Sensor Reliability Impact on Predictive Maintenance Program Costs

Accelerometers with lower mean time between failures (MTBF) values result in higher costs for permanently installed vibration sensor applications - as much as $60 per vibration sensor. By taking the MTBF and manufacturing quality into account when making an accelerometer purchase, you can achieve lower overall program costs.

MTBF Rates Translate to Expected Costs

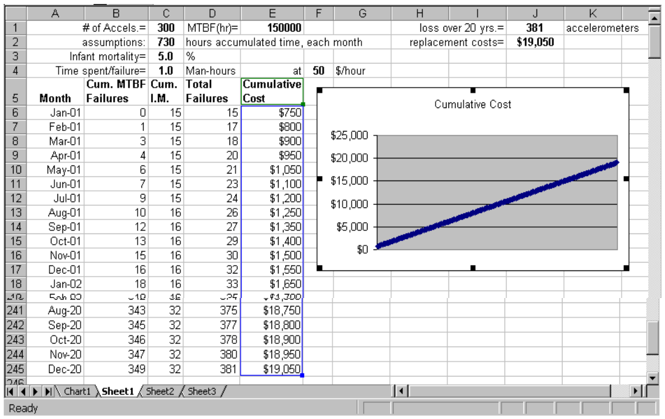
To give some idea of the relative cost differences due to various MTBF rates, we will use an example installation of 300 accelerometers with a program "life" of 20 years, a common period used for depreciation of capital equipment.

There are two acceptable methods for calculating the MTBF of an accelerometer, which can be found in Appendix A. For this example, we will use the field-failure MTBF calculation.

Assumptions

- Each time an accelerometer fails, it takes a total of one man-hour to isolate the failure, replace the accelerometer, and perform all the tasks necessary to return the unit for a warranty replacement. Appendix B provides an example of this process.
- The fully burdened cost of replacement time is $50 per hour. This assumption is quite conservative since most companies have fully burdened rates that are in the $70 to $80 range.
- We will consider infant mortality (IM) as occurring every Nth sensor, where N = 1/IM%. Therefore, a 5% IM rate means that for every 20 new accelerometers 1 will fail. Appendix C explains infant mortality in accelerometers.
- Each time the total exposure of accelerometers reaches the MTBF, one accelerometer will fail. Appendix D details the causes of accelerometer failures.
- The "lifetime cost" is the additional cost per accelerometer that accrues after the sensors are bought, not including the original purchase price.
- All accelerometers are replaced for zero cost. This is equivalent to having accelerometers with a "lifetime warranty" against failures.

A spreadsheet example is illustrated here.



# of Accels.= 300 MTBF(hr)= 150000 loss over 20 yrs.= 381 accelerometers
assumptions: 730 hours accumulated time, each month replacement costs= $19,050
Infant mortality= 5.0 %
Time spent/failure= 1.0 Man-hours at 50 $/hour

Month	Cum. MTBF Failures	Cum. I.M.	Total Failures	Cumulative Cost
Jan-01	0	15	15	$750
Feb-01	1	15	17	$800
Mar-01	3	15	18	$900
Apr-01	4	15	20	$950
May-01	6	15	21	$1,050
Jun-01	7	15	23	$1,100
Jul-01	9	15	24	$1,200
Aug-01	10	16	26	$1,250
Sep-01	12	16	27	$1,350
Oct-01	13	16	29	$1,400
Nov-01	15	16	30	$1,500
Dec-01	16	16	32	$1,550
Jan-02	18	16	33	$1,650
Aug-20	343	32	375	$18,750
Sep-20	345	32	377	$18,800
Oct-20	346	32	378	$18,900
Nov-20	347	32	380	$18,950
Dec-20	349	32	381	$19,050

Example Project 1 – Low Quality

In the first example project, we calculate replacement costs based on a 5% IM rate and a 150,000-hour (17-year) field-failure MTBF. This is comparable to what would be experienced with low-quality accelerometers. The total lifetime cost to the project owner, after purchasing the accelerometers, would be $19,050.

Example Project 2 – Moderate Quality

In the second example project, we calculate replacement costs based on a 2% IM rate and a 500,000-hour (57-year) field-failure MTBF. The results indicate a 20-year lifetime cost of $5,600.

Example Project 3 – High Quality

In the third example project, we calculate replacement costs based on an IM rate of 0.3% and a field-failure MTBF of 2,000,000 hours (228 years), as expected for high-quality accelerometers. The total lifetime cost of the program would be $1,350.

Table 1- Added lifetime costs modeled for various quality levels

Project:	300 permanently installed accelerometers, 20-year program life				
Quality	IM	MTBF	Replaced sensors	Lifetime cost	Cost per accelerometer (300)
Low	5.0%	150 K-hrs.	381	$19,050.00	$63.50
Moderate	2.0%	500 K-hrs.	113	$5,600.00	$18.67
High	0.3%	2 M-hrs.	27	$1,350.00	$4.50

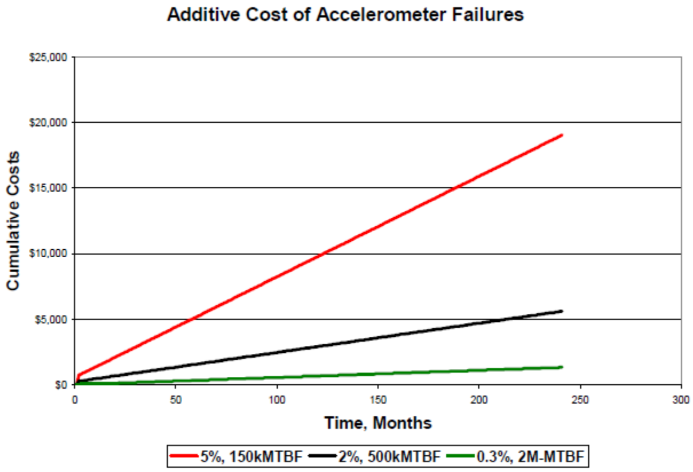


Table 1 summarizes the cumulative costs over twenty years. The example does not account for the time value of money or the effects of inflation. Those rates would have to be applied to all numbers.

The lowest quality accelerometers result in a 20-year lifetime cost of $19,050 for identifying and replacing failed accelerometers. Compared to the lifetime costs of $1,350 for the highest quality accelerometers, the additional expense of purchasing low-quality sensors is $17,700. Stated differently, this adds $59 to the cost of each of the 300 low-quality accelerometers purchased. (The model does not account for the long-term aggravation of having to replace almost 400 sensors over 20 years.)

The moderate-quality accelerometers result in a 20-year lifetime cost of $5,600. Compared to the lifetime costs of high-quality accelerometers, the additional cost of purchasing moderate-quality accelerometers is $4,200 or $14 per sensor. Ultimately, choosing a higher quality, potentially higher-priced sensor up front can help save time, money, and patience in the long run.

Appendix A – MTBF Methodologies

Mean time between failures (MTBF) represents the average expected time that will elapse between failures of like units under like conditions. Standard methods to calculate the MTBF have been developed. Purchasers should consider the MTBF of an accelerometer before buying them. Accelerometers with a low (short) MTBF mean higher costs due to the manpower for troubleshooting and replacement of bad accelerometers and lost data associated with the more frequent failures.

Modeled MTBF Calculation

The Department of Defense, through the Air Development Center in Rome, NY developed a calculation "cookbook" to be used for electronic systems and circuits. It is the Military Handbook MIL-HDBK-217. This document has gone through revisions over the years, but it still provides very good guidance for computing the MTBF for hermetically sealed electronic circuits. Most accelerometers contain hybrid circuit boards with electronic components and the accelerometers are usually hermetically sealed. If the accelerometers are hermetically sealed, then MIL-HDBK-217 "cookbook" computation of the MTBF is useful for comparing designs before they are actualized.

The handbook uses the term "Total Hybrid Failure Rate" and identifies it as λ_ρ.

$\lambda_\rho = [\Sigma N_C \lambda_C]\,(1 + 0.2\,\pi_E)\,\pi_F\,\pi_Q\,\pi_L$ failures per 1,000,000 hours

Where N_C = number of each particular component
λ_C = failure rate of each particular component
π_E = environmental factor
π_F = hybrid function factor
π_Q = quality (screening) factor
π_L = longevity (experience) factor

Field-Failure MTBF Calculation

Once equipment has been fielded, measurements can be made of the MTBF of installed equipment. The simplest expression of MTBF for fielded systems is MTBF = total time exposure / # failures. For example, if 100 units were operated for 1,000 hours before the first unit failure was experienced, the MTBF would be 100 (units) x 1,000 hours per 1 failure, or MTBF = 100,000 hours. If there had been 5 failures during that same period, the resulting MTBF would be 20,000 hours (100,000/5).

MTBF of Wilcoxon Accelerometers

Modeled MTBF Calculation

MIL-HDBK-217 is a useful reference for computing MTBF for Integrated Electronic Piezoelectric (IEPE) accelerometers. N is determined simply from the part or connection count; all other factors are determined through reference to MIL-HDBK-217 for the particular component or element. Table 2 on the next page calculates the MTBF of Wilcoxon’s 786A, one of the most widely used accelerometers for industrial machinery health monitoring. Four field-failure MTBF calculations follow that.

Table 2 – MTBF calculation for the 786A accelerometer

N components/elements	60° C
48 connections	.018122
4 plated through holes	.000041
1 crystal	.0058
1 bipolar transistor	.00029
1 FET	.0135
3 diodes	.00731
3 capacitors	.016082
5 resistors	.00363
Individual $N_C\lambda_C$	.064775

Calculated total hybrid failure rate (786A):

@ 60° C
$\lambda\rho$ = [.064775] 70.18
= 4.5459 / 106 hrs
= 4.5459 per 10^6 hrs
= 219,978 hours MTBF
= **25.1 years MTBF**

Field-Failure MTBF Calculation

Field Example 1

Manufacturing environment with production lines where the operating temperature of the 786A accelerometers was approximately 60℃

Total installed number of accelerometers:	270
Total operating time of accelerometers:	3 years
Total number of actual failures:	3 units

(270 units) x (8,760 hours/year) x (3 years) = 7,095,600 operating hours
MTBF in practice = 7,095,600 hours/3 failures = 2,365,200 hours/failure = **270 years/failure**

Field Example 2

O.E.M. application at unknown temperatures with the 786A installed on a variety of general manufacturing and processing machines

Total installed number of accelerometers:	627
Total operating time of accelerometers:	3 years
Total number of actual failures:	7 units

(627 units) x (8,760 hours/year) x (3 years) = 16,477,560 operating hours
MTBF in practice = 16,477,560 hours/7 failures = 2,353,937 hours/failure = **268 years/failure**

Field Example 3

O.E.M. application at unknown temperatures with the 786A installed on a variety of general manufacturing and processing machines

Total installed number of accelerometers:	385
Total operating time of accelerometers:	44 months (3.67 years)
Total number of actual failures:	1 unit

(385 units) x (8,760 hours) x (3.67 years) = 12,377,442 operating hours
MTBF in practice = 12,377,422 /1 failure = 12,377,422 hours/failure **= 1,412 years/failure**

Field Example 4

Wilcoxon tracks returned accelerometers. The percentage of accelerometers returned in any given year is less than 0.3% of those produced. This quality level is commensurate with an **MTBF of nearly 3,000,000 hours, or 342 years**.

Appendix B – Example Accelerometer Replacement Process

Cost of Installed Accelerometer Failures

Every time an accelerometer fails it costs time and effort to diagnose the failure and replace the accelerometer. This diverts skilled manpower from their primary task of prognostication to test and replace failed sensors.

Locating Faulty Accelerometers

For this analysis, we will consider permanently installed accelerometers because they are the ones most difficult to diagnose and replace. Portable accelerometers can be readily changed out with little or no investment of time, so we will not investigate portable accelerometer failure.

There are many indicators of faulty accelerometers: the bias output voltage (BOV) can be outside the normal range; the data can contain serious "ski slopes" at low frequencies; or the spectrum may "flat line" because of no signal. Whatever the cause, it usually means that the vibration technician must take time to determine that all cable connections are tight and clean, that the accelerometer is solidly mounted, and that the cable is not broken.

It has long been held that connection failures account for at least half of electrical system problems. Consequently, the first thing a vibration technician usually does when a vibration reading has a problem is to determine whether the fault is in the cabling. Depending on the accessibility of the accelerometer, this could take two to thirty minutes. It might involve changing accelerometers, cleaning connections, returning to the shop at least once for spare cables, or any of a myriad of other possible expenses of time.

Failed Sensor Replacement

While there may be some disagreement, it will likely involve at least one person for at least 30 minutes to determine that an accelerometer is not functioning correctly. This time will increase when the accelerometer is mounted in a position that involves "high work," such as being on a cooling tower fan, in a hazardous classified area, or requiring any kind of work permit to be written. It typically takes upwards of one man-hour to determine that an accelerometer has failed and replace it.

Then there is the additional time and expense involved in returning accelerometers to the manufacturer. Telephone calls need to be made, return authorizations obtained, bad accelerometers packaged, and shipping papers prepared. Don’t forget the shipping cost itself. This process could add 5 to 30 minutes per accelerometer to the original time taken to find, verify, and replace the failed accelerometer.

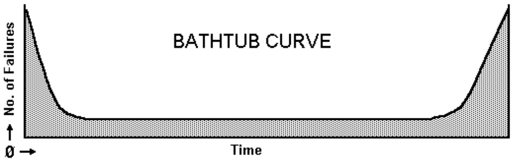
Example Process for Diagnosing and Replacing a Failed Accelerometer

1. Test the accelerometer for BOV and signal
2. Obtain cold work permit (high work permit if >6’ up)
3. Shut down the machine
4. Lockout and tag-out the machine
5. Access and remove the accelerometer
6. Replace the accelerometer with a “spare” from stock
7. Test the new accelerometer for BOV and signal
8. Remove the lock-out and tag-out
9. Restart the machine
10. Package the faulty accelerometer
11. Prepare shipping document for faulty accelerometer
12. Contact manufacturer for warranty replacement (shipping or purchasing dept)
13. Receive replacement accelerometer into “stock” room

Appendix C – Infant Mortality Explained

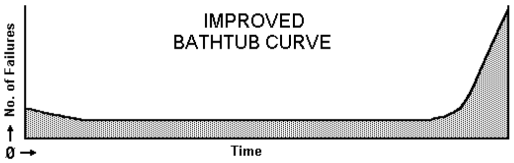
The "Bathtub Curve", "Infant Mortality" and "Root Cause Analysis"

Here is an example of a "bathtub curve" showing "infant mortality," from RG Associates[1]. "The following graph, commonly called the 'bathtub curve,' illustrates the life or reliability of products. Some fail in their infancy (infant mortality) and those that survive should go on to live a long trouble-free life before finally wearing out."



The bathtub shape of the curve originates from the fact that a plot of the number of unit failures versus time results in that kind of curved shape. The curve also resembles the mortality plot that would result from an actuary when the number of deaths versus the age of people is plotted. Mortality data indicates that people at the youngest ages (infants) die at a rate higher than adolescents or adults. Consequently, the failures occurring early in the life of physical systems are called "infant mortality."

When the infant mortality rate of electronics can be reduced, the result is an improved bathtub curve. This accomplished with what engineers call "root cause analysis." An analysis of the causes of early failures can result in "lessons learned" that can be applied to other systems. Electronic component pre-aging and environmental stress screening can further reduce component infant mortality.



Effect of High Infant Mortality on PdM Programs

Early failure rates for accelerometers mean that Predictive Maintenance technicians will be quickly faced with learning to diagnose accelerometer problems. It will also make those users spend valuable time early in a new installation just trying to sort out the "bad" accelerometers from all the fresh data that must be analyzed.

Certain machine problems can also look like accelerometer failure modes. PdM technicians may quickly lose confidence in the newly installed accelerometers as they sort through the data. The direct costs of these early accelerometer failures are those associated with finding and replacing the accelerometers, enumerated in Appendix B. The indirect and difficult-to-quantify costs are those that cause valuable time for data analysis to be lost when working with bad accelerometers. The ultimate cost to the vibration PdM program is that it will diminish the return on investment (ROI) of the PdM effort and may cost the support of upper management because of a loss of confidence.

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[1] http://www.rgassocs.com/page5.htm as of May 12, 2006.

Appendix D – Causes of Accelerometer Failures

Installation and Operation Errors

When evaluating how accelerometer quality and MTBF impact the lifetime cost of purchasing accelerometers, it is important to remember that not all accelerometer failures are defects. Human error that damages accelerometers during installation can lead to an internal electronic amplifier board failure. Damage to the sensor is not typically covered under lifetime warranties.

High-quality accelerometer manufacturers will install protection in the circuitry of the IEPE accelerometer to safeguard against common installation mistakes. While MTBF calculations are based upon manufacturer defects and sensor aging, not mishandling, these safeguards have the practical effect of reducing the lifetime cost of the sensor.

Installation errors	**Safeguards in high-quality accelerometers**
Excessive powering voltage from wiring an accelerometer directly to a DC power supply and not using a constant-current diode	Overload protection
Electrostatic discharge to the sensor	ESD protection
High shock levels from dropping an accelerometer during installation can produce high voltages out of the crystal stack that exceed the withstanding voltage	Shock rating of 5,000 g, the level produced when an accelerometer is dropped onto steel
Wiring an accelerometer backward with the negative supply voltage going to the positive terminal	Reverse-wiring protection

Operating accelerometers outside their specifications, such as above the maximum operating temperature, will cause degradation and eventual failure. Manufacturers cannot design protection for exceeding the operating specifications. It is important to match the accelerometer capabilities to the operating environment. Choose high-performance accelerometers to meet high temperatures and other extreme environments.

Manufacturing Processes

Besides exposing the accelerometer to temperatures beyond the accelerometer design, long-term failures are usually associated with circuit board connection faults (bad solder joints), circuit board and component failures, or contamination.

Circuit Board Connection Faults

Faulty connections of electrical components to the solder pads of a printed circuit board will cause an accelerometer to fail. This is no different than any other electronic item. "Cold" solder joints are a known failure mode for electronic circuits. They are formed when the solder fails to reach a proper melting temperature during manufacturing. Hybrid circuit boards are usually run through a wave soldering process or an oven. If the process is not adjusted correctly, the solder does not melt and run into the joints properly. Heat cycling over the life of the accelerometer causes the connection to develop high resistance by forming an oxidation layer. Therefore, it is important for manufacturers to properly set the heat levels in soldering operations and to use the right amount and type of solder to minimize the occurrence of faulty joints. Additionally, high-quality accelerometer manufacturers try to preclude any oxidation potential by filling the accelerometer with a chemically inert gas such as nitrogen that will not react with the solder.

The interface between the accelerometer and its mating connector can also be a source of connectivity problems. Many connectors that have been used for years have tin-plated contact surfaces. Tin in connectors will be subject to "fretting" and cause unreliable contacts[2]. One solution to this problem is to use gold-plated contact surfaces in instrumentation wiring. It has been considered a "best practice" in instrumentation to use gold-to-gold in connectors when low-level voltages must be transmitted through connectors. The gold-to-gold connection will aid in producing a total lower cost for accelerometer installations.

Circuit Board and Component Failures

Circuit board component failures will cause accelerometers to fail. Each component used in the circuit will be repeatedly stressed over its life by the voltages and temperatures imposed on it. The electron flow within the material will cause any impurities to become focused on that area of the part resulting in component failure. Using high-quality, screened parts will reduce these kinds of failures and produce a total lower cost for accelerometer installations.

Contamination

Contaminant ingress will cause accelerometers to fail. When contaminants cause a chemical reaction with circuit board components it may result in a change in resistance or capacitance. Semiconductors will lose their characteristics of amplification due to the entry of contaminants. The best defense against contamination is a true hermetic seal. Hermetic sealing can best be assured through helium leak testing (HLT). HLT is the industry standard for electronic circuit leak testing. It is the only way to accurately determine whether seals are truly hermetic. Guaranteeing hermeticity through HLT will result in an accelerometer with a total lower cost.

Poorly designed and protected accelerometers will not withstand the test of time. Mechanical parts must be able to tolerate the physical stresses of use and abuse. The electrical circuits must be properly protected against normal use and handling conditions.

The Role of ISO 9001

ISO 9001 is a part of a family of standards for companies to implement for certification of their processes and procedures. It establishes a method for companies to document their processes and then ensures that these processes are followed. It also addresses the controls over manufacturing contamination in the manufacturing process and component quality. ISO 9001 sets forth a pattern that companies can use to implement root cause analysis of system and equipment failures – but it does not ensure that rigorous root cause analysis is applied to process failures or, by itself, ensure that a manufacturer is applying "lessons learned" to their designs. While ISO 9001 ensures that companies can consistently manufacture items according to their processes and procedures, if those processes and procedures are never changed to reflect the lessons learned from failures, then there will be no improvement in the quality or the MTBF of accelerometers.

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[2] Contact Problems Due to Fretting and Their Solutions, Piet van Dijk & Frank van Meijl, AMP Journal of Technology Vol. 5 June 1996