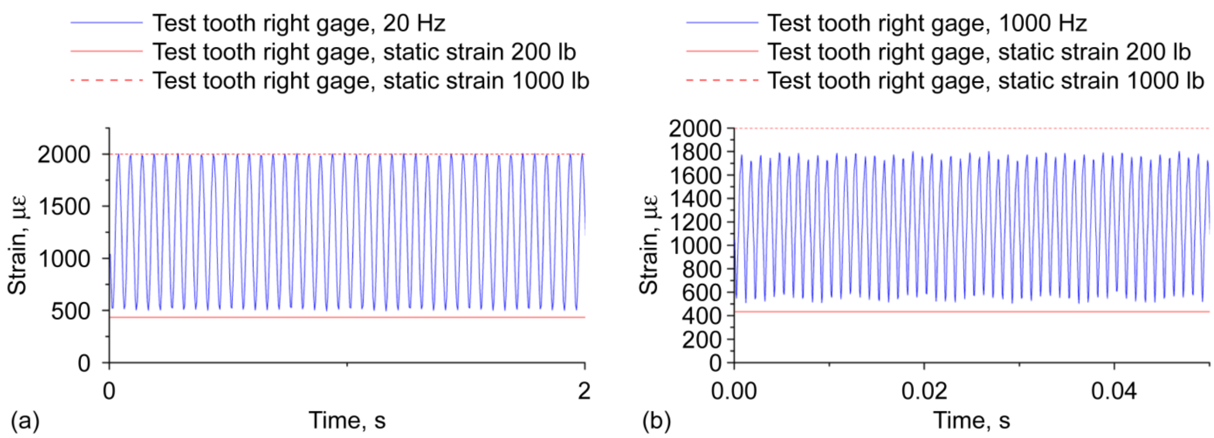

Figure 8.—Strain gage results of dynamic loading experiments. (a) Dynamic loading experiment—20 Hz. Time trace of measured strain from test tooth right gage during 20 Hz dynamic loading experiments. Static strain measurements from this gage at 200 lbf and 1000 lbf are also shown on the graph and verify that dynamic loading at this rate does not suffer from dynamic attenuation. (b) Dynamic loading experiment—1000 Hz. Time trace of measured strain from test tooth right gage during 1000 Hz dynamic loading experiments. Static strain measurements from this gage at 200 lbf and 1000 lbf are also shown on the graph and indicate that dynamic loading at this rate has some dynamic attenuation.

Additionally, a strain-gage instrumented spur gear was placed in the test rig to measure root-fillet strain in the gear under static load and dynamic load cycling to determine if dynamic attenuation would reduce the root stress under given peak-to-peak cyclic loads measured by the load frame.

Static measurements were taken from 0 to 3000 lbf of applied load. A series of dynamic loading experiments was conducted at 20, 100, 300, 600, and 1000 Hz for a cyclic load between 200 and 1000 lbf. However, damage to the strain-gages after the first experiments prevented strain measurements at higher dynamic loads. Sample results for 20 and 1000 Hz are presented in Figures 8(a) and (b), respectively.

The dynamic experiments showed that high frequency single tooth bending experiments on spur gears are valid up to the 1000 Hz maximum rate tested, although the actual strain experienced in the gear teeth may be on the order of 25 percent lower than anticipated. For the load cycle used in this study, the data does not show monotonically decreasing root strain as the load cycle rate increases. In other words, attenuation did not necessarily increase with load. However, some load adjustment is likely required for load rates of 100 Hz and above to account for the decreased cyclic strain measured in the test tooth.

Further investigation could provide improved understanding of the cyclic strain attenuation at various load rates and allow for more accurate corrections to be applied to the fatigue data to reduce scatter and bias error. A second instrumented strain-gage specimen will be used to perform a more comprehensive root strain study. However, the absence of a clear trend toward decreasing cyclic strain with increased loading rate is encouraging and suggests that data may continue to be collected using the test rig as is, with correction factors applied later.

Other load-path verification methods to include finite element modeling and three-dimensional optical surface strain measurement were conducted, but have been omitted here.

Conclusions

Experiments and validation efforts were performed to demonstrate a new high-speed, high-cycle, gear-tooth, bending fatigue capability co-operated by the NASA Glenn Research Center and the U.S. Army Research Laboratory. Such a facility provides the ability to explore the infinite-life region of the stress-cycle curve at bending stress loads of approximately 150 ksi and below in support of CBM and other component life-extension initiatives. A description of the facility was provided, as was data showing typical results from over 100 fatigue experiments. Characteristics of test results at different cycle rates were discussed and compared. These efforts support the following conclusions.

1. The NASA/ARL Single Gear Tooth Bending Test Facility is a unique test rig capable of conducting high-speed bending-fatigue tests. It enhances further research in the infinite-life regions of the stress-cycle curve, by enabling experiments in the 108 to 109-cycle range in the shortest amount of time possible.
2. Effective load output is dependent upon cycle-rate. Operation between 400 and 800 Hz is not recommended for any loading condition. The results demonstrate excessive dynamic anomalies within this range.
3. Experiments conducted at 1000 Hz did not exhibit adverse dynamic/transient loading effects, as demonstrated through data results and strain-gage measurement.
4. Fatigue data compared closely with previous data results in the literature.
5. A thorough sequence of additional strain-gage testing is necessary to determine strain/load correction factors and attenuation at different loading conditions and cycle-rates, as well as to decrease variability and eliminate bias in the results. This is currently underway.

References

1. McIntire, W. and Malott, R., “Advancement of Spur Gear Design Technology,” General Motors Corporation, USAAVLABS Technical Report 66–85, US Army Aviation Materiel Laboratories, Fort Eustis, Virginia, 1966.
2. Yang, Q., “Fatigue Test and Reliability Design of Gears,” *International Journal of Fatigue* 18 (3), 171–177, 1996.
3. Krantz, T. and Tufts, B., “Pitting and Bending Fatigue Evaluations of a New Case-Carburized Gear Steel,” NASA/TM—2007-215009, ARL TR 4123, 2007.
4. Inoue, K., Hanawa, K., and Masuyama, T., “Estimation of P+S+N Curves in View of Reliability Design of Carburized Gears,” *Proceedings* of the International Conference on Gears, Garching, Germany, September 14–16, 2005.
5. Handschuh, R., Krantz, T., Lerch, B., and Burke, C., “Investigation of Low-Cycle Bending Fatigue of AISI 9310 Steel Spur Gears,” NASA/TM—2007-214914, ARL TR 4100, 2007.
6. Fernandes, P., “Tooth Bending Fatigue Failures in Gears,” *Engineering Failure Analysis* 3 (3), 219–225, 1996.
7. Farfán, S., Rubio-González, C., Cervantes-Hernández, T., and Mesmacque, G., “High-Cycle Fatigue, Low-Cycle Fatigue and Failure Modes of a Carburized Steel,” *International Journal of Fatigue* 26, 673–678, 2004.
8. Eyercioglu, O., Walton, D., and Dean, T., “Comparative Bending Fatigue Strength of Precision Forged Spur Gears,” *Journal of Mechanical Engineering Science* 211 (4), 293–299, 1997.
9. Yamanaka, M., Inoue, K., Miwa, S., and Kawasaki, Y., “Bending Strength of Carburized Forged Spur Gear,” DETC Paper 2007–34882, *Proceedings* of the ASME International Design Engineering Technical Conferences and Computers and Information in Engineering Conferences, Las Vegas, Nevada, September 4–7, 2007, 903–908.
10. Lewicki, D., and Ballarini, R., “Gear Crack Propagation Investigations,” NASA TM 107147, ARL TR 957, 1996.
11. Ural, A., Wawrzynek, P., and Ingraffea, A., “Simulating Fatigue Crack Growth in Spiral Bevel Pinion,” NASA/CR—2003-212529, ARL CR 0531, 2003.
12. Kramberger, J., Šramel, M., Glodež, S., Flašker, J., and Potrč, I., “Computational Model for the Analysis of Bending Fatigue in Gears,” *Computers and Structures* 82, 2261–2269, 2004.
13. Wheitner, J., and Houser, D., “Investigation of the Effects of Manufacturing Variations and Materials on Fatigue Crack Detection Methods in Gear Teeth,” NASA CR 195093, 1994.
14. Zakrajsek, J., and Lewicki, D., “Detecting Gear Tooth Fatigue Cracks in Advance of Complete Failure,” NASA TM 107145, ARL TR 970, 1996.
15. Society of Automotive Engineers, “Single Tooth Gear Bending Fatigue Test,” SAEJ1619 SAE International, 1997.
16. Blazakis, C., “Effects of Thin-Rimmed Geometry on Crack Propagation Path and Single Tooth Bending Fatigue Life of Spur Gears,” Master of Science Thesis, Ohio State University, Columbus, Ohio, USA, 1993.
17. Sonti, N., Rao, S., and Anderson, G., “Bending Fatigue, Impact and Pitting Resistance of Ausform-Finished Powder-Metal Gears,” *Gear Technology*, 44–53, June 2010.
18. Höhn, B., “Modern Gear Calculation,” *Proceedings* of the International Conference on Gears, Munich, Germany, 2002, VDI-Berichte 1665, 23–43.

19. Decker, H., Certo, J., Handschuh, R., and Krantz, T., "Development of a New Single Gear Tooth Bending Fatigue Test Capability," Presented at the American Helicopter Society 62nd Annual Forum, Phoenix, Arizona May 9–11, 2006.
20. Townsend, D., "Surface Fatigue Life and Failure Characteristics of EX53, CBS 1000M, and AISI 9310 Gear Materials," NASA TP 2513, 1985.
21. Townsend, D., Chevalier, J, Zaretsky, E., "Pitting Fatigue Characteristics of AISI M50 and Super Nitralloy Spur Gears," NASA TN D-7261, 1973.
22. Dudley, D. *Handbook of Practical Gear Design*. Boca Raton, Florida: CRC Press, 1994, pp. 3–93.
23. Pope, E., ed. *Rules of Thumb for Mechanical Engineers: A Manual of Quick, Accurate Solutions to Everyday Problems*. Houston, Texas: Gulf Publishing Company, 136–141.

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14. ABSTRACT A new high-speed test capability for determining the high-cycle bending-fatigue characteristics of gear teeth has been developed. Experiments were performed in the test facility using a standard spur gear test specimens designed for use in NASA Glenn's drive system test facilities. These tests varied in load condition and cycle-rate. The cycle-rate varied from 50 to 1000 Hz. The loads varied from high-stress, low-cycle loads to near infinite life conditions. Over 100 tests were conducted using AISI 9310 steel spur gear specimen. These results were then compared to previous data in the literature for correlation. Additionally, a cycle-rate sensitivity analysis was conducted by grouping the results according to cycle-rate and comparing the data sets. Methods used to study and verify load-path and facility dynamics are also discussed.					
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