EVALUATION OF STANDARD GEAR METRICS IN HELICOPTER FLIGHT OPERATION

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Abstract: Six well known gear metrics were computed from vibration signals previously recorded from an OH-58C helicopter under controlled flight conditions. For the pinion gear studied, an optimal number of rotations was found for the average. Stationarity decreased as the number of rotations increased. It is conjectured that the dynamic environment of the helicopter is the primary contributor to the decrease in stationarity that was observed during long averaging periods. The six metrics exhibited a complex relationship with torque and rotor rpm. The relationships of metrics to torque differ from that found in the literature on test rigs. Using thresholds derived from earlier test rig results, several metrics exceeded their nominal thresholds a significant number of times, and most of these occurred during descending forward flight maneuvers.

Key Words: Gear, Gear Metrics, Helicopter Flight Test, Stationary Signals

Introduction: Each false alarm made by a machine monitoring system carries a high price tag. The machine must be taken out of service, thoroughly inspected with possible disassembly, and then made ready for service. Loss of use of the machine and the efforts to inspect it are costly. In addition, if a monitoring system is prone to false alarms, the system will soon be turned off or ignored. For aircraft applications, one growing concern is that the dynamic flight environment differs from the laboratory environment where fault detection methods are developed and tested.

Several metrics have been introduced to detect localized damage in gears. In 1977, Stewart [1] introduced several metrics, including FM0 and FM4, for evaluating the health of a gear. These metrics are single valued functions of the vibration signal that indicate if the signal deviates from an ideal model of the signal. FM0 increases if a periodic signal contains a local increase in amplitude. FM4 increases if a signal contains a local increase in amplitude or local phase change in a periodic signal. Zakrajsek [2] introduced NA4 to detect onset of damage like FM4 and continue to react as the damage increases. Martin [3] introduced M6A and M8A for detection of faults in surfaces. These have also been applied to damage detection in gears by Zakrajsek [2]. Zakrajsek [4] introduced NB4, which identifies localized phase changes in a periodic signal. Decker [5] introduced NA4* to improve trending. Dempsey [6] introduced NA4 reset to decrease the sensitivity of NA4 to torque changes.

These metrics have detected faults in several gear tests in experimental test rigs [1,2, 4-11]. Conditions in these tests have been steady state in the sense that the rpm, torque and

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forces on the gear have been held steady. For gears used in a dynamic environment such as that occurring in aircraft, the rpm, torque and forces on the gear are constantly changing, especially for helicopters. The authors have measured significant variation in rotor rpm and torque in helicopters under controlled steady flight conditions flown by highly proficient test pilots. Statistical analyses of the data taken in flight show significant nonstationarity in the vibration measurements [12, 13]. These deviations from stationarity may give rise to different behavior of the metrics when applied to flight data.

In this paper, the authors report more in-depth analyses of the vibration measurements made in flight on an OH-58C Kiowa helicopter. The number of rotations used in creating a time synchronous signal is first studied in terms of the stationarity of the vibration measured on the helicopter. The dynamic torque and rpm are then examined and proposed as a primary cause of decreased stationarity of the vibration signals. Finally, the six metrics discussed above are examined for exceedances of a threshold that we derived from earlier test rig reports and for their relationship to torque and rotor rpm.

Test Description: Two test pilots flew an OH-58C Kiowa helicopter through a matrix of controlled maneuvers in August and September of 2000 at NASA Ames Research Center. Operationally, no mechanical problems were observed with the transmission or the helicopter itself, during the flights. The helicopter was flown 127 hours from the end of the flight test through the end of December 2001, also with no mechanical problems observed in the transmission. Hence, the helicopter transmission may be assumed to have been in good operating condition. The pilots flew fourteen maneuvers (Table I) to cover a large range of the flight envelope of the aircraft. The pilot set up on the maneuver, then initiated the 34-sec. data collection. During a total of eight flights, data were collected for twelve repetitions of each flight maneuver, and also for ground and hover maneuvers at the beginning and end of each flight. The order of the maneuvers was scheduled for each flight to vary the weight of the helicopter over repetitions of the maneuvers and to have each pilot fly the same schedule.

Table I Flight Test Conditions

	Maneuver Description	Minimum Torque	Median Torque	Maximum Torque	Minimum rpm	Median rpm	Maximum rpm
A	level, forward, ~55% torque	51.7	55.4	58.7	354.6	357.5	360.9
B	level, forward, ~80% torque	78.9	79.9	83.3	352.6	354.9	358.7
C	level, sideways left, ~25 kt	43.8	58.3	66.6	350.2	355.2	365.1
D	level, sideways right, ~ 25 kt	44.5	58.4	67.8	348.8	354.2	361.4
E	climb, ~ 55% torque, ~ 60 kt	50.8	55.5	59.5	353.3	357.3	360.0
F	descent, ~10% torque, ~80 kt	8.5	15.0	22.0	358.5	365.1	372.5
G	flat pitch on ground	23.3	25.9	27.8	354.1	356.0	359.3
H	hover, ~ 10ft	60.2	73.6	82.6	349.7	352.6	357.8
I	hover ~ 10 ft, turn left, ~12…/sec	65.1	73.8	80.8	349.3	352.1	357.2
J	hover ~ 10 ft, turn right, ~12…/sec	66.0	73.2	82.6	349.6	352.4	357.5
K	20… bank left turn, ~80kt	56.4	60.8	67.8	354.3	355.7	358.2
L	20… bank right turn, ~80kt	55.3	61.2	67.5	354.4	355.7	358.6
M	climb, ~ 80% torque, ~ 80 kt	76.0	80.3	84.5	352.3	353.8	355.5
N	descent, 35% torque, ~80kt	31.5	35.1	39.4	357.8	359.5	363.0

These flight maneuvers are from steady state flight conditions, most relatively smooth aerodynamic conditions except for decent and hover. The maneuvers do not include some of the extremes in the flight envelope such as maximum torque and autorotation. The test protocol excludes more dynamic flight maneuvers such as transitional states and nap-of-the-earth flight. All tests were flown during low surface wind conditions ranging from calm to a maximum of 5 kt, measured at the start and end of flights. The test was designed to collect vibration measurements of the transmission under steady and relatively benign flight conditions in order to study the helicopter vibration in flight and under the most controlled circumstances. The data collected are meant to provide insight into the vibration characteristics under the easiest to interpret flight conditions. Vibrations produced under routine operating conditions, however, are expected to exhibit more dynamic behavior due to transitions, wind, turbulence, higher loads and more dynamic loads. Such vibration measurements have been made under more characteristic cruise and terminal area maneuvering conditions, and will be reported at a later time.

Measurements were taken with three uniaxial and one tri-axial accelerometer mounted on vertical bolts on the transmission housing. Accelerometers 1, 2 and 3 were horizontal and oriented radial to the transmission at —154¡, -51¡ and +51¡ from the pinion shaft. Accelerometers 4, 5 and 6 were on the tri-axial mount at 129¡ from the pinion shaft with number 4 vertical, number 5 horizontal and tangential to the transmission housing and number 6 horizontal and radial to the transmission housing. These six channels of vibration measurements along with a once-per-rotation signal and engine torque were digitized and stored on a PC based data acquisition system. Torque was derived from engine oil pressure. All signals were digitized to 12 bits at 50 kHz after an 18 kHz low pass anti-aliasing filter. Gains were set to maximize the signal in the digitizing range without clipping, based upon measurements made in earlier flights. Huff [13] contains more information concerning the helicopter, test flights and data acquisition.

The main transmission on the OH-58C Kiowa contains two reduction stages. A 19-tooth pinion on the output shaft of the engine meshes with a 71-tooth spiral bevel gear to provide the first stage. An epicyclic gearbox provides the second stage with the sun gear on the shaft also containing the spiral bevel gear in the first stage. The planet cage section of the epicyclic system, in turn, drives the main rotor. This report presents results pertaining to the pinion gear, because the metrics being studied were not designed for detecting damage in the more complicated vibration signals from an epicyclic gearbox. The pinion gear was chosen over its mating gear because it provides a very interesting example where gears outside the transmission, in this case in the engine, must be taken into consideration. The turbine engine powering the helicopter contains an output gearbox with extensive gearing to provide much of the necessary speed reduction prior to entering the transmission. A 50-tooth gear on the output of the turbine gearbox is on the other end of the shaft that drives the pinion in the transmission. Since the 50-tooth gear is rotating at exactly the same speed, it must be taken into consideration when testing the 19-tooth pinion gear.

Computation of Time Synchronous Averages: All of the metrics use data that have been time synchronously averaged. Synchronously averaging periodic signals to increase the signal-to-noise ratio is a common practice. When averaging N signals together, the amplitude of independent noise will decrease as the reciprocal of the square root of the sample size, $1/\sqrt{N}$. The amplitude of other components depends upon the phase relationship of the components in each signal in the average. If a component has a discrete frequency that is not a multiple of the rotation frequency, yet is a multiple of a rational fraction of the rotation frequency, the component will average to zero when the average includes an integer number of periods. Thus the averaging process can eliminate some known discrete frequency components.

A time index was found for each rotation of the main rotor by linear interpolation to a constant amplitude on the rise of the once-per-rotation interrupter signal. This index became the boundary between each rotation of the main rotor. A cubic spline interpolation was used to change from a time based sample to rotation based sample of 512 samples per rotation of the pinion. This resampling frequency is above twice the cutoff frequency of the low-pass analog filter so as not to induce aliasing into the data.

Averages were made using various numbers of pinion rotations per average. For a baseline, 71 rotations were combined into an average. Because the pinion contains 19 teeth and the mating gear contains 71 teeth, this is the minimum number of rotations for the pinion to cycle through and return to the original gear mating position. By using multiples of 71 pinion rotations, the averaging process removes the effect of nonumiformities in the mating gear. Averages were made with 71 and multiples of 71 rotations. To examine the effect of the number of rotations on the signal rms and amplitude of the pinion gear mesh frequency, averages containing fewer than 71 rotations were also constructed.

Table II Averages for each Flight Record

Rotations per Average	71	142	284	568	1136	3408	48	24	12
Basic Cycles	1	2	4	8	16	48	<1	<1	<1
Averages	48	24	12	6	3	1	71	142	284
Total Rotations	3408	3408	3408	3408	3408	3408	3408	3408	3408

For each of the averages, the presence of statistically significant trends in the rotation-by-rotation signal properties were evaluated by use of a nonparametric "runs test" [14]. Four measures characterizing the underlying vibration signal were evaluated separately in this manner: (1) overall signal rms; (2) residual signal rms with all gear mesh harmonic frequencies filtered out; (3) amplitude of the pinion gear mesh frequency; and (4) amplitude of the turbine gear mesh frequency. Procedurally, the number of runs of these parameters, above and below their respective medians in the sample, were inspected to determine if they conformed to a binomial process with a parameters $p = q = .5$, i.e., the null hypothesis. If the null-hypothesis were accepted, at a conservative significance level of $\alpha = 0.01$, the data were assumed to be stationary. If the null-hypothesis were rejected, a complex alternate hypothesis was accepted that unknown trends exist in the signals entering into the average. In these instances the data are referred to as nonstationary.

Computation of Metrics: Six standard metrics were computed from the time synchronous averages (Table III). All filtering was done in the frequency domain on the time synchronously averaged signals.

Table III Metrics and their Formula

Metric	Filtering	Formula	Numerator	Denominator	Nominal Value	Threshold Value
FM0	none	$\dfrac{\text{P to P}}{\sum A_k}$	peak-to-peak amplitude	sum amplitude of gear mesh harmonics	2.8	>7
FM4	difference, remove gmhs, 1st order side bands, 1/rev, 2/rev	$\dfrac{\frac{1}{N}\sum_{n=1}^{N}\left(d_n-\bar{d}\right)^4}{\left[\frac{1}{N}\sum_{n=1}^{N}\left(d_n-\bar{d}\right)^2\right]^2}$	4th moment about mean of difference signal	square of variance of difference signal	3	>7
N6A	difference, remove gmhs, 1st order side bands, 1/rev, 2/rev	$\dfrac{\frac{1}{N}\sum_{n=1}^{N}\left(d_n-\bar{d}\right)^6}{\left[\frac{1}{N}\sum_{n=1}^{N}\left(d_n-\bar{d}\right)^2\right]^3}$	6th moment about mean of difference signal	cube of variance of difference signal	15	>45
N8A	difference, remove gmhs, 1st order side bands, 1/rev, 2/rev	$\dfrac{\frac{1}{N}\sum_{n=1}^{N}\left(d_n-\bar{d}\right)^8}{\left[\frac{1}{N}\sum_{n=1}^{N}\left(d_n-\bar{d}\right)^2\right]^4}$	8th moment about mean of difference signal	4th power of variance of difference signal	105	>300
NA4	residual, remove gmhs, 1/rev, 2/rev	$\dfrac{\frac{1}{N}\sum_{n=1}^{N}\left(r_n-\bar{r}\right)^4}{\left[\frac{1}{M}\sum_{m=1}^{M}\frac{1}{N}\sum_{n=1}^{N}\left(r_{n,m}-\bar{r}_m\right)^2\right]^2}$	4th moment about mean of residual signal	square of average variance of all residual signals up to current time	3	>7
NB4	band pass	$\dfrac{\frac{1}{N}\sum_{n=1}^{N}\left(s_n-\bar{s}\right)^4}{\left[\frac{1}{M}\sum_{m=1}^{M}\frac{1}{N}\sum_{n=1}^{N}\left(s_{n,m}-\bar{s}_m\right)^2\right]^2}$	4th moment about mean of envelope of band pass signals	square of average variance of envelope of band pass signals up to current time	3	>7

Spectra from the time synchronous averages contain two sets of harmonically related frequency components with amplitudes substantially above the broadband signal level. One set at 19 per rotation and its multiples is associated with the pinion meshing with its mated gear, the other set at 50 per rotation and its multiples is associated with the meshing of the output gear and its mate in the turbine output gearbox. Both sets of gear mesh harmonics along with the rotation and twice the rotation frequency were filtered out of the time synchronous average to produce the residual signal used to evaluate NA4. Additional filtering of the once-per-rotation order side bands for both the 19-tooth gear and 50-tooth gear harmonics from the residual signal yielded the difference signal used to evaluate FM4, M6A and M8A. NB4 was evaluated separately for each gear. To prepare the band passed envelope signal for NB4, the FFT of the signal was high pass filtered at 1/2 the gear mesh frequency and low pass filtered at 3/2 the gear mesh frequency. The IFFT was applied only to positive frequency components to form the analytic signal. The envelope was generated by taking the absolute value of the complex valued analytic signal. For NA4 and NB4 the order of the data records was kept the same as flight.

A threshold value of the metrics was chosen in order to examine the potential for false alarms in a simple test of each instance of a metric. Engineering threshold values for the metrics were established by review of the literature of test rig experiments [1, 2, 7, 8, 10, 11]. Mostly, no specific threshold levels were given. Usually, values of the metrics were associated with measurements from gears in known and assumed conditions. Threshold levels were selected so that metrics measured from gears in good condition fell below the threshold and metrics from gears in damaged conditions fell near or above the threshold. In a few cases, especially for FM4, some measurements of metrics from gears with faults fell below the chosen threshold [2, 8]. This procedure kept all known measurements made in test rigs of gears in good condition below the threshold, and thus produced no false alarms in the test rig measurements. Since they were selected without regard for the metric levels measured in flight, any measures above the threshold found in flight could be considered false alarms for straightforward evaluation purposes.

Results of Time Synchronous Averaging: With too few rotations in an average, the signal for the gear under study will contain higher levels of noise and other aircraft components, and thus a lower signal-to-noise ratio than might otherwise be achieved. With too many rotations in an average, the signal from the gear under study will change too much over the time in the averages and thus signal information will be distorted in the average. Figure 1 shows the amplitude of the pinion gear mesh frequency and the overall amplitude (rms) as a function of the number of rotations averaged in a selected data record. Each individual measure for an average is indicated with a gray circle and the means are indicated with a black star. The average amplitude of the pinion frequency decreases very little from no averaging to an average made with 3408 rotations, indicating that the amplitude and phase of the gear mesh frequency changes very little over the data record. The rms level decreases substantially with 12 rotations. The rms level decreases a little more when more rotations are added to the average. Taken together, this indicates that substantial signal enhancement has been achieved by combining 71 rotations into the average.

Several opportunities for stationarity to be evaluated occurred for each synchronous average. With six channels and four parameters, 24 stationarity evaluations were computed for each synchronous average. These constitute a 24 element binary vector, which was turned into a total "stationarity score" by calculating the percentage of 1s in each vector. Perfect stationarity, therefore, would be all 1s, and perfect nonstationarity would be all 0s. Figure 2 shows clearly that the average stationarity for each of these 24 evaluations improved on a percentage basis as the number of rotations in an average diminished. The box plots show the median, quartiles, and range of the average stationarity. To avoid confusion, a few outliers were suppressed in the plot. Overall average stationarity was found to be 14.6%, or essentially unusable, for signal averages constructed of 3408 pinion rotations compared to 98.5% for signal averages constructed from 71 rotations. The low boundary of about 90% for 71 rotations is an acceptable degree of stationarity. It should be emphasized that at each level of averaging, exactly the same raw data were used, but simply combined in different ways. It may also be noted that the measured range of stationarity was extremely broad for averages made from 1136, 568 and even 284 rotations. The optimum was obtained at 71 rotations. So with regard to stationarity the less averaging the better, a fact that is in accord with the potential need to evaluate the signal as often as possible in flight. Figure 3 shows that for all practical purposes the degree of measured stationarity was approximately the same for each of the six accelerometers at each level of averaging.

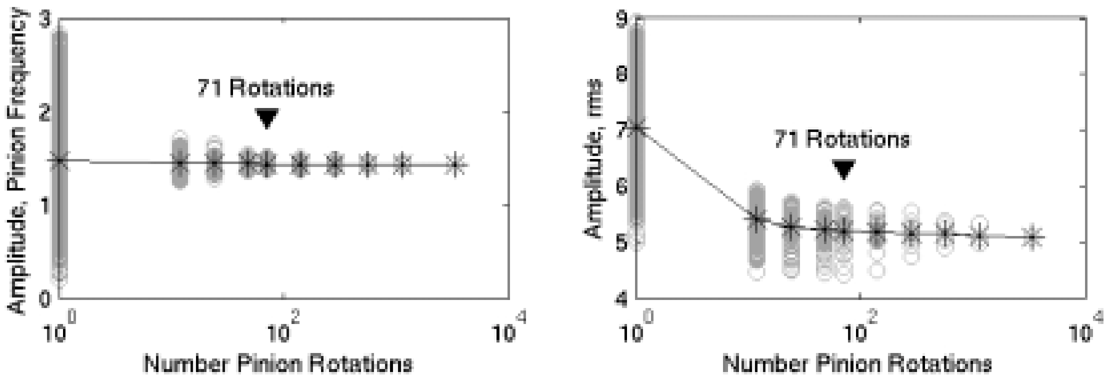

Figure 1. Amplitude of gear mesh frequency and signal rms for each average in a single flight record for a low forward speed maneuver (A).

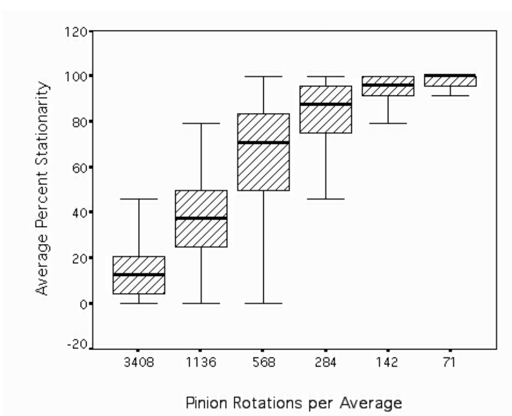

Figure 2. Overall stationarity by degree of averaging.

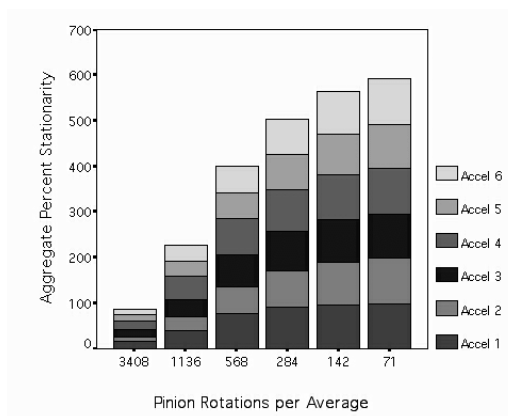

Figure 3. Composite stationarity by accelerometers.

For the remainder of this report, the averages constructed from 71 rotations of the pinion are used to examine the metrics. Although the stationarity results highlight the value of minimizing the number of rotations in an average, using less than 71 rotations might allow faults in the mating gear to contaminate the average for the pinion gear. If any nonuniformity exists on the mating gear, that nonuniformity will not be averaged out unless the number of averages is a multiple of the tooth mating repetition cycle of 71 pinion rotations for this gear. Any nonuniformity on the mating gear might even cause the overall stationarity to decrease. For this study, 71-pinion rotations are found to be the optimum number for averaging, with both good noise reduction and stationarity.

Observed Signal Characteristics: The time synchronous averaged vibrations consist mainly of frequency components at the pinion gear mesh frequency of 19 per rotation, at the turbine gear mesh frequency of 50 per rotation and integer multiples of both the gear mesh frequencies. Figure 4 shows two amplitude spectra made from averaging 71 consecutive pinion rotations and taken from accelerometer number 3. The spectra were computed up to 256 shaft orders; amplitudes for frequencies above 150 are at much lower levels compared to the lower frequencies shown.

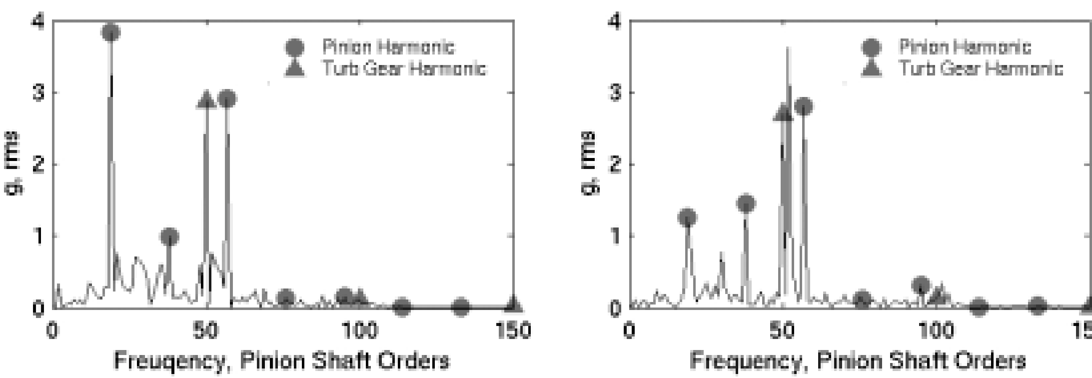

Figure 4. Amplitude spectra from flight conditions F and J for accelerometer number 3.

High amplitude levels occur at frequencies other than those predicted for the pinion and turbine gears. Specific frequencies and amplitudes vary throughout the measurements. A global picture of these other discrete frequencies was obtained by identifying the frequency component with the largest amplitude in the difference signal. Figure 5 shows the distribution of this frequency component. Except for frequencies 48 and 52, which are two-per-rotation side bands of the turbine gear mesh frequency, the 32 separate frequencies identified with maximum amplitude in the difference signal are not apparently related to the gears. The nondimensional amplitude for these frequency components range from 0.031 to 0.366, well above the average amplitude level of about .004.

A notable aspect of this finding is the inconsistency with the common assumption that the difference signal is composed primarily of Gaussian noise, which is implied by the nominal values associated with the metrics. These unexplained discrete frequencies lower the values of FM4, NA4, M6A and M8A because the difference and residual signals contain strong periodic components. Equally important, these metrics have unknown sampling distributions, which possibly places them outside the domain of classic parametric detection theory.

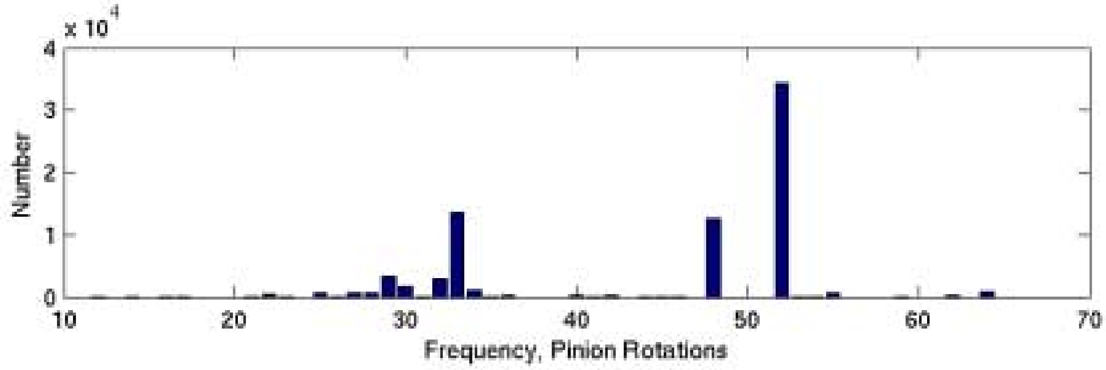

Figure 5. Distribution of Discrete Frequency Components in the Difference Signal.

Observed Metrics: Table IV summarizes the metrics overall measurements, except maneuver G on the ground. The distributions of the metrics generally contain a large central peak with slight asymmetry of shape, steeper on the low side. The tail on the high side is sometimes quite long as is reflected in the table by the large distance between the mean and maximum values and by the large kurtosis particularly in NA4, NB4 for pinion and M8A. Table V lists the measurements over threshold by maneuver. Most instances (79%) of a metric exceeding its threshold occur for the two forward decent maneuvers, F and N. Torque levels are lower in decent than in the other flight conditions tested. At low torque levels backlash may be occurring in the gears. Also, in decent, the helicopter is subjected to greater dynamic loads because the main rotor may be flying through its own wake. These dynamic forces would be transmitted to the transmission through the main rotor shaft coupled to the planet gears in the epicyclic gearbox.

Table IV Metric Evaluations

	Minimum	Maximum	Mean	Std. Dev.	Kurtosis	Nominal	Threshold	Exceedances
FM0	1.65	6.67	2.42	0.47	12.96	2.8	>7	0.000
FM4	1.81	4.92	2.65	0.34	5.09	3.0	>7	0.000
NA4	0.01	72.80	3.22	4.25	54.51	3.0	>7	0.090
NB4, pinion	0.11	54.52	3.19	6.01	36.71	3.0	>7	0.021
NB4, turbine	0.00	38.49	2.95	2.55	18.07	3.0	>7	0.011
M6A	4.09	63.94	10.83	3.73	12.84	15	>45	0.000
M8A	10.62	1213.8	58.88	40.20	49.49	105	>300	0.004

Table V Measurements Over Threshold by Maneuver in %.

A	B	C	D	E	F	H	I	J	K	L	M	N
0.008	0.018	0.005	0.013	0.001	0.145	0.002	0.001	0.002	0.000	0.000	0.019	0.112

Observed Torque and Speed Effects: Researchers have noted a relationship between torque and vibration level [12, 13]. Dempsey [6] shows NA4 increasing and decreasing as torque increases and decreases in a test rig. Campbell [11] fit FM4, NA4, M6A and M8A to functions of torque and speed, all with positive slopes relating torque to each metric. The rotation speed has also been identified with a relationship to vibration levels [4, 11, 12, 13]. The metrics were examined by making scatter plots for each metric independently with torque and main rotor rpm. To give a global view in terms of simple linear relationships, Table VI shows the correlation coefficients that were obtained. Note that many of the trends are weak as correlation coefficients are small and sometimes of opposite sign for different accelerometers. The widely varying correlations indicate the metrics have complex relationship to torque and rpm. The correlation coefficient is negative where the trend with torque is consistent among accelerometers, and more frequently negative where the trend is inconsistent. The relationship of metrics with torque in this flight test differs from that observed in test rigs. In these flights, the torque is always below 100% load, the forces are more dynamic and the gears are presumed to be in good condition. In the test rigs, often the torque was above 100% load, the torque and forces are steady and often the gears are damaged. Any or all of these differences may contribute to the metrics behaving differently in flight and test rigs.

Table VI Correlation coefficients of metrics with torque and rpm .

		Accel 1	Accel 2	Accel. 3	Accel. 4	Accel. 5	Accel. 6
FM0	torque	0.18	-0.41	-0.40	-0.28	-0.06	-0.64
FM0	rpm	-0.33	0.53	0.36	0.39	0.09	0.68
FM4	torque	0.21	-0.28	-0.44	-0.12	-0.14	0.25
FM4	rpm	-.12	0.24	0.35	0.12	0.17	-0.24
NA4	torque	0.01	-0.35	-0.55	-0.45	-0.01	-0.49
NA4	rpm	0.05	0.38	0.56	0.40	0.08	0.48
NB4, pinion	torque	-0.63	-0.53	-0.76	-0.48	-0.64	-0.70
NB4, pinion	rpm	0.65	0.45	0.74	0.47	0.62	0.62
NB4, turbine	torque	-0.14	0.03	-0.27	-0.42	-0.05	-0.25
NB4, turbine	rpm	0.26	0.00	0.26	0.37	0.09	0.22
M6A	torque	0.17	-0.25	-0.41	-0.11	-0.13	0.20
M6A	rpm	-0.08	0.19	0.32	0.09	0.15	-0.17
M8A	torque	0.13	-0.22	-0.37	-0.09	-0.12	0.14
M8A	rpm	-0.04	0.16	0.28	0.07	0.12	-0.09

Dynamic Flight Considerations: Torque and rotation speed display different variability in flight than in test rigs. Torque variations are observed on three distinct time scales in the flight test. The largest time scale is associated with the maneuver. For maneuvers covered in this test, the torque on low power decent (maneuver F) fell below 20% while the torque for high power climb (maneuver M) was about 80%. The medium time scale torque variations involve oscillations with periods of about 5 to 7 seconds observed during one 34-sec. data record. These low frequency oscillations are believed due to the dynamic response of the aircraft to control and aerodynamic inputs. In many data records, these low frequency oscillations decay with time as would be expected with a dynamic aircraft response. The shortest time scale looks like noise. Figure 6 shows the torque and main rotor rpm for the test record with the median torque range of 5.8% from a high power decent case (maneuver N). The maximum torque range observed in a data record is 23% of the full power.

Note that the torque and rpm are not related to each other in any simple way for the 34-second maneuver. If the power were constant, torque and rpm would be inversely related, but that is clearly not the case. In general, the torque changes appear to lead the rpm. The median of the extrema for the cross-correlation of the rpm and torque (with means subtracted) is —0.677 with a median lag of about —0.758 seconds.

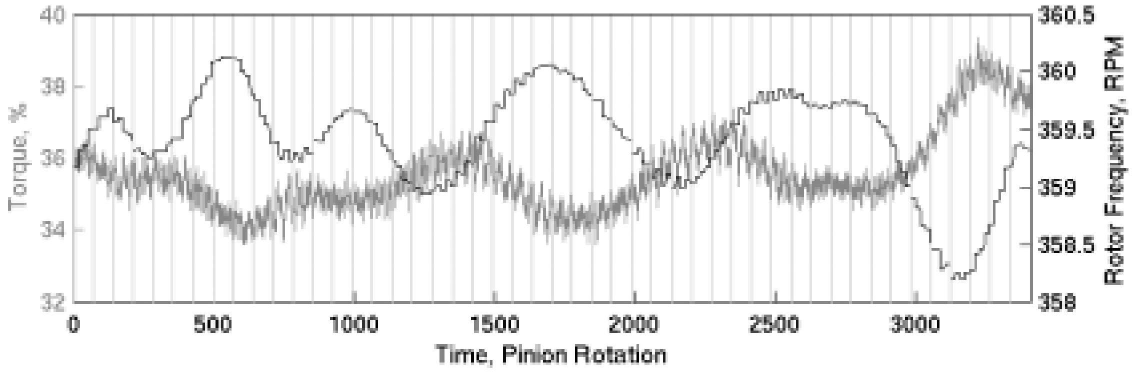

Figure 6. Torque and rotor rpm for data record with median torque range.

The changing torque and rpm levels in flight may be affecting the stationarity of the vibration measurements. Light vertical lines on Fig. 6 indicate the boundary between averages of 71 rotations. The torque and rpm vary much less over 71 pinion rotations than over the longer 3408 pinion rotations.

Conclusions: Vibration measurements of an OH-58C Kiowa helicopter transmission were studied. Several gear metrics, FM0, FM4, NA4, NB4, M6A and M8A were computed for the pinion gear.

For this pinion gear, 71 rotations were found to be the optimum number to combine into time synchronous averages of the vibration signals. Integer multiples of 71 are preferred for the pinion in this transmission because signal components due to nonuniformities in the mating gear will be removed. When considering only multiples of 71 rotations, blocks 71 rotations long showed the most stationarity. Substantial signal-to-noise enhancement occurred with 71 rotations in an average.

The vibration signals from the OH-58 helicopter transmission measured in actual flight do not conform to the underlying signal model of gear mesh harmonics plus first order side bands plus Gaussian noise. The measured vibration signals contain other high-level discrete frequency components that are not apparently related to the gears. These discrete frequencies will lower the values of the FM4, M6A and M8A because the normalized moments of a sine wave are smaller than the normalized moments of Gaussian noise. The means of FM4, M6A and M8A measured from flight are significantly less than the nominal values for the metrics. The nominal values correspond to the difference signals being Gaussian noise. This behavior could delay the detection of faults with these metrics early in the onset of damage.

Metrics in flight showed different characteristics than metrics measured in test rigs and reported in the literature. Thresholds derived from test rig measurements resulted in false alarms when applied to the metrics measured in flight. Some metrics measured from test rigs reported in the literature increased with higher torque on the test gear while the metrics measured in flight do not show this trend. The major differences between these flights and test rigs are torque and rpm are constantly changing in flight while steady in the test rig, the load in the flights was between 20% and 80% while the load in test rigs is often above 100% and the gears in flight are presumed in good condition while the gears in the test rigs usually contain planted or seeded faults.

Most of the cases of a metric exceeding its threshold occurred in the two descending maneuvers (79%). Any gear fault detection system in helicopters must account for the distinct vibration signals that occur in decent.

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