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DIAGNOSTIC FEATURE COMPARISONS FOR EXPERIMENTAL AND THEORETICAL GEARBOX FAILURES

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Abstract: As part of a combined experimental-theoretical analysis investigation effort related to equipment diagnostic and prognostic feature development, an experimental gearbox testbed was previously developed and transitional failure data was obtained for several runs. A finite element model representing the rotating components on the testbed was developed to perform simulations for both healthy and selected gearbox fault conditions. The fault simulations are focused on gear tooth fracture since this was witnessed to be the primary gearbox failure mode during the test runs. Comparisons between the response of several common diagnostic features using both the gearbox testbed experimental data and the simulated data are provided. The knowledge obtained from evaluations of the simulated data sets and the feature comparison studies can be used to develop features with improved physical understanding of underlying mechanisms and optimize preprocessing methods for the existing diagnostic indicators. The results of the comparisons are presented and recommendations for future enhancements to the model are provided.

Key Words: Condition-Based Maintenance; dynamic systems; model-based diagnostics; simulation; statistical feature; transitional failure data.

Introduction: Condition-Based Maintenance (CBM) has been driven in part by the demand to increase system readiness/availability and reduce operations and maintenance costs. CBM accomplishes this through timely identification of equipment failures and elimination of unnecessary maintenance. Numerous authors have highlighted the cost and safety benefits of using CBM. [1, 2] This approach to maintenance relies on monitoring the condition of a system in order to detect and isolate anomalous conditions in a timely manner. An ultimate goal is to develop a health prognosis or prediction of Remaining Useful Life (RUL) with an associated functional impact assessment considering contextual information so that appropriate maintenance can be optimally scheduled. Technology maturation in the areas of measurement sensors, signal processing, digital processing hardware, dynamic system simulation, multi-sensor data fusion, and approximate reasoning have enabled the recent advancements in CBM.

Machinery fault detection generally involves comparing historical and nominal values to identify any statistically significant changes. During the diagnosis process, specific fault recognition

parameters (figures of merit) are calculated and often compared to threshold limits. [3] Additional processing may be used to enhance the diagnostic robustness using data fusion and reasoning modules to automate fault classification and damage assessment. Equipment health prognostics builds upon the diagnostic assessment with a tracked parameter that is related to damage and a future damage state prediction. These diagnostic and prognostic analyses can be based on extensive statistical experimental data with an associated empirical model of the particular system, an estimate made using predictions from a detailed system model, or a hybrid approach using a combination of both methods. The current work investigates comparisons between figures of merit calculated using results of a dynamics model and empirical results from transitional failure tests.

The transitional failure tests were conducted at the Penn State Applied Research Laboratory (ARL) using the Mechanical Diagnostics Test Bed (MDTB). The MDTB was built as an experimental research station for the study of fault evolution in mechanical gearbox power transmission components. [1, 2] It consists of a motor, gearbox, and generator mounted on a steel platform. The gearbox is instrumented with accelerometers, thermocouples, acoustic emission sensors, and oil debris sensors. A dynamics model of the MDTB was developed and is used to perform simulations of the system for both healthy and faulty gearbox conditions. [4] The simulations are focused on gear tooth failures since these are observed to be the most common type of fault encountered with the MDTB test runs.

Model-Based Methods and Considerations: The development of a model-based diagnostic/prognostic capability for CBM requires a proven methodology to create and validate physical models that capture the system response under normal and faulted conditions. For a majority of systems, operational demands induce a slow evolution in material property and/or component configuration changes. The potential thus exists to track the fault during the failure progression and provide an advanced warning of impending failure with a RUL estimate.

Model-based diagnostics, one of many CBM techniques, can be an optimum method for damage detection and condition assessment because empirically validated mathematical models at many state conditions are still deemed the most appropriate knowledge bases. [5] One approach for using model-based diagnostics is shown in Figure 1. The figure illustrates a conceptual method to identify the type and amount of degradation using a validated system model. The actual system output response (event and performance variables) is the result of nominal system response plus fault effects and uncertainty. The model-based analysis and identification of faults can be viewed as an optimization problem that produces the minimum residual between the predicted and actual response.

A consideration that differentiates the modeling of the MDTB from more common rotordynamic systems is the fact that the rotor system contains a pair of meshing gears. One of the most powerful and popular tools for modeling a rotordynamic system has been the finite element method (FEM). [6] Gearbox dynamics problems differentiate themselves from other structural dynamic systems by the branching of transmitted power through a gear mesh that leads to parametric excitation.
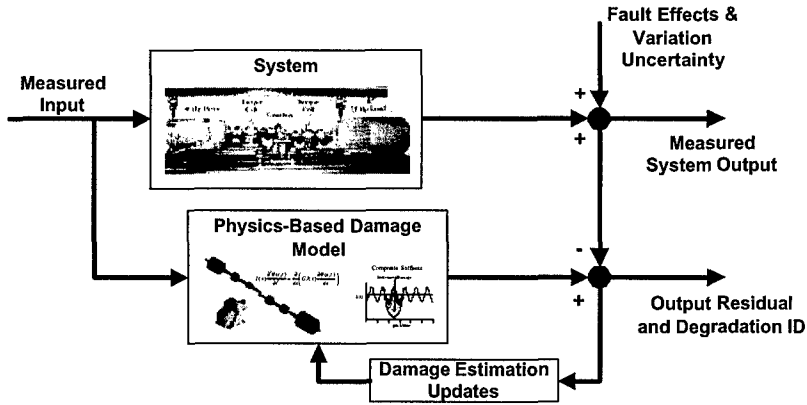
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Figure 1. Model-Based Diagnostics Process

Some common practices have been established in dynamic modeling of geared rotor power transmission systems with full-face width hub gearing. [7, 8] For instance, the base rotor hub is treated as a rigid disk with gear tooth contact, body, and root deflections lumped together to represent a dependent function of both pinion and gear rigid rotational motion. The dynamic response between gear pairs can be treated as a transmission error [9] or by defining the dynamic forces using effective gear tooth deflection forces and apparent variable stiffness. [10] The latter more accurately characterizes a system in terms of effective parameters for dynamic system analysis.

MDTB Dynamics Model: The topology of the MDTB mechanical structure is shown in Figure 2. The rotor system finite element model of the MDTB is made up of five subsystems: 1) drive motor, 2) torque transducer at gearbox input, 3) single reduction helical gearbox, 4) torque transducer at gearbox output, and 5) load motor. The subsystems are linked with 1 chain and 3 gear couplings, which are modeled using lumped mass polar moments of inertia and elastic gear tooth mesh compliance.

The system rotor model is comprised of 36 structural finite elements and 38 nodal points. The structural finite elements include: rotational axisymmetric, axial translational, and 2-dimensional bending type elements for circular shafts. [11] A translational spring (representing gear mesh tooth stiffness) is incorporated into a rigid hub/elastic tooth gearbox pinion and gear coupling matrix. [12] The nodal points include: 16 single degree-of-freedom axisymmetric rotational nodes at rotary torsional element connections of the driveline outside of the gearbox, and 22 six degree-of-freedom nodes along the gearbox shafts. Nodes are placed at discrete steps in shafts, at the axial center of shaft couplings, and at the center of gearbox shaft bearing seats. Only torsionally driven axisymmetric rotations about the system driveline shaft are considered. Shaft axial and bending type displacements of the rotor train are eliminated at the input and output gear couplings due to the effective kinematic joint associated with the gear coupling.

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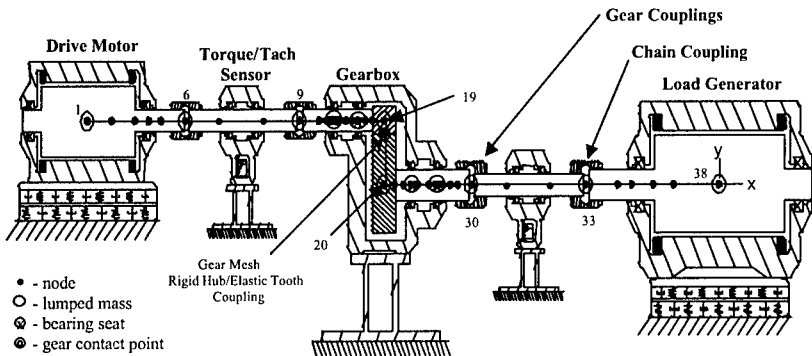
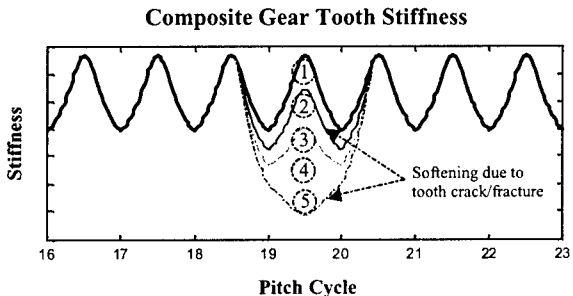**Figure 2. MDTB Topology and Rotordynamic Model with Node Points**

The nominal lumped parameter (FEM) system model parameters (inertia-[M], damping-[C], gyroscopic-[G], and stiffness-[K]) can be modified to incorporate system faults for response simulations. However, the fault simulations in this study were limited to gear tooth faults, and thus only perturbations due to a time varying stiffness were present, see Equation (1).

$$[M]\ddot{\bar{s}} + ([C]+[G])\dot{\bar{s}} + ([K]-[\Delta K(t)])\bar{s} = \omega^2 \bar{R}e^{i\omega t} + \bar{S}_g \qquad (1)$$

Few structural dynamic models of dynamic, *in situ*, gear tooth fracture appear in the literature. However, variable stiffness tooth profiles have been modified for use in dynamic simulation of a root fracture in a gear tooth. [13] The damaged tooth's stiffness profile is lessened by some degree (that is assumed proportional to the damage) per damaged gear mesh contact cycle. Figure 3 shows the stiffness profile used for the current modeling effort. Additional information regarding this model and the simulations performed can be found in [14].

Diagnostic Figures of Merit: Many types of defects or damage in rotating machinery are manifested as increases in the vibration levels. These vibration levels can be converted to electrical signals for data measurement recording through the use of

Composite Gear Tooth Stiffness

Figure 3. Nominal Gear Tooth Stiffness Variation for a Cracked Tooth

accelerometers. In principle, information concerning the relative condition of the monitored machine can be extracted from this vibration signature, and health assessments can be made through the comparison of the vibration response with prior responses to identify any anomalous

conditions. In practice, however, such direct comparisons are not effective mainly due to the large variations between subsequent signals. Instead, several more useful techniques have been developed over the years that involve feature extraction from the vibration signature. [15] Generally these figures of merit, or "features", are more stable and well behaved than the raw signature data itself. In addition, the features constitute a reduced data set since one feature value may represent an entire snapshot of data, thus facilitating additional analysis such as pattern recognition for diagnostics and feature tracking for prognostics. Moreover, the use of feature values instead of raw vibration data will become extremely important as wireless applications, with greater bandwidth restrictions, become more widely used.

The feature extraction method may require several steps, depending on the type of feature being calculated. Some features are calculated using the "conditioned" raw signal, while others may use a time-synchronous averaged signal that has been filtered to remove the "common" spectral components. A detailed discussion of a variety of feature processing methods is provided in [16].

Many features have been developed and are discussed in the literature. [15] The results presented in this paper will focus on only a few of the common features, namely FM4, FM0, NA4, M6A, and M8A. A detailed discussion of each of these features can be found in [16].

Feature Results: Simulations were performed for several degrees of tooth softening, as illustrated in Figure 3, to generate torsional acceleration predictions. Selected features were then applied to these signals and compared to the features obtained from the MDTB acceleration measurements. The comparisons focused on data obtained during MDTB Run 14 since this run resulted in gear tooth breakage and has a ground truth capability via borescope images taken during the run. These images, albeit limited in their ability to show tooth crack lengths, will facilitate comparisons between the simulated and empirical results. A plot of one of the common diagnostic features, FM4, is provided in Figure 4 for Run 14 during the time period several hours prior to the fault initiation and through the end of the run.

As shown in this figure, FM4 begins to react prior to any visible damage. This area is highlighted in Figure 4 and is labeled "incipient tooth crack". All comparisons in this paper will focus on this region since the simulations were performed for the degradation of one gear tooth. While not the intent of the present work, multiple gear tooth faults could be simulated by modifying the tooth stiffness profile shown in Figure 3. However, the number of faulty consecutive gear teeth that can be modeled using this method will be limited by the contact ratio of the gear set.

One difficulty in comparing the theoretical and empirical results involves relating the tooth stiffness to a particular point in the test run. The limited capability to ground truth the test data to an actual crack length precludes an accurate estimation of the stiffness parameter. Moreover, the complex geometry of the helical gear set further obscures the correlation between tooth damage and stiffness change. Therefore, the results presented below should be interpreted with the understanding that the location of the simulated results are not necessarily tied to the abscissa in each plot. In fact, one method for determining a system's degradation level would be to match measured feature values with simulated features based on a specific degradation
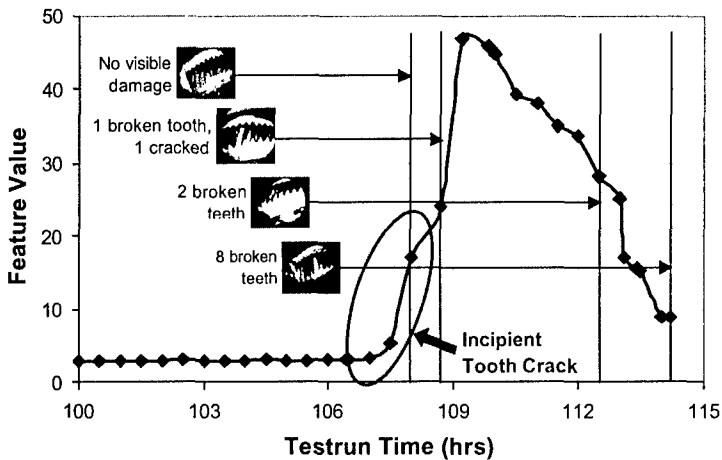
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Figure 4. FM4 Applied to MDTB Run 14 Accelerometer Data

using a validated model. *In other words, a validated model could be used to infer the actual degree of damage by simply correlating and aligning the relevant diagnostic features.*

Plots of feature values for both the measured MDTB data and the simulated data are provided below for FM4, NA4, FM0, M6A, and M8A. The simulated data points are numbered such that they can be related to the stiffness profile shown in Figure 3.

Except for FM0, each of these plots show increased feature levels at around 107.5 hours into the test run for the MDTB data. The simulated data for tooth profile number 4 closely matches the results of the features at this point, and thus were plotted accordingly. The results for the first 3 profiles did not show any significant increase in value, and some actually decreased. The results for the 5th profile were plotted at 107.7 hours into the test run. Assuming the model provides an accurate representation of the system, these results could be used to infer the actual state of tooth degradation. However, note that in addition to the modeling approximations these results assume damage is limited to a single gear tooth. It is unclear at this point what caused the discrepancies between FM0 for the data sets. Further investigation is required to resolve these differences.

A descriptive overview and the respective fault sensitivity for these figures of merit with supporting references is provided in [17]. FM4 is a bootstrap recognition figure of merit and depends upon the normalized kurtosis value. Since the simulation includes the parametric excitation forces due to stiffness change, there is an expected increase in kurtosis (4th moment) energy that can be correlated with the experimental data. Clearly, the simulated FM0 feature, which should vary with the amplitude of the mesh tones in the gear average, is affected by the change in compliance. Thus, the traditional features dependent on higher order moments (4th, 6th, 8th) seem to be sensitive to the parametric excitation produced by stiffness profile changes in
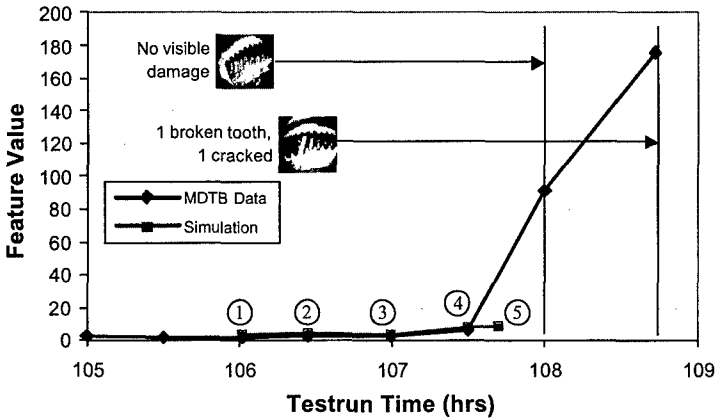
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the simulation. This excitation produces the amplitude and phase modulations that typically occur in geared systems. Amplitude modulation produces sidebands around the carrier (gear meshing and harmonics) frequencies and in non-faulted components are often associated

FM4
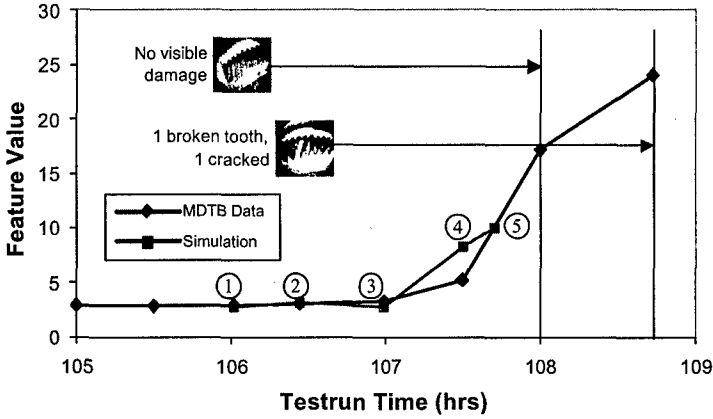
Figure 5. FM4 Diagnostic Feature

NA4

Figure 6. NA4 Diagnostic Feature

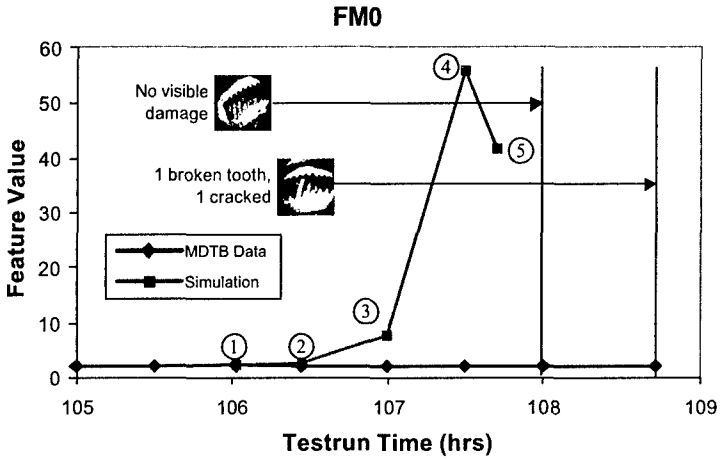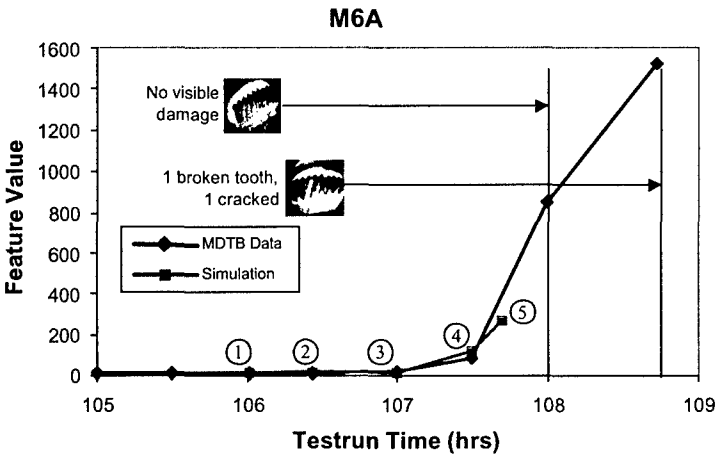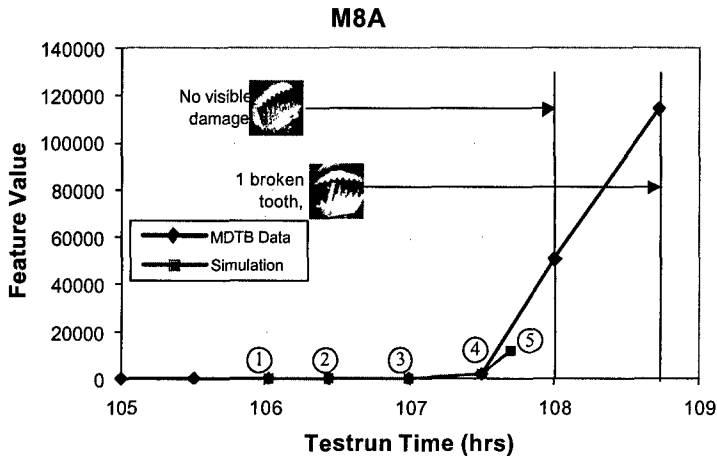Figure 7. FM0 Diagnostic Feature

Figure 8. M6A Diagnostic Feature

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Figure 9. M8A Diagnostic Feature

with eccentricity, uneven wear, or profile errors. Phase or frequency modulation will produce a family of sidebands. How these occur in real systems will either add or subtract to produce an asymmetrical family of sidebands.

The lower order figure, FM0, and modified 4th order moment, NA4, do not provide correlation between the experimental and simulated cases. The reasons are not clear. Perhaps the mesh tone energy level is not suitably impacted by the simplified stiffness profile, thus causing the large values for FM0. The apparent correlation of FM4 but not NA4 leads one to conjecture that some artifact of the processing has produced this effect. Clearly, this is an area of future investigation among others.

Future Work: There are several aspects of this damage modeling effort that can be extended in the future. Accurate methods for relating gear tooth crack length to the composite mesh stiffness is one area for investigation. Better estimates may be obtained based on a finite element model of the gear mesh. The ability to simulate damage to multiple, juxtaposed gear teeth represents another fruitful area for future work. This capability would be helpful for identifying advanced damage conditions. Another extension of this effort would be to expand the model to include the gearbox casing and compare features taken from vibrations measured on the MDTB gearbox casing with the simulated results. Such a model would allow a more accurate representation of the system and would facilitate simulations of other fault types.

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