DfR Solutions
reliability designed, reliability delivered

Vehicle Prognostics to Enable Optimized Maintenance and Logistics

DfR Solutions

August 22, 2008

5110 Roanoke Place, Suite 101 College Park, Maryland 20740
Phone (301) 474-0607 Fax (240) 757-0053
www.DfRSolutions.com

Introduction

- Current
  - Diagnostics – what has gone wrong already
  - “Check Engine Light” when something goes wrong
  - Scheduled maintenance
  - Warehouse of parts
- Future
  - Prognostics – what will go wrong if not fixed soon
  - “Maintain Engine Light” when something would go wrong on the next mission
  - Material Condition drives maintenance
  - “Just in Time” Maintenance and Logistics

5110 Roanoke Place, Suite 101, College Park, Maryland 20740
Phone (301) 474-0607 Fax (240) 757-0053
www.DfRSolutions.com

Onboard Prognostics

- Sensors on mission critical components
- Onboard prognostics software
  - Lifetime prediction models
  - Wear accumulation data
- Data output capability
  - Fleet health monitoring
- Integrated material system
  - Maintenance parts arrive just in time

5110 Roanoke Place, Suite 101, College Park, Maryland 20740
Phone (301) 474-0607 Fax (240) 757-0053
www.DfRSolutions.com

Operation of Prognostics

- Complex component life prediction model
  - Physics of failure and data driven
- Data is monitored during each mission
- Cumulative wear is reported out after each mission
  - Related to product life
  - Warning can be set when life falls below a certain percent

5110 Roanoke Place, Suite 101, College Park, Maryland 20740
Phone (301) 474-0607 Fax (240) 757-0053
www.DfRSolutions.com

CONOPS – Clutch Disk

- Physical analysis reveals a harmonic on the drive shaft that varies with clutch thickness
  - 1kHz = 1” thickness
  - 2kHz = 0.5 “ thickness
- A tuning fork is mounted on the drive shaft to monitor Clutch disk thickness
  - Initial thickness 1.00 inches
- Clutch consumption
  - During 1 hour paved road mission
    - 0.03”
  - During 1 hour off road mission
    - 0.09”
- When the clutch wears to a certain point (based on logistics lag time) a new clutch will be automatically ordered and maintenance scheduled
- Maintenance
  - Scheduled at 0.30” clutch thickness
  - Performed at 0.20” clutch thickness (two mission safety buffer)

5110 Roanoke Place, Suite 101, College Park, Maryland 20740
Phone (301) 474-0607 Fax (240) 757-0053
www.DfRSolutions.com

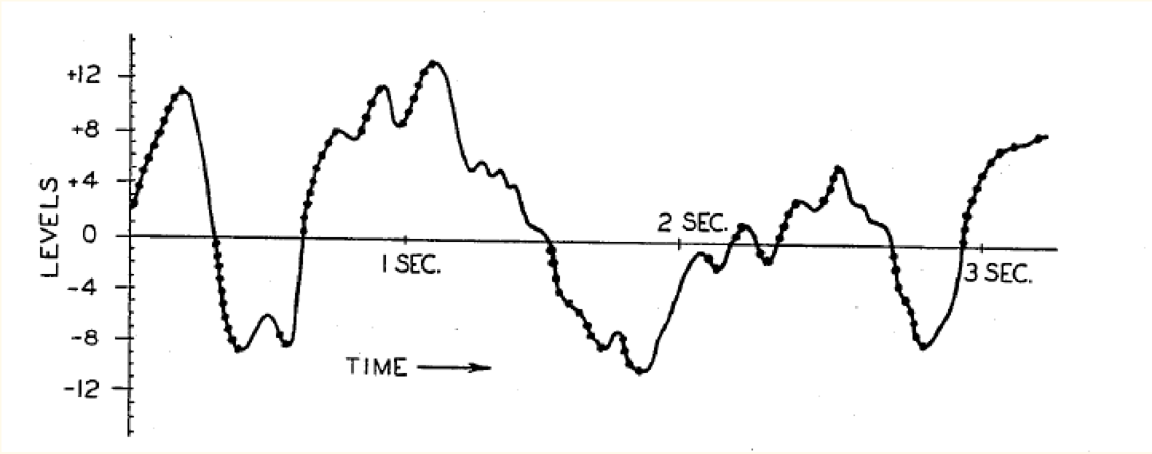
Application – Wheel bearings

- Can not monitor directly
- Life is based on many conditions
  - Stress of mission
    - Accel. and decel.
    - Rough or smooth roads
    - Abrupt shock (rocks or nearby explosions)
  - Age of bearing
  - Weight of vehicle (load)
  - Environment (heat, humidity, contamination, etc.)
- Prognostic model developed using
  - Physics of failure
  - Empirical data
- Sensors on vehicle to monitor enough data to feed model
- Life consumption based on operational characteristics of each mission
- Logistics details selected by user
  - Parts ordering at XX% of life
  - Maintenance scheduled at XX% of life
  - Maintenance performed at XX% of life

5110 Roanoke Place, Suite 101, College Park, Maryland 20740
Phone (301) 474-0607 Fax (240) 757-0053
www.DfRSolutions.com

No Two Missions are Alike

- The mission stress profiles vary from minute to minute
- It is impossible to make an accurate estimate (it is possible to make a worst case estimate)
- Worst case estimate results in frequent, unnecessary maintenance



5110 Roanoke Place, Suite 101, College Park, Maryland 20740
Phone (301) 474-0607 Fax (240) 757-0053
www.DfRSolutions.com

Degradation Modeling

- A Physics of Failure model can be made for any wearout mechanism
- Bearings:

$$L = \left[\frac{f_c Z^{a_1} D_a^{a_2} \left(i \cos \alpha \right)^{a_3}}{P} \right]^p$$

  - Z = number of balls
  - Dn= ball diameter in inches
  - i=number of rows
  - α = contact angle
  - *P* =bearing load in pounds – measured by a sensor
  - *L*=number of million revolutions that a specified percentage of bearings will fail, if the percentage is 10 then L=L10 and is termed the rating life – measured by a sensor
  - *p, a1, a2, a3, a3, fc,* are unknown parameters that must determined from available data – measured by sensors

5110 Roanoke Place, Suite 101, College Park, Maryland 20740
Phone (301) 474-0607 Fax (240) 757-0053
www.DfRSolutions.com

Applicability

- Cumulative damage models based on Physics of Failure can be applied to virtually any circumstance
  - Electronics
    - Circuits
    - Packages
    - Boards
    - Modules
  - Mechanics
    - Dynamic systems – engines, suspensions, actuators
    - Statics systems – spars, airframe/seaframe, bridges
  - Complex systems
    - Electro-hydraulic

5110 Roanoke Place, Suite 101, College Park, Maryland 20740
Phone (301) 474-0607 Fax (240) 757-0053
www.DfRSolutions.com

Logistics System Integration

- Vehicle prognostics integrates with logistics system
  - Automate Just In Time Logistics
  - Parts ordered to arrive immediately before maintenance operation
- Reduced warehousing for common maintenance items
- Reduced maintenance costs as component life lengthened through continuous monitoring

5110 Roanoke Place, Suite 101, College Park, Maryland 20740
Phone (301) 474-0607 Fax (240) 757-0053
www.DfRSolutions.com

Implementation

- Existing Systems
  - Sensors integrate seamlessly at major system interconnections
  - Phased implementation
    - Sensors and onboard computer
    - Wireless Data Integration
    - Logistics integration
- New Start
  - Build in the entire system
  - Interface with existing logistics software

5110 Roanoke Place, Suite 101, College Park, Maryland 20740
Phone (301) 474-0607 Fax (240) 757-0053
www.DfRSolutions.com

Summary

- Onboard Prognostics based on Physics of Failure allows
  - Just in time maintenance
  - Just in time logistics
- Reduces mission risk
- Reduces downtime
- Reduces warehousing costs
- DfR Solutions develops mission specific:
  - Prognostics
  - Sensors
  - Software
  - **Solutions**

5110 Roanoke Place, Suite 101, College Park, Maryland 20740
Phone (301) 474-0607 Fax (240) 757-0053
www.DfRSolutions.com

- **DISCLAIMER**
  DfR represents that a reasonable effort has been made to ensure the accuracy and reliability of the information within this report. However, DfR Solutions makes no warranty, both express and implied, concerning the content of this report, including, but not limited to the existence of any latent or patent defects, merchantability, and/or fitness for a particular use. DfR will not be liable for loss of use, revenue, profit, or any special, incidental, or consequential damages arising out of, connected with, or resulting from, the information presented within this report.

- **CONFIDENTIALITY**
  The information contained in this document is considered to be proprietary to DfR Solutions and the appropriate recipient. Dissemination of this information, in whole or in part, without the prior written authorization of DfR Solutions, is strictly prohibited.

From all of us at DfR Solutions, we would like to thank you for choosing us as your partner in quality and reliability assurance. We encourage you to visit our website for information on a wide variety of topics.

Best Regards,
Dr. Craig Hillman, CEO