Advanced Vibration Analysis Techniques for Diagnosing and Repairing Systemic Machine Faults on Tactical Power Sources

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Abstract

The PATRIOT Missile Defense System (MDS) Launcher Station (LS) requires an onboard source of precise and reliable electrical power to meet combat mission requirements. The LS uses a 15 kW/400 HZ Advanced Medium Mobile Power Sources (AMMPS) tactical generator, with a customized PATRIOT Applications Kit (PAK), to power its electronic control systems. LS power system failures significantly increase the probability of launch failure. During initial AMMPS fielding in Kuwait, PATRIOT units reported stator weld failures causing catastrophic failure of the AC generator on over 75% of the fleet. Initial weld inspection analysis supported no root cause conclusions. The Cintel Team performed an independent root cause analysis, on behalf of the Integrated Fires Mission Command (IFMC), to characterize the problem, determine the causal chain, analyze all covariates, including the existing PAK, and develop an effective treatment through modification of the existing PAK. Cintel used a set of vibration testing and analysis techniques – to include Cross-channel Phase (CCP), Experimental Modal Analysis (EMA) and Operational Deflection Shapes (ODS) - to determine that the weld fractures were caused by a structural resonance at 3rd harmonic order causing excessive vibration amplitude during operation at normal operating speed. Cintel's work also modeled weldment voids as a moderating effect in the causal path between the resonance and weld fracture and determined that sub-optimal welds are particularly sensitive to the high amplitudes in first bending mode and torsional movements recorded and identified in the ODS. This paper demonstrates the effectiveness of CCP, EMA, and ODS techniques as a comprehensive analytical approach to machine fault diagnoses on combat equipment. This paper also advances the theory that the structural resonance identified during the analysis, if left untreated, is a catalyst for multiple potential failure modes and mechanisms on the AMMPS, to include weld fractures, rotor-stator contact, and rotor bearing degradation.

Keywords

Vibration analysis; Causal Analysis; Experimental Modal Analysis (EMA); Operational Deflection Shapes (ODS); Cross-channel Phase (CCP); Structural Resonance; Natural Frequency (Fn); Bending Mode; Coherence; Bayesian Network (BN); Probabilistic Structural Equation Model (PSEM); Machinery Health Analyzer; Accelerometer; Modal Hammer; Phase; Campbell Diagram; Antinode; Isolators; Durometer; Damping, Magnification Factor.

Introduction

The 15 kW/400 HZ AMMPS LS generators are a direct replacement for the 15 kW/400 HZ Tactical Quiet Generators (TQG), fielded to PATRIOT units in the late 1990s. During initial TQG operational use, PATRIOT units reported several main AC generator failures. Initial inspections of the main AC generator failures showed evidence of rotor-stator contact consistent across all of the population of failed sets. Noting that no such failures were occurring in the 15 kW/60 HZ TQG fleet, analysts focused on the differences between the two 15 kW configurations: turning speed and mass. The 15 kW diesel engine is configured to operate at 2000 RPM; the 60 HZ set engine is configured to operate at 1800 RPM. The 15 kW/400 HZ set is 30 lbs. heavier than the 60 HZ due to the additional stator windings required for 400 HZ. Vibration analyses showed these failures were attributable to a structural resonance occurring just below turning speed of 33 HZ. This was causing bending mode amplitudes sufficient to close the rotor-stator air gap and cause friction between the two surfaces, ultimately leading to short circuit and failure. PATRIOT personnel developed a stiffening and damping treatment to mitigate the problem.

During the initial AMMPS fielding, PATRIOT units reported stator weld fractures causing catastrophic failure of the AC generator. Inspection of the failed AMMPS sets showed a rotor-stator contact, similar to the TQG inspection findings, across the whole population of failed sets. Initial analyses of inspection data suggested the failure mode and mechanism was similar to the TQG problem. These initial data supported no causal conclusions but indicated a high probability of a vibration problem given the similarity between the TQG and AMMPS generators in mass, geometry, and turning speed.

During initial inspection and analysis of failed sets, the Original Equipment Manufacturer (OEM) noted some weld quality issues on distribution of sets in a specific serial number range. During more detailed follow-on analysis, the OEM also performed a set of destructive and non-destructive inspection tests on production welds. Test analyses showed voids in the stator welds between the joined members and the weld fillet. Based on combined data on, and analysis of, weld quality and production process issues, the OEM implemented production weld process improvements to eliminate problems with weld. These data did not suggest a causal connection between the weld quality and the weld fractures, but rather supported that weld quality could be a moderator in the indirect causal connection between a resonance at turning speed, the weld fractures, and rotor-stator contact causing AC generator failure.

Given these combined historical and current TQG and AMMPS data, Cintel initiated a vibration analysis process to determine the root cause, model the exact causal relationships, and identify a treatment. In parallel with the vibration analysis process, Cintel used a knowledge engineering (KE) process to develop a Bayesian Networks (BN)-based causal model of the problem domain using.

The KE process is used to combine data and expert knowledge in a Probabilistic Structural Equation Model (PSEM). The PSEM are graphical models that qualify and quantify a specific domain and are then used to facilitate understanding of multivariate relationships in varying conditions. The BN development process was ongoing throughout and was used to update beliefs based on vibration test data and expert analysis.

For all vibration testing and analysis used herein, Cintel used an Emerson AMS 2140 Machinery Health Analyzer, “VibView” and “MeScope” software for the CCP, EMA, and ODS testing and analysis, ICP Triaxial Accelerometers for all measurements, and an Emerson Impulse model force/modal hammer for the EMA testing.

The analytical approach is detailed in six distinct (6) phases.

Phase 1: Initial Cross-channel Phase (CCP) Testing

Based on initial evidence presented from the stator weld fractures, and on historical data from the 15 kW LS generators sets, Cintel identified structural resonance as a potential cause with high probability. Phase testing, in general, is used to determine how two points are moving relative to one another. And in all cases, a structural resonance causes a phase difference, or shift. The CCP test was then indicated for an initial test to reduce entropy in the problem domain and provide decision support for the follow-on test strategy. The CCP leverages the dual channel capability of the Emerson 2140 to provide the test data while the generator is operating at normal operating speed of 2000 RPM (33 HZ). The test was constructed with one accelerometer placed on the main generator at the top center, and a second accelerometer placed 90 degrees from top. The analysis team collected test data for reference/response, response/reference, and coherence values. These data showed an 8:1 ratio between the displacement velocity (in/sec) values at both sensors at a given time in the waveform, with coherence values over 9.0. These data indicated a phase shift with coherence – typical of a structural resonance baseline. This supported the structural resonance hypotheses and a *potential* causal/associative relationship between a resonance at Turning Speed (TS) and/or TS orders, and the weld fractures.

In this phase also began the process of eliminating the LS trailer, the PAK, and weld penetration/quality as covariates for the stator weld failures and subsequent generator failure. The team performed the same CCP tests in all configurations - on/off LS; with/without PAK - and noted no significant difference in values in any combination. This result was not conclusive but suggested that the LS trailer and PAK did not have a direct effect. For the weld quality, the analysis team performed CCP on AMMPS with original stators (pre-production process improvement) and improved stators (post-production process improvement). Data from these tests showed no significant difference between stator types. The team modeled this accordingly in the BN as a structural indirect causal connection from the resonance to the weld to rotor-stator contact to main generator failure. In this model, weld quality values have a moderating effect, wherein suboptimal welds would be more susceptible to failure and optimal/conforming welds would make other vibration-related failure mechanisms more probable, e.g., rotor-stator contact from any of the following individually or in combination: first bending mode action, bearing failure, or winding bond failure.

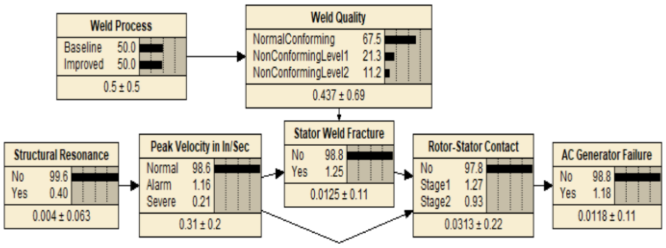

Figure 1. *Bayesian Network (BN) showing the causal relationships between structural resonance, stator weld, and AC generator variables.*

Further testing phases were then specifically designed to confirm the structural resonance hypotheses by characterizing and quantifying it through a set of Experimental Modal Analysis (EMA) and Operational Deflection Shape (ODS) tests. These tests would also provide further characterization of LS trailer, PAK, and weld quality effects.

Phase 2: EMA Baseline

The analysis team constructed an EMA test plan using the Vibration Analyzer, the triaxial accelerometer, and the modal hammer. The test design was to rove the accelerometer at eight (8) points, 45 degrees apart, around the circumference of the main generator – starting at the circumference around the rotor bearing end and moving towards the circumference around the driven end at approximately 4” lateral increments. This design produced five (5) sets of 360 degree test iterations consisting of 40 individual test points. With the accelerometer positioned at a test point, the vibration analyst struck the stator with the modal hammer, one strike at each axis: vertical, radial, and axial. This process produced 120 individual data points covering the entire stator geometry. Cintel used these EMA test data to establish a Natural Frequency (Fn) baseline and to generate a Campbell diagram to show any specific frequencies with major amplification around TS (Figure 2.)

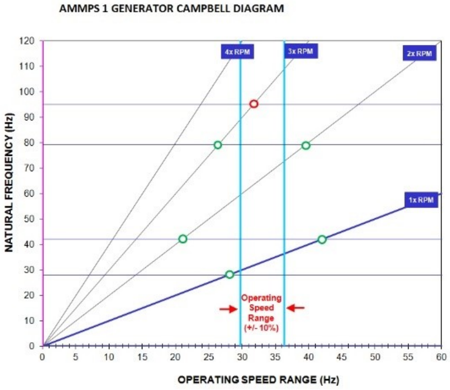

Figure 2. *Campbell Diagram: Representative of Baseline OEM Configuration and OEM with PAK, both on and off LS, Configurations. Fn are relative to Turning Speed (2000 RPM/33.3 HZ) and multiples of Turning Speed (TS). Red, or Bold, circles indicate major amplification points relative to the 10% band around TS*

The 3 x TS peak (~ 96 HZ, in Red), located within the +/- 10% of TS band was indicated for follow-on ODS testing to characterize the movement of the AMMPS at turning speed. To further evaluate the effects of the different AMMPS configurations on the structural dynamics of the AMMPS, the EMA tests were all repeated for the different configurations of on/off LS, PAK/No PAK, and original weld/improved weld. The EMA data from these tested indicated a sharp null of no effect and effectively eliminated the PAK and LS variables from consideration as covariates for the stator weld fractures – further strengthening the arguments underpinning the structural resonance hypothesis. These data did not alter the causal model as regards the potential moderating effect of weld quality.

Phase 3: ODS Baseline

In this phase Cintel focused on building and analyzing a working ODS structural model of the machine using the Analyzer and ODS software. This ODS test was constructed as a process: first building a finite element model of the AMMPS in the ODS software, then collecting ODS data at turning speed, and then interpolating the test data on the ODS structural model. The model development involves creating a grid-like, three-dimensional model of the set and then creating test points as the vertices between grid lines. The test points are then formatted so they are oriented for accelerometer position and location. The end state is comprehensive model of the AMMPS generator and engine geometry with 280 built-in test points. The ODS data were collected by roving a triaxial accelerometer to each test point in sequence and activating an ODS capture at each test point. This process generated 280 data points for each axis (axial, radial, and vertical) for a total of 840 data points. These data were then interpolated on the ODS grid model and then animated at different frequencies – TS and harmonics – to show how the AMMPS set was moving during operation. The initial animations showed a complex movement shape with a first bending mode shape component and a twisting/torsional movement component – both at elevated amplitude levels. The velocity of displacement (in/sec) peaks for these modes and movements were most pronounced at a peak of ~ 99 HZ, or 3 x TS. The ODS data were consistent with the EMA results and confirmed the structural resonance hypothesis. This result indicated for a guided process for developing an initial treatment prototype.

Phase 4: Treatment 1

In this phase Cintel used the combined EMA and ODS results to determine optimum location and geometry of a stiffening bracket designed to move the 3 x TS FN out of the +/- 10% significance band around TS. The existing AMMPS configuration uses two sets of isolators: one set under the engine; one set under the stator. Both sets are affixed to brackets. The engine bracket is part of the engine casting; the generator bracket is welded to the stator frame. Each bracket is fitted with a rubber shock mount to isolate the engine/generator from the frame. The Team determined that the existing engine block boss used to mount the transportation bracket - located at the approximate antinode between the engine and generator - would be a viable location. This effectively created a “middle row” set of brackets (with shock mounts) to stiffen the structural beam created by the engine and generator. After fabricating and installing the prototypes, Cintel repeated the EMA test, and these test data showed the brackets were successful in moving the Fn out of the TS band (Figure 3.)

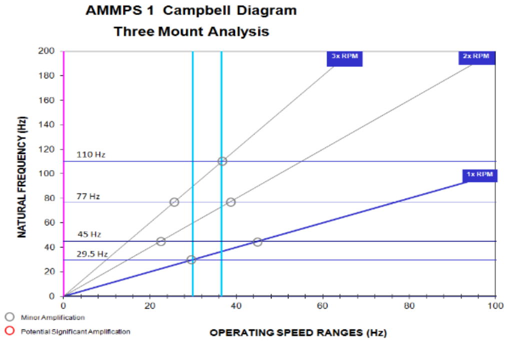

Figure 3. Campbell Diagram: Treatment 1 Fn relative to Turning Speed (2000 RPM/33.3 HZ) and multiples of Turning Speed. Clear circles indicate minor amplification points relative to the 10% band around turning speed. Note absence of any points inside of +/- 10% of TS and absence of red, or bold, circles.

Phase 5: Treatment 1 + 2

In this phase, Cintel first performed another ODS test on the new baseline configuration with stiffening brackets to assess the impact of the brackets on the AMMPS movement at turning speed. These test data showed a significant improvement (decrease in vibration energy) but also showed that further stiffening would not be effective. The ODS showed that a moderate damping treatment- decreasing the isolator shock mount durometer value - could improve performance by reducing the magnification factor, or Q factor, around TS. Figure 4 shows the effectiveness of replacing the existing 70 durometer mounts with 50 durometer mounts.

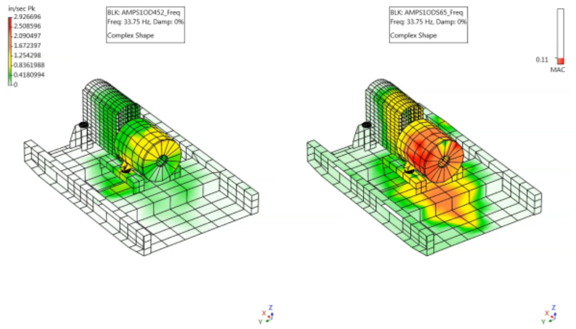

Figure 4. ODS Animation: Snapshot of AMMPS at 33 HZ with amplitude shown on color scale and in inches/sec in Black and White. The snapshot on the right is the Treatment 1 configuration with just the brackets. Note that with only the stiffening bracket there is significant decrease in vibration energy but still some moderate peaks (velocity = ~ 1.6 ips.). The snapshot on the left is the Treatment 1 + 2 configuration with the brackets and 50 durometer isolators. Note the significant decrease in amplitude and vibration energy with the combined treatment (velocity = ~.1 ips)

Testing

In this phase Cintel tested the new prototype treatment against PATRIOT reliability standards. The most critical was the "Shaker Table" test due to the sensitivity of the rubber compound isolators. The original PAK baseline 70 durometer isolators were already proven to pass PATRIOT standards. Cintel's task was to ensure the softer durometer performance would not come at the expense of durability to meet endurance testing requirements. Cintel tested the new 50 durometer isolators in both the original configuration and in the new middle row configuration - using new sets of isolators in each test. These test data showed no significant damage to the isolators or brackets after testing to equivalent of 10000 hours of operation.

Conclusions

Cintel's prototype Treatment 1 + 2 (stiffening and damping) was accepted by IFMC as an approved update to the existing PAK Engineering Change Proposal (ECP) and the vibration mitigation "kit" was fully integrated on all IFMC 15 kW stock. This kit, combined with weld process improvements, provides for a more reliable power source for the PATRIOT MDS. Cintel's work in this problem domain establishes the primacy of CCP, EMA and ODS techniques for testing and analysis of post-design PATRIOT MDS power problems. The versatility of these techniques combined with causal analysis tools provides a potential for much broader applicability to all combat systems as a comprehensive and precise analysis tool.

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