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Continued Evaluation of Gear Condition Indicator Performance on Rotorcraft Fleet

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Abstract

This paper details analyses of condition indicator performance for the helicopter nose gearbox within the U.S. Army's Condition-Based Maintenance Program. Ten nose gearbox data sets underwent two specific analyses. A mean condition indicator level analysis was performed where condition indicator performance was based on a 'batting average' measured before and after part replacement. Two specific condition indicators, Diagnostic Algorithm 1 and Sideband Index, were found to perform well for the data sets studied. A condition indicator versus gear wear analysis was also performed, where gear wear photographs and descriptions from Army tear-down analyses were categorized based on ANSI/AGMA 1010-E95 standards. Seven nose gearbox data sets were analyzed and correlated with condition indicators Diagnostic Algorithm 1 and Sideband Index. Both were found to be most responsive to gear wear cases of micropitting and spalling. Input pinion nose gear box condition indicators were found to be more responsive to part replacement during overhaul than their corresponding output gear nose gear box condition indicators.

Acronyms

AEA	Army Engineering Analysis
CBM	Condition-Based Maintenance
CI	Condition Indicator
DA1	Condition Indicator: Diagnostic Algorithm 1
FM0	Condition Indicator: Zero Order Figure of Merit
FM4	Condition Indicator: Figure of Merit 4
NGB	Nose Gearbox
RMS	root-mean square
SI	Condition Indicator: Sideband Index
TSA	Time-Synchronous Averaged Data
TDA	Tear-Down Analysis

Introduction

This paper further analyzes condition indicator (CI) performance based on the U.S. Army helicopter nose gearbox (NGB) vibration data as previously reported by Antolick et al. (Ref. 1). Antolick and others reviewed several helicopter NGB data sets with known gear damage against several gear specific condition indicators. A ‘batting average’ was used to assess condition indicator performance in which the total number of true negatives and true positives were divided by the total number of available data points. The purpose of this analysis was to correlate CI performance to available tear-down analysis (TDA) and Army Engineering Analysis (AEA) wear data and to evaluate how specific CIs respond to part replacement. CIs are used in the Army’s Condition-Based Maintenance (CBM) Program to monitor helicopter transmissions and are required to be compliant with U.S. Army ADS-79C-HDBK (Ref. 2). The handbook prescribes required detection rates for CIs. This analysis evaluates current CIs used to monitor U.S. Army helicopter NGBs and is based, in part, on the average CI value both before and after part replacement. The analysis also takes a closer look at TDAs in relation to gear damage as noted per ANSI/AGMA 1010-E95 Standards (Ref. 3). A total of seven NGB data sets were used in the CI versus gear wear analysis.

Figure 1.—U.S. Army Helicopter with white circle showing nose gearbox location (Ref. 4).

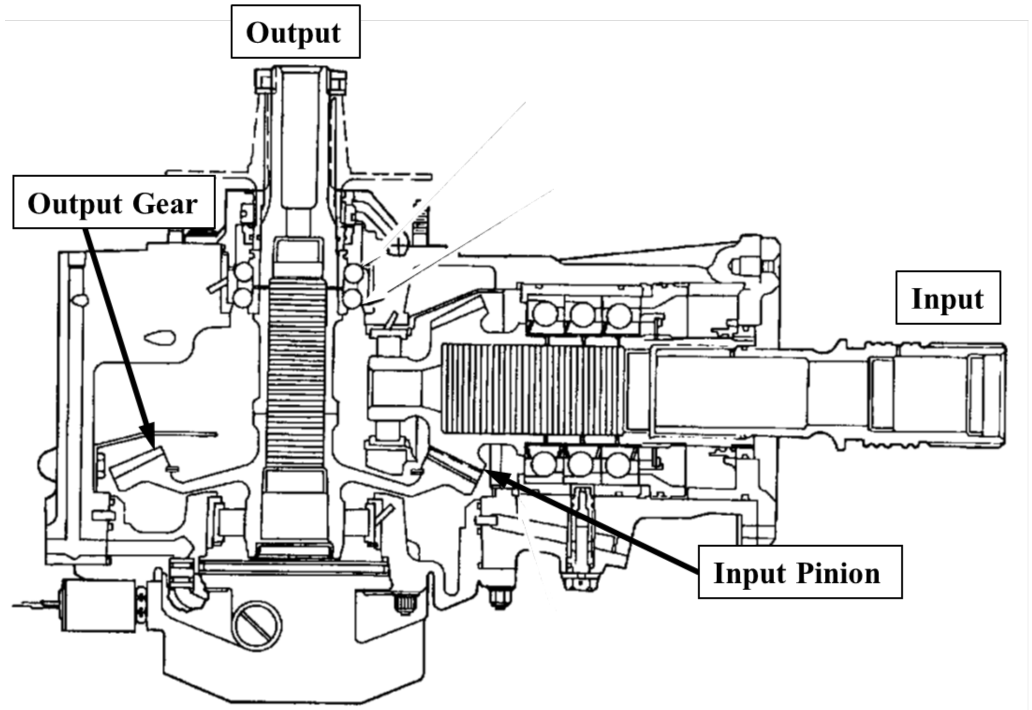

Figure 2.—U.S. Army Helicopter Nose Gearbox showing input pinion and output gear locations (Ref. 5).

Methodology and Results

Dataset Down-Select

An initial pool of 20 data sets was reviewed and reduced to 10 data sets due to insufficient CI data or lack of TDA photographs. Data sets selected for the study are shown in Table 1. Due to data availability limitations, some data sets were used for either the Mean CI analysis or CI versus gear wear analysis as described below. Seven data sets were used for both analyses.

TABLE 1.—HELICOPTER NGB DATA SETS USED IN MEAN CI AND TDA ANALYSIS.

NGB designation	Mean CI level analysis	CI versus gear wear analysis
01	Y	Y
02	Y	Y
03	Y	N
04	Y	Y
05	Y	Y
06	Y	Y
07	Y	Y
08	Y	N
09	Y	N
10	Y	Y

Condition Indicator Descriptions

Condition indicators FM0 (Ref. 6), FM4 (Ref. 1), SI (Ref. 7), and DA1 (Ref. 1) were used in the analysis.

- FM0 is the peak-to-peak value of the time synchronous averaged (TSA) data normalized by the sum of the spectral components of the TSA at the regular gear meshing frequencies.

$$\mathrm{FM0} = \frac{PP}{\sum_{i=1}^{n} A(f_i)} \tag{1}$$

where: PP = peak-to-peak level of signal average
A = amplitude at mesh frequency (i=1_ and harmonics (i>1)

- FM4 is calculated from TSA data with filtering performed in the frequency domain on the TSA.

$$\mathrm{FM4} = \frac{\frac{1}{N}\sum_{n=1}^{N}\left(d_n - \bar{d}\right)^4}{\left[\frac{1}{N}\sum_{n=1}^{N}(d_n - \bar{d})^2\right]^2} \tag{2}$$

where: d = difference signal
$\bar{d}$ = mean value of difference signal

- Sideband index (SI) is a measure of local gear faults and is defined as the average of the first order sidebands of the fundamental gear meshing frequency. The increase in magnitude of the sidebands of the fundamental gear meshing frequency drives this CI and indicates a local fault.

$$\mathrm{SI} = \frac{R_{I,-1}^{sb}(x) + R_{I,+1}^{sb}(x)}{2} \tag{3}$$

where: R = regular meshing components
sb = sideband

- DA1 is the RMS of the TSA subtracted from the mean of the synchronous time average. DA1 detects the overall energy increase in the signal indicating a distributed gear fault.

$$DA1 = RMS\left(TSA - \overline{TSA}\right) \tag{4}$$

Statistical Analysis Based on Mean CI Levels

Two statistics were used to assess CI performance:

$$\Delta\mathrm{mean} = CI_{\mathrm{pre-replacement}} - CI_{\mathrm{post-replacement}} \tag{5}$$

$$\%\Delta\mathrm{mean} = 100\left(\frac{CI_{\mathrm{pre-replacement}} - CI_{\mathrm{post-replacement}}}{CI_{\mathrm{pre-replacement}}}\right) \tag{6}$$

A positive value in Δmean was marked green (e.g., good part indication). A negative value was marked red (e.g., bad part indication). The percent difference in the mean, %Δmean, was evaluated at the 25 and 50 percent level. Percentages exceeding these arbitrary minimum values were marked green, respectively. Based on the data set analyzed thus far an initial uncertainty of ±10 percent is given on the CI data until more data sets can be analyzed. These data points are marked as orange. Values not meeting these baseline percentages and above the 10 percent uncertainty range were marked yellow (e.g., marginal). Percentages that were negative and exceeded the 10 percent uncertainty range were marked red. Figure 3 gives an example of this mean CI analysis for condition indicator, input pinion SI, NGB Tail 04. This graphical result is repeated 80 times for each CI, input pinion/output gear, NGB Tail combination and is tabulated in Table 2 and Table 3. Further, the CIs were ranked in terms of 'batting average' similar to Antolick et.al. (Ref. 1) as follows:

$$\text{Batting Average} = \frac{\left[\#\text{Green} + \left(\frac{\#\text{Yellow}}{2}\right)\right]}{\left[\#\text{Green}+\#\text{Yellow}+\#\text{Red}\right]} \quad (7)$$

A summary is shown in Table 4. On the input pinion side, DA1 and SI performed best in all three statistical measures: Δmean, Δmean(25 percent), and Δmean(50 percent). Both DA1 and SI condition indicators performed relatively well on the output gear side. Input pinion FM4 performed the worst. FM4 again performed poorly on the output gear side. FM0 results were mixed. On the input pinion side, with the exception of FM4, the CIs performed better than their output gear side counter-parts. Based on this analysis DA1 and SI were used in the subsequent CI versus gear wear analysis.

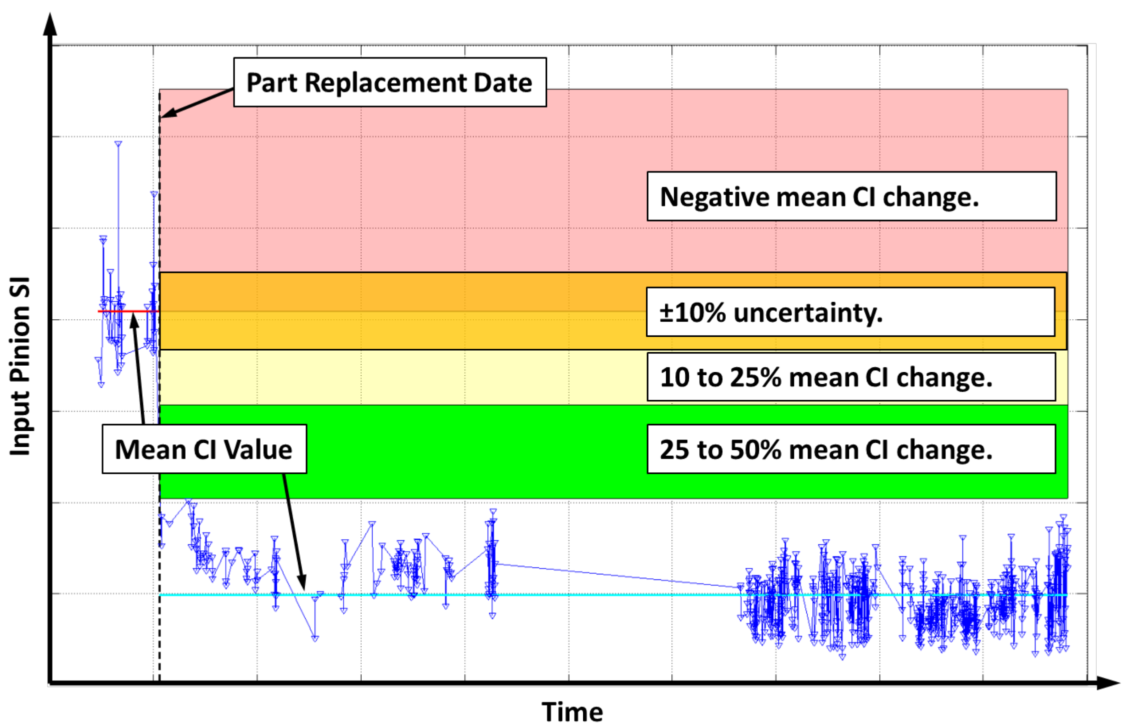

Figure 3.—Example mean CI analysis result for NGB Tail 04, Input Pinion SI.

TABLE 2.—MEAN CI ANALYSIS RESULTS: TAILS 01 TO 06

Tail	Time period	Statistic	In_DA1	In_FM0	In_SI	In_FM4	Out_DA1	Out_FM0	Out_SI	Out_FM4
01	Pre Replacement	min	8.31	4.48	1.79	2.02	6.98	3.83	1.39	2.46
		max	54.06	14.29	8.00	3.00	54.67	9.09	10.79	3.30
		mean	21.72	5.94	4.26	2.56	21.80	5.50	4.76	2.93
	Post Replacement	min	0.42	3.67	0.07	2.02	0.36	3.40	0.05	2.38
		max	25.38	19.58	1.70	3.61	24.09	31.72	1.28	3.43
		mean	5.99	6.91	0.75	2.55	4.39	6.72	0.66	2.84
		Δ mean	15.72	−0.97	3.50	0.01	17.40	−1.23	4.10	0.09
		%Δ mean (25%)	72.41	−16.37	82.31	0.53	79.84	−22.32	86.08	3.02
		%Δ mean (50%)	72.41	−16.37	82.31	0.53	79.84	−22.32	86.08	3.02
02	Pre Replacement	min	0.01	3.19	0.00	2.47	0.03	3.22	0.00	2.36
		max	90.39	25.95	7.13	4.02	89.62	82.23	5.02	3.68
		mean	66.98	4.53	4.33	2.83	66.66	6.61	4.17	3.01
	Post Replacement	min	0.57	3.34	0.15	2.20	0.77	3.19	0.13	2.50
		max	18.97	15.74	2.30	4.05	17.61	47.55	2.31	4.49
		mean	12.18	4.74	1.39	2.91	11.13	4.35	1.35	3.22
		Δ mean	54.80	−0.20	2.94	−0.08	55.53	2.27	2.82	−0.22
		%Δ mean (25%)	81.82	−4.45	67.97	−2.87	83.31	34.28	67.65	−7.19
		%Δ mean (50%)	81.82	−4.45	67.97	−2.87	83.31	34.28	67.65	−7.19
03	Pre Replacement	min	31.09	4.42	3.85	2.38	24.69	3.17	1.40	2.66
		max	55.46	6.14	7.22	2.92	45.65	4.34	2.54	4.43
		mean	38.39	5.16	5.02	2.58	30.32	3.64	1.99	3.06
	Post Replacement	min	3.96	3.13	0.30	2.13	5.20	3.24	0.68	2.48
		max	50.61	9.88	1.75	3.69	50.41	11.24	2.80	3.33
		mean	11.77	4.88	0.80	2.77	12.37	5.88	1.29	2.78
		Δ mean	26.61	0.28	4.22	−0.19	17.95	−2.25	0.71	0.28
		%Δ mean (25%)	69.33	5.34	83.98	−7.37	59.21	−61.82	35.41	9.21
		%Δ mean (50%)	69.33	5.34	83.98	−7.37	59.21	−61.82	35.41	9.21
04	Pre Replacement	min	18.79	4.10	3.29	2.41	18.70	3.79	2.25	1.89
		max	42.66	6.42	5.92	3.62	42.18	7.95	3.60	2.80
		mean	36.10	4.61	4.09	2.98	34.60	4.48	2.83	2.51
	Post Replacement	min	2.82	3.07	0.31	2.18	2.29	3.40	0.25	2.47
		max	58.21	7.71	2.02	4.33	57.35	17.22	4.62	4.55
		mean	13.48	4.05	0.99	2.80	14.45	5.55	1.93	3.03
		Δ mean	22.63	0.55	3.10	0.19	20.14	−1.07	0.89	−0.51
		%Δ mean (25%)	62.67	12.01	75.85	6.24	58.22	−23.79	31.61	−20.45
		%Δ mean (50%)	62.67	12.01	75.85	6.24	58.22	−23.79	31.61	−20.45
05	Pre Replacement	min	5.23	3.32	0.69	2.26	5.59	3.41	0.86	2.38
		max	49.40	5.49	6.09	3.57	46.04	9.00	4.20	3.41
		mean	13.35	4.16	1.48	2.80	13.26	4.50	1.64	2.89
	Post Replacement	min	18.30	2.87	0.38	2.12	18.79	3.22	0.56	1.96
		max	69.34	3.42	1.52	4.33	75.30	4.99	3.71	3.64
		mean	29.76	3.10	0.84	2.91	31.59	4.07	1.86	2.47
		Δ mean	−16.40	1.06	0.63	−0.12	−18.34	0.43	−0.22	0.41
		%Δ mean (25%)	−122.81	25.48	42.92	−4.12	−138.32	9.56	−13.62	14.27
		%Δ mean (50%)	−122.81	25.48	42.92	−4.12	−138.32	9.56	−13.62	14.27
06	Pre Replacement	min	8.19	5.42	1.58	2.00	11.26	4.73	0.59	2.12
		max	156.15	38.83	14.75	3.59	47.67	58.20	4.20	4.94
		mean	81.17	18.08	6.89	2.64	28.72	9.53	2.07	3.04
	Post Replacement	min	10.88	3.67	1.10	1.95	9.22	3.64	1.97	2.83
		max	30.97	6.41	1.53	2.27	32.55	6.41	3.45	3.27
		mean	20.93	5.04	1.32	2.11	20.88	5.03	2.71	3.05
		Δ mean	60.24	13.04	5.57	0.53	7.84	4.51	−0.64	−0.01
		%Δ mean (25%)	74.22	72.10	80.87	20.04	27.29	47.25	−30.74	−0.46
		%Δ mean (50%)	74.22	72.10	80.87	20.04	27.29	47.25	−30.74	−0.46

TABLE 3.—MEAN CI ANALYSIS RESULTS TAILS 07 TO 10 WITH BATTING AVERAGE CALCULATION

Tail	Time period	Statistic	In_DA1	In_FM0	In_SI	In_FM4	Out_DA1	Out_FM0	Out_SI	Out_FM4
07	Pre Replacement	min	7.09	4.06	0.42	2.11	6.27	3.62	0.78	2.41
		max	27.60	14.98	3.19	3.25	22.85	9.60	2.45	3.54
		mean	14.04	5.98	1.17	2.66	12.11	5.07	1.36	2.86
	Post Replacement	min	5.48	3.61	0.27	2.46	5.94	4.09	0.49	2.56
		max	17.44	15.97	1.30	4.09	18.21	20.14	2.61	3.49
		mean	8.92	7.32	0.55	3.03	10.07	9.24	1.05	2.97
		Δ mean	5.13	–1.34	0.62	–0.37	2.04	–4.17	0.30	–0.11
		%Δ mean (25%)	36.50	–22.35	52.95	–13.75	16.83	–82.18	22.45	–3.75
		%Δ mean (50%)	36.50	–22.35	52.95	–13.75	16.83	–82.18	22.45	–3.75
08	Pre Replacement	min	0.02	4.43	0.00	2.46	0.03	4.80	0.00	2.71
		max	13.98	6.58	1.15	3.64	13.83	10.05	1.68	3.08
		mean	8.38	5.53	0.82	2.81	8.78	6.87	1.14	2.95
	Post Replacement	min	0.31	2.83	0.08	2.23	0.40	3.11	0.05	2.34
		max	58.81	28.85	3.81	4.70	56.87	40.84	4.58	3.74
		mean	22.79	3.62	1.39	2.94	23.71	4.55	2.60	2.84
		Δ mean	–14.41	1.92	–0.57	–0.13	–14.94	2.32	–1.46	0.11
		%Δ mean (25%)	–172.00	34.67	–70.43	–4.60	–170.15	33.80	–128.03	3.60
		%Δ mean (50%)	–172.00	34.67	–70.43	–4.60	–170.15	33.80	–128.03	3.60
09	Pre Replacement	min	0.57	3.02	0.17	1.80	0.68	3.07	0.09	2.06
		max	52.51	31.30	3.53	4.49	51.59	21.45	3.00	3.55
		mean	17.15	4.48	1.06	2.40	17.11	4.82	1.89	2.84
	Post Replacement	min	1.37	2.71	0.20	2.16	0.99	3.06	0.19	2.41
		max	39.49	13.40	2.00	3.87	40.64	13.62	3.99	3.77
		mean	19.53	3.52	1.00	2.76	20.69	4.17	2.49	2.85
		Δ mean	–2.38	0.96	0.06	–0.36	–3.58	0.65	–0.60	0.00
		%Δ mean (25%)	–13.86	21.40	5.60	–15.12	–20.95	13.56	–31.86	–0.09
		%Δ mean (50%)	–13.86	21.40	5.60	–15.12	–20.95	13.56	–31.86	–0.09
10	Pre Replacement	min	10.62	2.98	0.75	2.14	9.44	3.39	2.24	2.35
		max	70.44	8.35	6.40	3.93	71.42	16.59	11.51	4.16
		mean	25.26	4.35	3.09	2.86	26.10	4.90	4.48	2.93
	Post Replacement	min	3.48	2.86	0.23	2.11	5.99	3.08	0.42	2.44
		max	85.19	11.27	2.01	3.99	88.11	21.77	5.28	3.73
		mean	12.87	4.61	0.75	2.76	15.05	7.24	2.12	2.90
		Δ mean	12.38	–0.27	2.34	0.10	11.05	–2.34	2.37	0.03
		%Δ mean (25%)	49.03	–6.17	75.73	3.62	42.32	–47.74	52.82	1.10
		%Δ mean (50%)	49.03	–6.17	75.73	3.62	42.32	–47.74	52.82	1.10
	Δ mean	Green	7	5	8	1	7	4	6	1
		Orange	0	3	1	6	0	1	0	8
		Yellow	0	0	0	0	0	0	0	0
		Red	3	2	1	3	3	5	4	1
		Percent	0.700	0.500	0.800	0.100	0.700	0.400	0.600	0.100
	%Δ mean(25%)	Green	7	3	8	0	6	3	5	0
		Orange	0	3	1	6	0	1	0	8
		Yellow	0	2	0	1	1	1	1	1
		Red	3	2	1	3	3	5	4	1
		Percent	0.700	0.400	0.800	0.050	0.650	0.350	0.550	0.050
	%Δ mean(50%)	Green	5	1	7	0	4	0	3	0
		Orange	0	3	1	6	0	1	0	8
		Yellow	2	4	1	1	3	4	3	1
		Red	3	2	1	3	3	5	4	1
		Percent	0.600	0.300	0.750	0.050	0.550	0.200	0.450	0.050

TABLE 4.—RANK SUMMARY (BATTING AVERAGE) OF THEPERFORMANCE OF 4 CIS BASED ON STATISTICAL MEAN LEVELS

Rank summary				
	Input gear CIs			
	DA1	FM0	SI	FM4
Δmean	0.700	0.500	0.800	0.100
%Δmean (25%)	0.700	0.400	0.800	0.050
%Δmean (50%)	0.600	0.300	0.750	0.050
	Output gear CIs			
	DA1	FM0	SI	FM4
Δmean	0.700	0.400	0.600	0.100
%Δmean (25%)	0.650	0.350	0.550	0.050
%Δmean (50%)	0.550	0.200	0.450	0.050

Standard Gear Wear Terminology

U.S. Army documents give specific maintenance procedures for the helicopter NGB. Specific inspection instructions during NGB teardown for the input pinion and output gear shaft teeth require ‘no pitting, scuffing, scoring, metal flow, or measurable wear steps.’ Also, inspection definitions are given on pitting, scoring, and wear. Pitting is described as ‘small indentations in a surface.’ Army TDAs provide both descriptive and photo documentation of gear wear during NGB tear-down. However, some inconsistencies were observed in describing the gear damage seen from one TDA report to another. Standardizing the description of gear wear would provide a number of advantages to the CBM community:

1. Provide data on component performance with respect to the specific way the gear failed (e.g., wear, scuffing, plastic deformation, contact fatigue, cracking, fracture, bending fatigue).
2. Provide data on CI performance.
3. May provide insight on improving overall helicopter safety, maintenance practices, and performance.

Describing the gear wear from Army TDAs using the terminology from the ANSI/AGMA 101-E95 standard, Table 5, is one specific method of standardizing the gear wear descriptions. Gear pitting per the AGMA standard is classified as contact fatigue which is subdivided into three general modes: pitting (macropitting), micropitting, and subcase fatigue. Macropitting is further divided into specific modes or degrees, including initial pitting, progressive pitting, flaking, and spalling. This is shown in Figure 4. Further definitions for the specific mode or degree of pitting can provide clues to the gear inspector responsible for classifying the type of gear failure. Definitions are given as follows per ANSI/AGMA 1010-E95, with example photographs, in Figure 5 through Figure 10.

- Initial Pitting—Small pits less than 1 mm in diameter. They occur in localized areas and tend to redistribute the load by removing high asperities.
- Progressive Pitting—Characterized by pits significantly larger than 1 mm in diameter. Pitting of this type may continue at an increased rate until a significant portion of the tooth surface has pits of various shapes and sizes.
- Flake Pitting—Pits that are relatively shallow but large in area. The fatigue crack extends from an origin at the surface of the tooth in a fan shaped manner until thin flakes of material break out and form a triangular crater.
- Spalling—Progressive pitting where pits coalesce and form irregular craters that cover a significant area of the tooth surface.

- Micropitting—Gear surface appears frosted, matted, or gray stained. Under magnification, the surface appears to be covered by very fine pits.
- Subcase Fatigue—Origin of the fatigue crack is below the surface of the gear teeth in the transition zone between the case and core. Fatigue beach marks may be evident on the crater bottom formed by propagation of the main crack.

Depending on material, processing, use, etc., pitting damage may not appear exactly as described above. A database of typical pitting damage should be considered for the gear in question and used in place of the sample descriptions noted above.

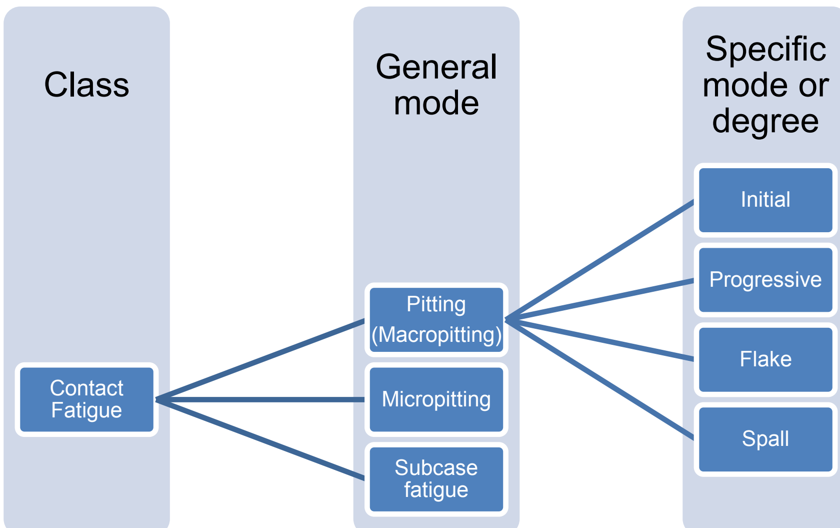

Figure 4.—Example gear failure mode nomenclature: Contact Fatigue.

Figure 5.—Example of Initial Pitting. Extracted from ANSI/AGMA 1010-E95, Appearance of Gear Teeth Terminology of Wear and Failure, with the permission of the publisher, the American Gear Manufacturers Association, 1500 King Street, Suite 201, Alexandria, Virginia 22314.

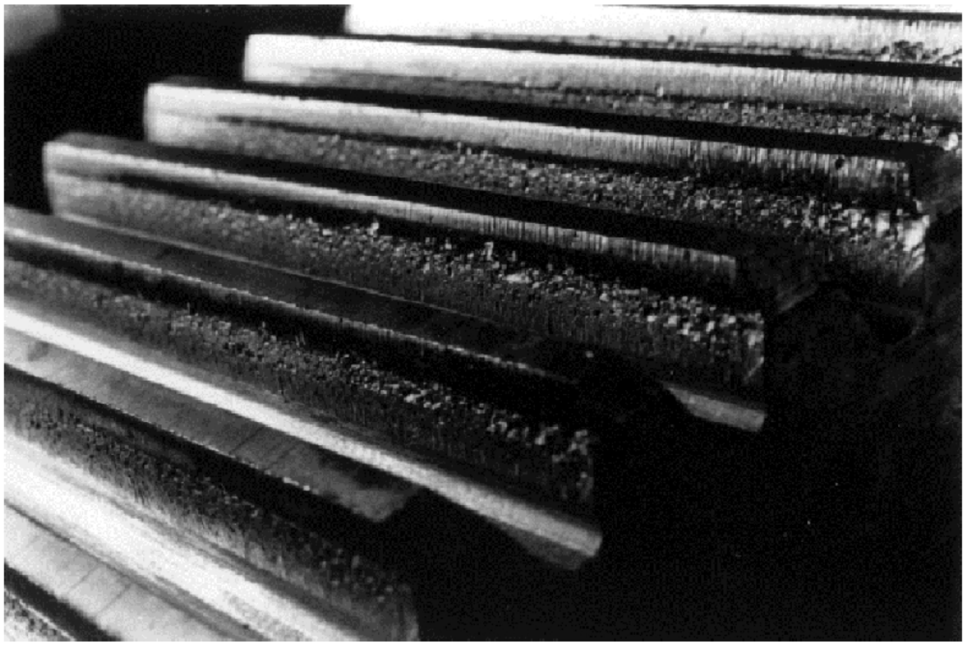

Figure 6.—Example of Progressive Pitting. Extracted from ANSI/AGMA 1010-E95, Appearance of Gear Teeth Terminology of Wear and Failure, with the permission of the publisher, the American Gear Manufacturers Association, 1500 King Street, Suite 201, Alexandria, Virginia 22314.

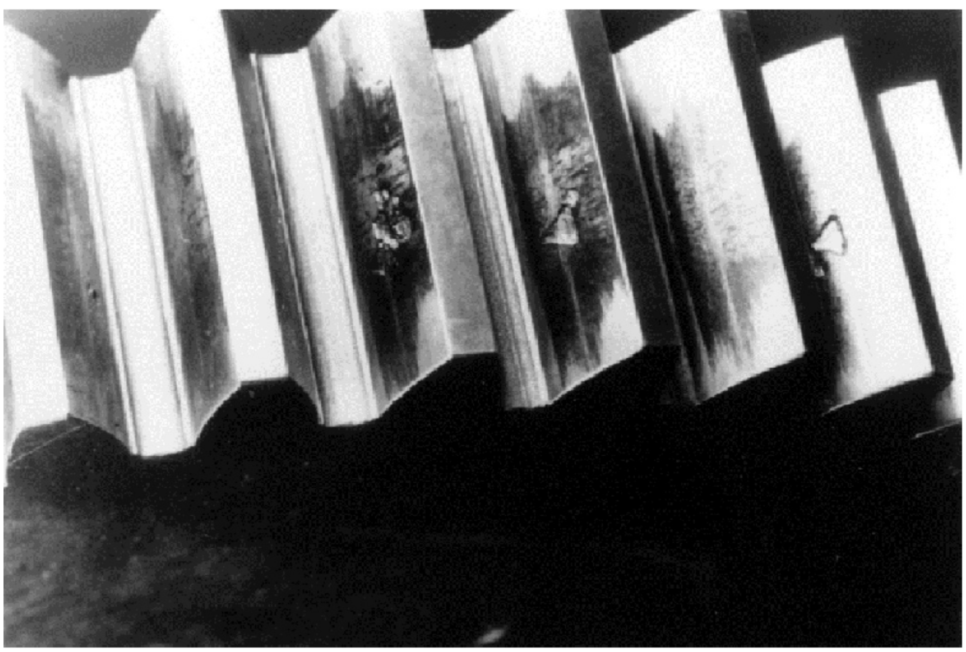

Figure 7.—Example of Flake Pitting. Extracted from ANSI/AGMA 1010-E95, Appearance of Gear Teeth Terminology of Wear and Failure, with the permission of the publisher, the American Gear Manufacturers Association, 1500 King Street, Suite 201, Alexandria, Virginia 22314.

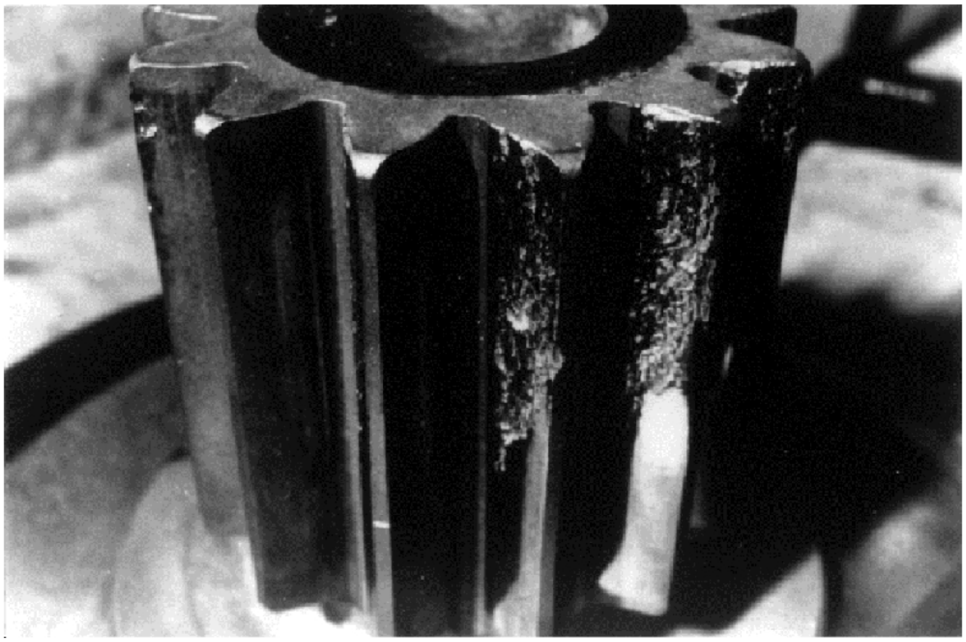

Figure 8.—Example of Spalling. Extracted from ANSI/AGMA 1010-E95, Appearance of Gear Teeth Terminology of Wear and Failure, with the permission of the publisher, the American Gear Manufacturers Association, 1500 King Street, Suite 201, Alexandria, Virginia 22314.

Figure 9.—Example of Micropitting. Extracted from ANSI/AGMA 1010-E95, Appearance of Gear Teeth Terminology of Wear and Failure, with the permission of the publisher, the American Gear Manufacturers Association, 1500 King Street, Suite 201, Alexandria, Virginia 22314.

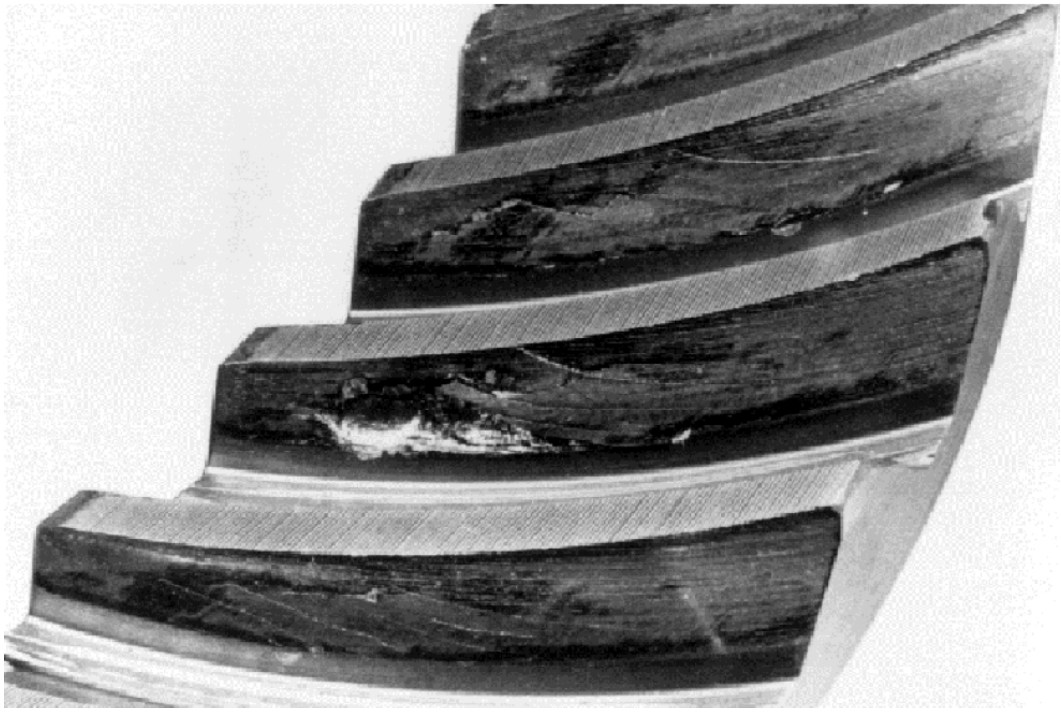

Figure 10.—Example of Subcase Fatigue. Extracted from ANSI/AGMA 1010-E95, Appearance of Gear Teeth Terminology of Wear and Failure, with the permission of the publisher, the American Gear Manufacturers Association, 1500 King Street, Suite 201, Alexandria, Virginia 22314.

Consider the following spiral bevel gear wear description from an Army tear-down analysis (TDA) Report.

> "The input gear and the output gear teeth both showed abnormal wear. Not only did they show abnormal wear but it was uneven wear and bluing that appears to be from excessive heating. The input gear was marked with … and is shown in Figures 6.3-1 thru 6.3-6. Figure 6.3-1 is an overall picture, Figures 6.3-2 to 6.3-5 show the uneven wear and Figure 6.3-6 is a close up of the teeth. The output gear was marked on one side with … and is shown in Figures 6.3-7 thru 6.3-21. Figure 6.3-7 is an overall view, Figures 6.3-8 to 6.3-12 shows the uneven wear, Figures 6.3-13, 14, and 15 are close ups, Figures 6.3-16 to 6.3-20 are taken under a low power microscope, and Figure 6.3-21 shows the heating on the gear. DMWR 1-3010-204 Page 0057 00-6 shows the loaded contact pattern limits. The splines on the output gear also showed wear and is shown in Figures 6.3-22 and 6.3-23. A Non Destructive Inspection (NDI) of the output gear did not show evidence of cracks."

Figure 6.3-16 of the TDA shown below as Figure 11 could be further classified, at least on one of the output gear teeth, as either progressive pitting or micropitting. A dimension marker on the original wear photo would aid in better estimating damage feature dimensions. Further, the use of a numbering scheme could streamline the identification of gear damage particularly during tear-down analyses at a U.S. Army

Engine Overhaul Depot. Consider the following numbering scheme for Table 5 shown in Table 6 which is similar to a coding scheme for a work breakdown structure. The Class of gear mode failure represents the top of the hierarchy. The General Mode and Specific Mode or Degree represents subsequent sub-classes. Thus, the progressive pitting example from Figure 11 can be re-categorized as 4.3.2. Performing TDA gear wear descriptions using this classification system could streamline and standardize analyses. Another potential advantage of using this system is further refinement of failure prediction algorithms.

Figure 11.—Output gear damage—progressive pitting.

TABLE 5.—NOMENCLATURE OF GEAR FAILURE MODES (ANSI/AGMA 1010-E95)

Class	General mode	Specific mode or degree	Not preferred
Wear	Adhesion	Mild	Running-in wear
		Moderate	
		Severe (see scuffing)	Scoring
			Scratching
	Abrasion	Mild, moderate, severe	Cutting
			Burnishing
	Polishing	Mild, moderate, severe	
	Corrosion		
	Fretting corrosion		
	Scaling		
	Cavitation		
	Erosion		
	Electrical discharge		
	Ripple		
Scuffing	Scuffing	Mild, moderate, severe	Scoring
			Cold scuffing
			Hot scuffing
			Welding
			Galling
			Seizing
Plastic deformation	Plastic deformation	Indentation	Bruising
			Peening
			Denting
			Brinelling
		Cold flow	Permanent deformation
		Hot flow	Overheating
		Rolling	
		Tooth hammer	
		Rippling	Fish scaling
		Ridging	
		Burr	
		Root fillet yielding	
		Tip-to-root interference	
Contact fatigue	Pitting (macropitting)	Initial	
		Progressive	Destructive
		Flake	Arrow head
		Spall	
	Micropitting		Frosting
			Gray staining
			Peeling
	Subcase fatigue		Case crushing
Cracking	Hardening cracks		Quenching cracks
	Grinding cracks		
	Rim and web cracks		
	Case/core separation		Internal rupture
	Fatigue cracks		
Fracture	Brittle fracture		Fast fracture
	Ductile fracture		Smearing
	Mixed mode fracture		Semi-brittle
	Tooth shear		
	Fracture after plastic deformation		
Bending fatigue	Low-cycle fatigue		
	High-cycle fatigue	Root fillet cracks	
		Profile cracks	
		Tooth end cracks	

TABLE 6.—NUMBERING SCHEME FOR NOMENCLATURE OF GEAR FAILURE MODES (ANSI/AGMA 1010-E95)

Class	General mode	Specific mode or degree
1.0 Wear	1.1 Adhesion	1.1.1 Mild
		1.1.2 Moderate
		1.1.3 Severe (see scuffing)
	1.2 Abrasion	1.2.1 Mild
		1.2.2 Moderate
		1.2.3 Severe
	1.3 Polishing	1.3.1 Mild
		1.3.2 Moderate
		1.3.3 Severe
	1.4 Corrosion	
	1.5 Fretting corrosion	
	1.6 Scaling	
	1.7 Cavitation	
	1.8 Erosion	
	1.9 Electrical discharge	
	1.10 Rippling	
2.0 Scuffing	2.1 Scuffing	2.1.1 Mild
		2.1.2 Moderate
		2.1.3 Severe
3.0 Plastic deformation	3.1 Plastic deformation	3.1.1 Indentation
		3.1.2 Cold flow
		3.1.3 Hot flow
		3.1.4 Rolling
		3.1.5 Tooth hammer
		3.1.6 Rippling
		3.1.7 Ridging
		3.1.8 Burr
		3.1.9 Root fillet yielding
		3.1.10 Tip-to-root interference
4.0 Contact fatigue	4.1 Subcase fatigue	
	4.2 Micropitting	
	4.3 Pitting (macropitting)	4.3.1 Initial
		4.3.2 Progressive
		4.3.3 Flake
		4.3.4 Spall
5.0 Cracking	5.1 Hardening cracks	
	5.2 Grinding cracks	
	5.3 Rim and web cracks	
	5.4 Case/core separation	
	5.5 Fatigue cracks	
6.0 Fracture	6.1 Brittle fracture	
	6.2 Ductile fracture	
	6.3 Mixed mode fracture	
	6.4 Tooth shear	
	6.5 Fracture after plastic deformation	
7.0 Bending fatigue	7.1 Low-cycle fatigue	
	7.2 High-cycle fatigue	7.2.1 Root fillet cracks
		7.2.2 Profile cracks
		7.2.3 Tooth end cracks

CI Versus Gear Wear Analysis

A pool of seven helicopter NGB tails were used out of a possible twenty available. To be included in this analysis, each tail required gear wear pictures to gauge the mode of gear failure per ANSI/AGMA 1010-E95 standards. However, some gear wear pictures were unavailable from existing TDAs and AEAs. Thus, certain tail numbers were left out of the analysis as noted above in Table 1. Condition Indicators DA1 and SI were analyzed with respect to 25 and 50 percent positive response levels. Positive responses are defined such that the change in mean CI levels were at least 25 and 50 percent lower than prior to the damaged component being changed. The CIs were chosen based on the mean CI level analysis as described above in Table 2 and Table 3. Five possible gear wear modes were determined from available TDA/AEA gear wear pictures: 1) micropitting, 2) progressive pitting, 3) flake pitting, 4) spalling, and 5) brittle fracture. The numbering scheme in Table 6 is used to describe the various gear failure modes.

Table 7(a) and Table 8(a) show positive response levels at the 50 and 25 percent levels. Per available TDA photos, for every helicopter tail listed in Table 7(a) for a specific gear wear mode, at least three teeth exhibited that particular wear pattern. Each of the seven helicopter NGB tails are assigned a row within each Gear Wear Mode so that tails having gears exhibiting multiple wear modes are readily seen. For example, Tail 02 is assigned the second row of each Gear Wear Mode and exhibits a 50 percent positive response for micropitting for both output gear CIs, DA1 and SI as well a 50 percent positive response for spalling at the input pinion CIs, DA1 and SI.

The positive responses were tabulated by number and percentage for each set of CI and specific gear wear mode pair, Table 7(d) to (e) and Table 8(d) to (e). At the 25 percent level, more positive responses were received for the input pinion CIs (33 percent or 23/70) than the output gear CIs (23 percent or 16/70). At the 50 percent level the positive responses decreased for both input pinion CIs (24 percent or 17/70) versus output gear CIs (16 percent or 11/70).

The CI/Gear Wear Mode combination with the most positive responses was input pinion SI with micropitting and spalling both at 57 percent at the 50 percent Positive Response Level (Table 7(d)) and with micropitting at 71 percent at the 25 percent Positive Response Level (Table 8(d)). On the output gear NGB side, output gear SI had the most positive responses with micropitting at 43 percent at the 50 percent Positive Response Level (Table 7(d)) while output gear DA1 had the most positive responses with micropitting at 57 percent at the 25 percent Positive Response Level (Table 8(d)).

Positive responses were also tabulated by percentage for each CI against any gear wear mode, Table 7(c) and Table 8(c). At the 50 percent Positive Response Level, SI had the most responses on the input pinion NGB side (31 percent) and on the output gear NGB side (20 percent). At the 25 percent positive response level, SI had the most responses on the input pinion NGB side (34 percent) while DA1 had the most responses on the output gear NGB side (26 percent).

Finally, positive responses were tabulated by percentage for each specific gear wear mode versus input pinion CIs and output gear CIs, in Table 7(b) and Table 8(b). At the 50 percent Positive Response Level, spalling (50 percent) was the most dominant gear wear mode observed on the input pinion NGB side while micropitting (36 percent) was the most dominant gear wear mode observed on the output gear NGB side. At the 25 percent Positive Response Level, micropitting was the most dominant gear wear mode observed on the input pinion NGB side (64 percent) and on the output gear NGB side (50 percent). It is noted that micropitting was the only Gear Wear Mode observed in all seven helicopter NGB tails at the 25 percent Positive Response Level.

TABLE 7.—HELICOPTER NGB TAILS SHOWING CI 50 PERCENT POSITIVE RESPONSE AFTER COMPONENT REPLACEMENT VERSUS GEAR WEAR MODE
[Blank spaces in (a) indicate no damage was found with the corresponding gear wear mode.]

(a) AH–64 NGB tails showing CI 50% positive response after component replacement versus gear wear mode.

Gear wear mode AGMA 1010 ↓	Condition indicator			
	Input pinion		Output gear	
	In_DA1	In_SI	Out_DA1	Out_SI
4.2 Micropitting	01	01	01	01
			02	02
	04	04		
		07		
		10		10
4.3.2 Progressive			01	01
		10		10
4.3.3 Flake	01	01		
4.3.4 Spalling	01	01	01	01
	02	02		
	06	06		
		10		10
6.1 Brittle fracture				
		10		

(b) Percent 'positive' response input NGB and output NGB versus wear mode.

	In_DA1	In_SI	Out_DA1	Out_SI
4.2	42.9		35.7	
4.3.2	7.1		21.4	
4.3.3	14.3		0.0	
4.3.4	50.0		21.4	
6.1	7.1		0.0	

TABLE 7.—CONCLUDED.

(c) Percent 'positive' response CI versus any wear.

	In_DA1	In_SI	Out_DA1	Out_SI
4.2 4.3.2 4.3.3 4.3.4 6.1	17.1	31.4	11.4	20.0

(d) Percent 'positive' response CI versus wear mode.

	In_DA1	In_SI	Out_DA1	Out_SI
4.2	28.6	57.1	28.6	42.9
4.3.2	0.0	14.3	14.3	28.6
4.3.3	14.3	14.3	0.0	0.0
4.3.4	42.9	57.1	14.3	28.6
6.1	0.0	14.3	0.0	0.0

(e) Cells with 'positive' response.

	In_DA1	In_SI	Out_DA1	Out_SI
4.2	2	4	2	3
4.3.2	0	1	1	2
4.3.3	1	1	0	0
4.3.4	3	4	1	2
6.1	0	1	0	0

(f) Number tails per CI versus wear mode.

	In_DA1	In_SI	Out_DA1	Out_SI
4.2	7	7	7	7
4.3.2	7	7	7	7
4.3.3	7	7	7	7
4.3.4	7	7	7	7
6.1	7	7	7	7

TABLE 8.—AH-64 NGB TAILS SHOWING CI 25 PERCENT POSITIVE RESPONSE AFTER COMPONENT REPLACEMENT VERSUS GEAR WEAR MODE
[Blank spaces in Table 8(a) indicate no damage was found with the corresponding gear wear mode.]

(a) AH–64 NGB tails showing CI 25% positive response after component replacement versus gear wear mode

Gear wear mode AGMA 1010 ↓	Condition indicator			
	Input pinion		Output gear	
	In_DA1	In_SI	Out_DA1	Out_SI
4.2 Micropitting	01	01	01	01
				02
	04	04		
		05		
			06	
	07	07		
	10	10	10	10
4.3.2 Progressive			01	01
	10	10	10	10
4.3.3 Flake	01	01		
4.3.4 Spalling	01	01	01	01
	02	02		
	06	06		
	10	10	10	10
6.1 Brittle fracture				
			06	
	10	10		

(b) Percent 'Positive' response input NGB and output NGB versus wear mode.

	In_DA1	In_SI	Out_DA1	Out_SI
4.2	64.3		50.0	
4.3.2	14.3		28.6	
4.3.3	14.3		0.0	
4.3.4	57.1		28.6	
6.1	14.3		7.1	

TABLE 8.—CONCLUDED.

(c) Percent 'Positive' response CI versus any wear.

	In_DA1	In_SI	Out_DA1	Out_SI
4.2				
4.3.2				
4.3.3	31.4	34.3	25.7	20.0
4.3.4				
6.1				

(d) Percent 'Positive' response CI versus wear mode.

	In_DA1	In_SI	Out_DA1	Out_SI
4.2	57.1	71.4	57.1	42.9
4.3.2	14.3	14.3	28.6	28.6
4.3.3	14.3	14.3	0.0	0.0
4.3.4	57.1	57.1	28.6	28.6
6.1	14.3	14.3	14.3	0.0

(e) Cells with 'Positive' response.

	In_DA1	In_SI	Out_DA1	Out_SI
4.2	4	5	4	3
4.3.2	1	1	2	2
4.3.3	1	1	0	0
4.3.4	4	4	2	2
6.1	1	1	1	0

(f) Number tails per CI versus wear mode.

	In_DA1	In_SI	Out_DA1	Out_SI
4.2	7	7	7	7
4.3.2	7	7	7	7
4.3.3	7	7	7	7
4.3.4	7	7	7	7
6.1	7	7	7	7

Conclusions

Based on the results of this study the following conclusions can be made:

1. From the Mean Condition Indicator Level Analysis, Diagnostic Algorithm 1 and Sideband Index were found to perform best while FM4 performed the worst. FM0 results were mixed. These findings were generally consistent with conclusions by previous studies.
2. Condition indicators, Sideband Index and Diagnostic Algorithm 1 were found to respond well to component changes where micropitting and spalling were the observed gear wear mode.
3. Overall, input nose gearbox condition indicators were found to respond better to part changes due to gear wear than corresponding output nose gearbox condition indicators.
4. Based on the condition indicator versus gear wear analysis, improvements to condition indicators should target both input Diagnostic Algorithm 1 and input Sideband Index to detect either gear tooth micropitting or spalling.

Recommendations for Improved Analysis Capabilities:

1. It is possible that not all gear teeth were photographed in the tear-down analysis reports. Thus actual damage levels may differ than from what was reported. It is suggested that all gear teeth on damaged nose gear box be photographed in a consistent manner such that the type of damaged can be documented per ANSI/AGMA 1010-E95 standards.
2. If not already implemented, any damaged gears should be stored for further analysis.

References

1. "Evaluation of Gear Condition Indicator Performance on Rotorcraft Fleet," Antolick, Lance; Branning, Jeremy; Dempsey, Paula; Wade, Daniel. 66th American Helicopter Society International Annual Forum 2010, Phoenix, AZ. 11-13 May 2010.
2. ADS-79C-HDBK, Aeronautical Design Standard Handbook for Condition Based Maintenance Systems for U.S. Army Aircraft. 12 Jan. 2012.
3. ANSI/AGMA 1010-E95. Appearance of Gear Teeth – Terminology of Wear and Failure.
4. http://aircraft-photographs.s3-website-eu-west-1.amazonaws.com/Airshow-h2.jpg
5. "A Perspective on condition Monitoring in U.S. Army Aviation," Keller, Jonathan, Ph.D. Wind Turbine Condition Monitoring Workshop, 20 Sep. 2011.
6. "An Investigation of Gear Mesh Failure Prediction Techniques," Zakrajsek, James J. NASA TM–102340, Nov. 1989.
7. Szczeptanik, J., "Time Synchronous Averaging of Ball Mill Vibration," Mechanical Systems and Signal Processing, Vol. 3, No. 1, p. 99, Jan. 1989.

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13. SUPPLEMENTARY NOTES

14. ABSTRACT
This paper details analyses of condition indicator performance for the helicopter nose gearbox within the U.S. Army’s Condition-Based Maintenance Program. Ten nose gearbox data sets underwent two specific analyses. A mean condition indicator level analysis was performed where condition indicator performance was based on a ‘batting average’ measured before and after part replacement. Two specific condition indicators, Diagnostic Algorithm 1 and Sideband Index, were found to perform well for the data sets studied. A condition indicator versus gear wear analysis was also performed, where gear wear photographs and descriptions from Army tear-down analyses were categorized based on ANSI/AGMA 1010-E95 standards. Seven nose gearbox data sets were analyzed and correlated with condition indicators Diagnostic Algorithm 1 and Sideband Index. Both were found to be most responsive to gear wear cases of micropitting and spalling. Input pinion nose gear box condition indicators were found to be more responsive to part replacement during overhaul than their corresponding output gear nose gear box condition indicators.

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