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Acceptance Screening of Turbopump Gears Using the Cepstrum Method

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Vibration measurements are used to assess the health of components in rotating equipment across a wide range of industries. The typical practice in most machinery analysis is to establish a baseline for a specific machine and subsequently implement a regular monitoring schedule. In a process known as trend analysis, changes in relevant parameters are then tracked over the life of the machine. In some cases the comparison of measurements between different machines is not recommended because of variability in transmission path effects caused by either manufacturing tolerances or differences in the instrumentation setup. Although these concerns are valid, the constraints imposed by the particular application to acceptance screening of rocket engine turbomachinery make a comparison between engines useful. It is suggested that engine-to-engine comparisons of vibration-related parameters can be used to provide information on abnormal gear behavior. Support for this proposal is presented in the context of parameters developed from a cepstrum analysis of gearbox vibration data acquired during actual ground-test acceptance firings of a rocket engine. The results obtained are also used to verify the ability of the cepstrum method to diagnose gear tooth damage in turbopumps. In this application the cepstrum is defined as the inverse discrete Fourier transform of the log of the two-sided autospectral density.

Nomenclature

C_{yy}	=	output cepstrum
f_k	=	discrete frequencies, Hz
f_{LOX}	=	frequency of LOX shaft rotation, Hz
N	=	number of data values per segment
n_d	=	number of segments per data record
S_{yy}	=	auto spectral density of output, g^2/Hz
T	=	length of single data record segment, s
x_i	=	multiple inputs, g
Y_m	=	fourier components of mth record
y	=	output, g
$\mathcal{F}^{-1}$	=	inverse discrete Fourier transform operator
Δt	=	sampling interval, s
τ	=	periodic time, s
τ_{LOX}	=	LOX periodic time, s

Introduction

IN an effort to increase performance, expendable launch vehicle (ELV) rocket-engine turbopumps are sometimes operated at speeds and loads for which they were not initially designed. The consequence of this is that structural margins are decreased and the potential for hardware damage or catastrophic failure increases. In the case of a particular ELV engine, two cases of liquid-oxygen (LOX) gear damage, including a catastrophic failure, have been observed during acceptance and development ground testing of the hardware. To mitigate the risk associated with the decreased structural margins, a drive-train diagnostic procedure has been implemented using gearbox vibration measurements. To date, the main goal of this process has been to prevent reoccurrence of the LOX gear failure during a mission by evaluating the preceding ground-test vibration signatures. To do this, the primary requirement is to provide an accurate technical explanation, supported by a credible mathematical foundation, for the unique vibration signature associated with the progression of the LOX gear defect toward failure. A secondary requirement is to describe this unique signature using a quantitative parameter that can be tracked over the operating life of a turbopump and also stored in a database and compared to other engines. These requirements are met using the cepstrum analysis method, which is used to provide a single quantitative parameter that appears to be directly related to the health of the LOX gear.[1] This parameter is stored in a database and used to assess the health of a gear in relation to other engines that have been previously characterized by known operating conditions and flight history. Unlike qualitative assessments that depend completely on the experience of the analyst, easily interpreted quantitative parameters serve to make acceptance or rejection of hardware a more logical process.

In conjunction with vibration measurements acquired during test or operation of a rotating machine, digital signal processing techniques are used extensively in condition assessment programs across a wide range of industries.[2–10] The cepstrum method,[11,12] in particular, has been used to detect damage in both rolling element bearings[13] and gears.[14–16] Partly because of the susceptibility of engine and transmission components to fatigue failures,[17] there has been a considerable amount of research directed at effective detection of gear tooth damage.[18–21]

Unlike typical rotating machinery that can be compared to its baseline over an expected operating life measured in years, an ELV's rocket engine turbopump life, including acceptance testing and mission requirements, is measured in minutes. For the engine in this study, a turbopump must be test fired at least twice prior to delivery to the customer in order to show that acceptable performance limits are met. These test firings generally last for several minutes each, and because of limited available engine life it is desirable to perform as few tests as possible to assure nominal performance. From a diagnostics perspective a consequence of this is that there is often a very limited amount of operating time on the engine during which to assess changes in the vibration signature. Therefore, whereas traditional trend analysis is always performed on a single engine it appears to be useful to be able to compare a specific engine's parameters to other engines whose parameters are characteristic of known operating conditions. The drawbacks inherent when comparing different pieces of hardware[22] are mitigated by maintaining a database of earlier comparisons between known hardware health and associated vibration characteristics. For example, the variability in vibration characteristics for engines that perform in a nominal

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fashion can be established with some simple statistics. Additionally, if a correlation has already been established between documented hardware damage and a unique vibration signature this information can be useful in providing an early differentiation between a nominally operating engine and one that contains a defect.

The purpose of this paper and the research documented here is twofold. Primarily, the results are intended to provide support for the suggestion that the cepstrum method is an effective gearbox monitoring tool for the particular turbopump failure described in detail in Ref. 1. Although this reference provides a technical rationale for the use of the cepstrum method, the usefulness of the achieved results has previously been difficult to evaluate because the limited number of engines analyzed provided poor statistics. Second, the results are also used to support the argument that engine-to-engine comparisons can be useful, provided that a database comparing hardware health to specific vibration characteristics is maintained. This suggestion is evaluated by comparing the parametric results from 14 different turbopumps (of similar manufacture), two of which exhibited gear tooth defects and 12 of which performed nominally.

Theoretical Development

As suggested in the preceding section, measurements obtained from an accelerometer mounted on the exterior of a turbopump gearbox are used to aid in the development of an acceptance screening criteria for the LOX gear in a particular rocket engine. Discrete time periods for these accelerations are expressed in the time domain by a data record $y(t)$ that is divided into n_d contiguous segments of length T. Each record segment $y_m(t)$ is represented in digital terms with a sampling interval of Δt by N data values $\{y_{mn}\}$, where $n = 0, \ldots, N-1$ and $m = 1, \ldots, n_d$. These data records are then assessed in the frequency domain using the two-sided auto spectral density (ASD) defined by

$$S_{yy}(f_k) = \frac{1}{n_d T} \sum_{m=1}^{n_d} |Y_m(f_k)|^2, \qquad k = -\frac{N}{2} + 1, \ldots, \frac{N}{2} \tag{1}$$

In all cases where the ASD is presented graphically in this paper, the one-sided ASD will be used. For a detailed discussion of the mathematics involved in these computations, the reader is referred to Bendat and Piersol.[23]

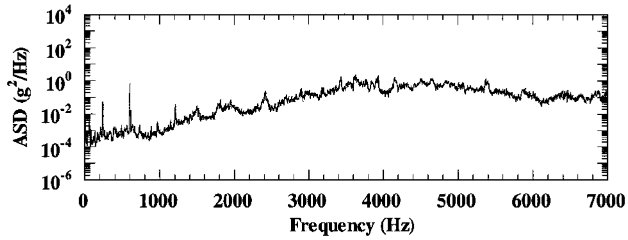
A qualitative assessment of engine health can sometimes be made by visual inspection of the ASD. In the case of discrete gear tooth defects, the damage can often be seen in the frequency domain as a family of spectral peaks that are spaced at integer multiples of the speed of the shaft upon which the faulty gear tooth is located. In the case of the gear failure discussed here, the source mechanism for this is a system resonant amplification of short-duration impulses spaced at time intervals corresponding to the disturbance induced by a LOX gear defect. This source mechanism is discussed at length in Ref. 1. For example, the difference between the ASD for a nominally operating turbopump and one that is several seconds away from catastrophic failure of its LOX gear is shown in Fig. 1. Figure 1a is the ASD corresponding to a 4-s time frame and data acquired at a rate of 25,575 samples per second during the final acceptance test firing of a production engine that operated nominally during its acceptance tests and later performed successfully during flight. The ASD is calculated via the finite Fourier transform method using 8192 data points and a Hanning window to suppress sidelobe leakage. In comparison, Fig. 1b is a similarly computed ASD taken just prior to catastrophic failure of the LOX gear on a development engine. Notice the existence of spikes in the ASD that are spaced at integer multiples of the LOX shaft rotation rate, which was 241 Hz during the data record analyzed.

Although the difference in spectral characteristics between the two ASDs of Figs. 1a and 1b is helpful in diagnosing the failure mechanism imminent in Fig. 1b, the goal of any diagnostic routine is to identify a defect as early and reliably as possible. To do this, it is desirable to quantify the degree of abnormality of the vibration signature. It is further useful if this abnormality can be quantified using a single parameter that can be stored in a database and used to make comparisons between engines that have operated nominally and those engines that have exhibited known defects. The cepstrum method is presented as a technique that provides a single quantitative parameter that appears to be related to the presence and growth of a gear tooth defect.

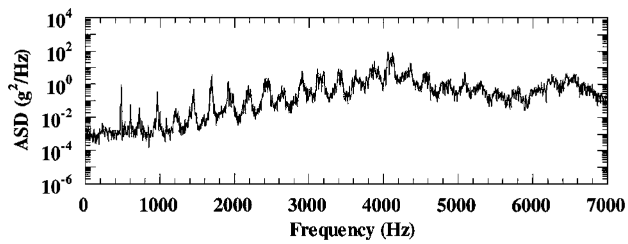
As a gear fault evolves, the harmonic pattern in the ASD can often be identified visually as shown in Fig. 1. However, by performing a cepstrum analysis the strength of an entire family of harmonics is primarily related to a single component in the cepstral domain. This can aid the analyst in quantifying the severity of the defect and monitoring the defect evolution using the magnitude of a single cepstrum component. Two additional advantages of using the cepstrum are that the frequency spacing of a periodic structure can be precisely determined and the appearance of harmonics can often be detected earlier than by using visual inspection of the ASD.

The form of the cepstrum used by different researchers tends to vary depending upon the specific application. After investigation of several cepstrum implementations, the form of the two-sided cepstrum, consistent with the notation in Eq. (1), that is used in this paper is defined by

$$C_{yy}(\tau_n) = \mathcal{F}^{-1}\{\log[S_{yy}(f_k)]\} = \Delta f \sum_{k=-N/2+1}^{N/2} \{\log[S_{yy}(f_k)]\} \times \exp(j2\pi kn/N), \qquad n = -\frac{N}{2} + 1, \ldots, \frac{N}{2} \tag{2}$$

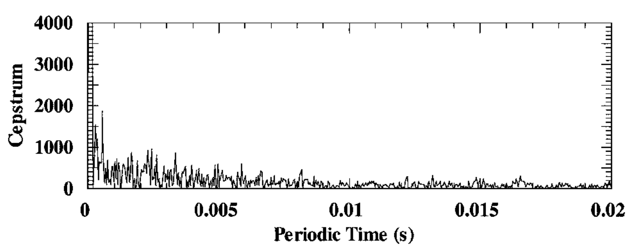


a) Nominal turbopump operation

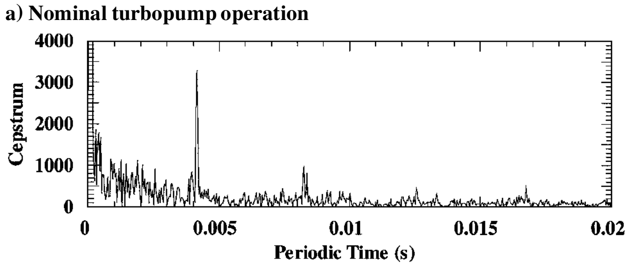


b) Turbopump just prior to LOX gear failure

Fig. 1 Comparison of ASD for a nominally operating engine with a turbopump just prior to failure of its LOX gear.



a) Nominal turbopump operation



b) Turbopump just prior to LOX gear failure

Fig. 2 Comparison of cepstrum for a nominally operating engine with a turbopump just prior to failure of its LOX gear.

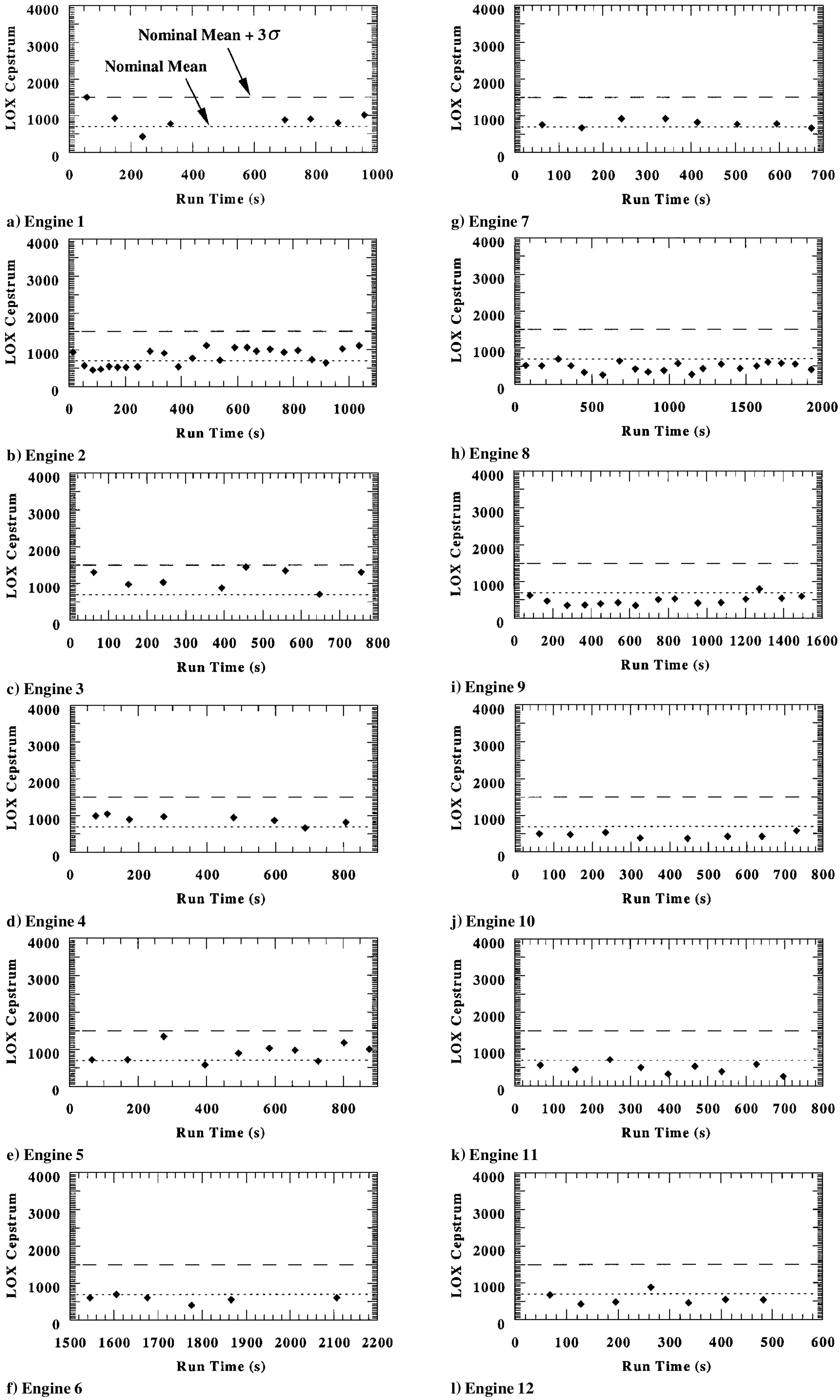


Fig. 3 LOX cepstrum parameters during nominal turbopump operation. The · · · · and - - - - lines in the plots are the mean value and the mean plus 3-σ value, respectively, for all nominal engine LOX cepstrum parameters.

at the discrete periodic times $\tau_n = n/N\Delta f$, where Δf is the line spacing of the ASD and $\mathcal{F}^{-1}$ denotes the inverse discrete Fourier transform (IDFT) operator. The cepstrum differs from the autocorrelation function only by virtue of the logarithmic conversion of the ASD before the IDFT is performed. Because the cepstrum is the IDFT of a function of frequency, its independent variable τ_n is actually time. However, the parameter τ_n can better be thought of as a delay time, as for the autocorrelation function. Therefore, although most researchers refer to τ_n as "quefrency," it seems more appropriate to use the term "periodic time," as suggested by Randall.[2] If the log of the ASD is periodic in nature with a frequency spacing of f_{LOX}, the contribution of all of the harmonics will be concentrated in the single cepstrum component $C_{yy}(\tau_{\mathrm{LOX}})$ at a value of

$$\tau_{\mathrm{LOX}} = 1/f_{\mathrm{LOX}} \tag{3}$$

The cepstrum defined in Eq. (2) is a real-valued, two-sided even function that is computed using the two-sided ASD defined in Eq. (1). Whenever the output cepstrum is presented graphically in this paper, the magnitude of only one side is shown.

The cepstrum plots corresponding to the ASDs shown in Figs. 1a and 1b are presented in Figs. 2a and 2b, respectively. Notice the existence of an easily identified spike in Fig. 2b that corresponds to a periodic time of $\tau_{\mathrm{LOX}} = 1/f_{\mathrm{LOX}} \cong 0.00415$ s. These plots indicate that this component is related to the growth in the frequency domain of the spectral components at fundamental and integer multiples of the defect frequency. Furthermore, by virtue of the correlation between the growth of these harmonics in the spectral domain and a defect in the LOX gear tooth[1] this single parameter appears to be directly related to the evolution of a LOX gear fault. Henceforth, the value of the cepstrum at a periodic time equal to the reciprocal of the LOX shaft speed is referred to as the LOX cepstrum parameter.

Turbopump Acceptance Screening and Engine-to-Engine Comparisons

In this section the ability of the LOX cepstrum parameter to diagnose discrete gear tooth defects is evaluated. This is done by comparing the LOX cepstrum parameters for 12 nominally operating turbopumps to the corresponding values for two engines that exhibited catastrophic failure and excessive gear wear and tooth chipping, respectively. The LOX cepstrum parameters for the 12 nominally operating pumps are shown in Figs. 3a–3l. The dotted and dashed lines in the plots are the mean value and the mean plus 3-σ value, respectively, for all nominal engine LOX cepstrum parameters. Nominal engines are defined as those that met both ground-test and mission requirements. The x axis in the graphs is run time on the particular engine build under consideration, and each engine is given a generic number in the plot titles. The total run time for the ground tests varies from engine to engine. The reason for this is that some engines required more than the minimum two ground tests because of performance, hardware, or instrumentation anomalies during the first two test firings. Also the time interval between discrete data points is not a constant because the data records available for assessment were not always of the analyst's choosing. Additionally, the high sample rates and hardware memory requirements prevented a continuous (in time) calculation of the parameters.

From a trend analysis standpoint the LOX cepstrum values for the nominally operating pumps do not increase significantly as operating time increases on a particular engine. Because of the variation of operating parameters (speed and pressure for example) during a ground test, the LOX cepstrum values exhibit an expected disparity over the life of a particular engine. There is also a considerable variation in the value of the LOX cepstrum parameter when different engines are compared to one another. This variation is not unexpected and is partly a result of engine-to-engine hardware variability. Possible contributors to this variation are residual imbalances in the LOX shaft or slight gear mesh imperfections.

The initial purpose of the implemented drive-train diagnostic procedure was to prevent reoccurrence of the catastrophic LOX gear failure that occurred during the development phase of a particular engine program. The LOX cepstrum parameters for the final build

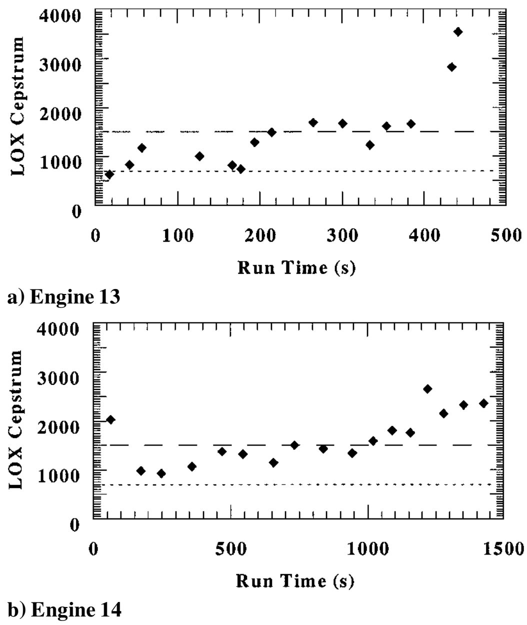


Fig. 4 LOX cepstrum parameters for cases of LOX gear hardware damage. The · · · · and - - - - lines in the plots are the mean value and the mean plus 3-σ value, respectively, for all nominal engine LOX cepstrum parameters.

of the failed engine (Engine 13) are shown in Fig. 4a. Notice the increase in the LOX cepstrum parameter as run time increases. The magnitude of these parameters after approximately 220 s of run time are higher than the mean plus 3-σ value. This indicates an out-of-family condition when compared to the database of nominally operating engines. The mean and standard deviation are used here to provide commonly accepted and well-defined values that are related to the distribution of LOX cepstrum parameters. The data have not been verified to be Gaussian, nor is it believed necessary to do so. The mean plus 3-σ value is used as a threshold simply because it has some statistically meaningful properties. The maximum value of the LOX cepstrum parameter for all nominally performing engines could just have easily been chosen as the threshold. In fact, as evidenced in Fig. 3a the maximum value of the LOX cepstrum parameter for nominally operating engines is, in fact, very similar to the mean plus 3-σ value.

One reason that the LOX cepstrum parameters do not increase monotonically in time for the damaged engines is that the operating conditions during the discrete data records analyzed are not necessarily the same. For example, the propellant mixture ratio of oxidizer to fuel is varied during the ground-test operations, thus leading to changes in pump speeds. If the data records are evaluated at relatively consistent operating conditions, the increase in the LOX cepstrum values tends to be more monotonic. Because of the complex nature of engine operation, however, evaluation of the parameters at a set of truly consistent operating conditions is difficult to achieve. Nevertheless, the increasing trend, even at varying operating conditions, suggests that the cepstrum is a robust diagnostic tool for detection of the LOX gear fault in the turbopump.

In addition to Engine 13 that failed, there is one other engine in the database that exhibited significant LOX gear tooth damage. In the case of Engine 14, six ground tests were conducted before the gears were inspected. At that time excessive gear wear and chipping were observed on the LOX pump assembly. Subsequent to this observation, the gear train was completely rebuilt and the turbopump used successfully on an actual mission. Figure 4b contains the LOX cepstrum parameters for the Engine 14 test firings previous to the rebuild. The LOX cepstrum parameters for this engine are also out-of-family high and increase with operating time in a fashion similar to that observed in the catastrophic failure of Engine 13. The magnitude of this parameter for Engine 14 at the end of its run time is approaching a value nearly as large as the value just prior to failure in Engine 13. It is believed that if the Engine 14 LOX gear was subjected to any significant additional run time the risk of potential failure would have been high. Finally, it is suggested that an additional parameter related to the change in LOX cepstrum values over the operating life of a particular engine might actually be more useful than the magnitude of the LOX cepstrum value relative to the mean plus 3-σ value for the nominally operating dataset. Although such a parameter is not defined explicitly here, the distinct evolution and growth of the LOX cepstrum parameter for the damaged engines in Fig. 4 are quite pronounced in comparison to the relatively stable values observed for the nominally operating engines in Fig. 3.

Conclusions

The results presented here provide confirmation that the cepstrum method is an effective diagnostic tool for gear damage assessment. Supporting data were acquired during ground-test operation of 14 actual rocket engines. Many diagnostic methods are validated using test rigs in which there are often few vibration inputs and the transducers are mounted in close proximity to the defect source. The verification of the cepstrum effectiveness in this paper, however, has been performed using a gearbox-mounted accelerometer to identify gear tooth defects immersed within the violent, multi-input vibration environment characteristic of a typical rocket-engine turbopump.

Based on the acquired data, the LOX cepstrum parameter appears to increase with operating time in engines containing LOX gear defects while the same parameter remains relatively constant in nominally operating pumps. Additionally, in the cases of documented hardware damage the LOX cepstrum parameter is larger than the corresponding values for nominally operating turbomachinery. These observations suggest that, in addition to the trend analysis always performed, engine-to-engine comparisons of vibration parameters can provide additional diagnostic information that can add confidence to a risk assessment that is dependent upon a limited amount of test data.

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