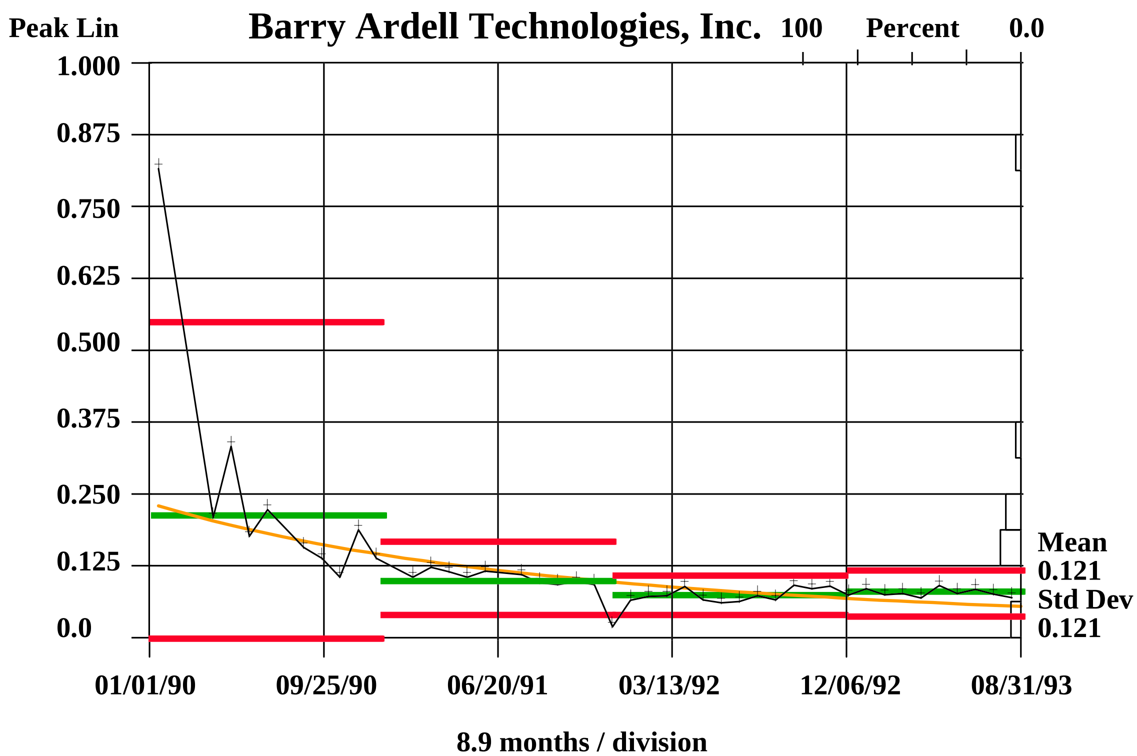
# Setting Vibration Alarm Specifications





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## Abstract

Vibration is a key characteristic of machinery condition. Vibration Monitoring Programs use this relationship to determine when a machine's condition is "Normal" or "Not Normal". Therefore, each point of vibration data requires an accurate alarm level.

How is the correct vibration alarm level determined and which type of alarm should you use?

- fixed alarms based on standards like ISO, NEMA, API or ANSI
- percentage change alarms
- trends
- narrow band alarms
- statistical by point, bearing, machine, direction or machine family

Let's look at the different alarm methods and levels to determine the best techniques for evaluating vibration monitoring data.


## Does Data Processing Affect You?

How many of your lives are affected by data processing? I made a reservation to arrive by plane. The airline reserved an aisle seat that wasn't behind a bulkhead. If that information had not been processed properly I would have been dissatisfied with the result. The airline's reservation system needs to "take the reservation" and "keep the reservation" that we have agreed to in order to be successful. If you purchased the airline ticket with a credit card you have also been touched by the airline's and credit card company's ability to process the data about your ticket purchase. If you checked in your bags you were at the mercy of the airline's baggage handling system.

So in spite of my objections, my quality of life is constantly affected by other people's ability to process data. The following quotation sums up the reality of data processing.

> **"The difference between world class and everyday -- is that average companies commit about 6,210 errors or defects per million parts or opportunities while industry leaders operate at about 3.4 errors per million chances. This is true whether the process is a welding operation at an auto assembly plant, a payroll processing step or a baggage handling procedure at an airport. – CEO Motorola Inc. in Ward's Auto World May 1993**

An error rate of 0.00621% must seem pretty good to the airline baggage crew, but as a customer this error rate means that I will loose a bag once per year. When the bag is lost it affects my ability to perform my job. This event adversely affects my customers and business. Therefore, I don't fly on airlines with an average baggage handling system.

Notice, I referred to the performance of the baggage handling system not the baggage handlers. To get consistently reproducible results a system or structure needs to be created to handle the flow of data. System performance can then be measured, evaluated and revised until it achieves the desired result.

Errors in vibration monitoring cause missed calls. There are actually two ways to miss a call. First, the maintenance system does not recognize a machine in need of repair. The machine subsequently fails in service and causes unplanned downtime and maintenance costs. This type of maintenance failure is obvious and is addressed by using machinery condition information to recognize incipient machinery problems. This information allows maintenance departments to plan and execute the required repair actions prior to failure.

The second type of error or missed call is much harder to identify. This error occurs when a machine that is not in need of repairs is removed from service and repaired. The costs associated with this problem include wasted: planning, parts, equipment and maintenance manhours. This problem may also extend the mill downtime required to complete all maintenance actions and require maintenance managers to prioritize repairs choosing between recommended maintenance actions. They perform this task without the benefit of knowing which maintenance problems are real and imaginary.

As the monitoring alarm sensitivity to machine failures is increased, the number of unwarranted machine repairs also increases. If the number of misidentified machine repairs are reduced the number of unidentified machine failures increases. **A conscience decision about the acceptable rates for both types of missed calls is required prior to setting the vibration point alarms.**

When I was in charge of a vibration program my manager initially set the in service machine failure rate low by setting the acceptable false alarm rate at 95%. As program manager I was responsible for 19,000 to 20,000 points of vibration data monthly. Each data point acquired was a new opportunity for the program to commit an error. If the vibration program's target error rate was set at 5% the condition of approximately 1000 data points would alarm falsely each month. This error rate would have overloaded the analysts and caused an increase in unwarranted repairs. The maintenance crews would have lost confidence in the analysts and the vibration program would have failed.

It is management's responsibility to develop a data processing system for the vibration analysts. This system needs to possess the capability to process data within the error rate determined by management.

During this talk we will discuss:

1. the nature of data
2. key characteristics of data
3. data distribution patterns
4. setting vibration point alarm levels

# The Nature of Data

**"It is important to understand what you CAN DO before you learn to measure how WELL you seem to have DONE it." Exploratory Data Analysis by J. W. Tukey**

The vast amount of machinery vibration data that is gathered by a monitoring program can be overwhelming. Our service requires us to extract meaningful information about machinery condition from this pile of raw data. We are going to use a tool called statistics to evaluate the quality of vibration data and the false alarm rates. You do not need to use statistical alarms for the statistical evaluation of the vibration data to be valid.

The Western Electric Statistical Quality Control Handbook defines a **process** as "any system of causes; any combination of conditions which work together to produce a given result." Any machine can be considered a process. A machine's operation results in useful work, heat, noise and vibration. Each process result can be considered a **key indicator** of the machine's condition.

A **population** is any data group containing all observations of a key indicator. All the real time vibration information from one data point would be an example of a population. Observing whole populations of data presents two problems: (1.) the excessive cost of continuously collecting and evaluating data and (2.) the large amount of data increases the number of opportunities for error.

A simpler monitoring system uses data **sampling** to predict the characteristics of the whole data population. As long as the samples remain representative of the population accurate predictions can be made.

You have little or no hope of understanding the large amounts of information contained in the raw data. A system that summarizes the raw data is needed. This system should be based on the different characteristics of the raw data.

The first characteristic, of raw data, is the **average** or **mean**. This number is generated by adding the numbers contained in the raw data and dividing by the total number of numbers. This concept should be familiar to you since most vibration data is averaged.

A second characteristic of raw data is **variance**. This is a measurement of the data's dispersion or spread. Variance describes the degree to which a group of numbers is scattered away from their average or mean. Variance is a good measure of dispersion, but the numerical value is not intuitive and therefore difficult to interpret.

A better measure of dispersion is derived by taking the square root of the variance. This third data characteristic is called a **standard deviation**. The units associated with a standard deviation are the same as the measurement units contained in the data. This makes the standard deviation easier to relate to the raw data and average.

A standard deviation possesses a couple of interesting properties. First, the percentage of numbers from any raw data within x standard deviations of the average is $100*(1-1/x^2)$. Therefore, at least 88.88% of the numbers in any raw database will be within 3 standard deviations of the mean.

The second property applies to raw data with a **normal distribution**. A normal distribution is produced when random numbers occur between limits. The dispersion of data is reduced by a normal distribution of data. The result is 99.74% of the numbers in a database with normal distribution are within 3 standard deviations of the average.

A fourth characteristic of the raw data is the **coefficient of variation**. This data property is attained by dividing a population's standard deviation by it's average. The coefficient of variation reveals when the dispersion of the raw data is large relative to the average.

Let's use these data characteristics and statistical tools to evaluate a process called "Coin Toss". A data population will be generated by flipping twenty coins twenty times each. Each toss may result in a "Head" or "Tail" outcome. The number of outcomes resulting in heads, for each coin, should be recorded in Table 1.

| Coin # | Individual Coins | Average 5 coins | Average 10 coins | Average 20 coins |
|---|---|---|---|---|
| 1 | | | | |
| 2 | | | | |
| 3 | | | | |
| 4 | | | | |
| 5 | | | | |
| 6 | | | | |
| 7 | | | | |
| 8 | | | | |
| 9 | | | | |
| 10 | | | | |
| 11 | | | | |
| 12 | | | | |
| 13 | | | | |
| 14 | | | | |
| 15 | | | | |
| 16 | | | | |
| 17 | | | | |
| 18 | | | | |
| 19 | | | | |
| 20 | | | | |

Table 1

The predicted results of an individual Coin Toss are shown graphically in Figure 1. The graph indicates that any number of heads between 0 and 20 is possible, but if the coins are fair 50% of the outcomes should be between 9 and 11. As the combined results of the 20 individuals tossing coins are tabulated the average should approach 10.

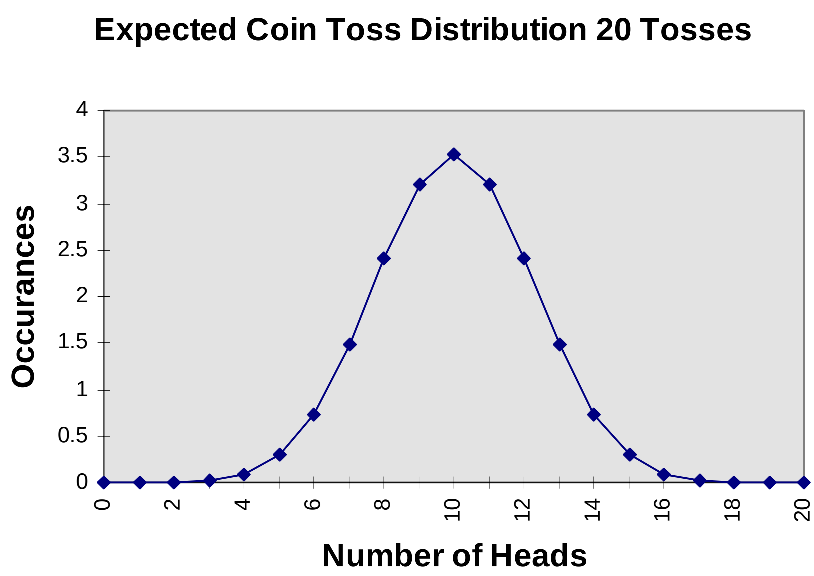


Figure 1

Let's proceed by marking the number of heads for each coin on the graph shown in Figure 2. Then calculate the average or mean number of heads for all 20 coins and mark it on the graph.

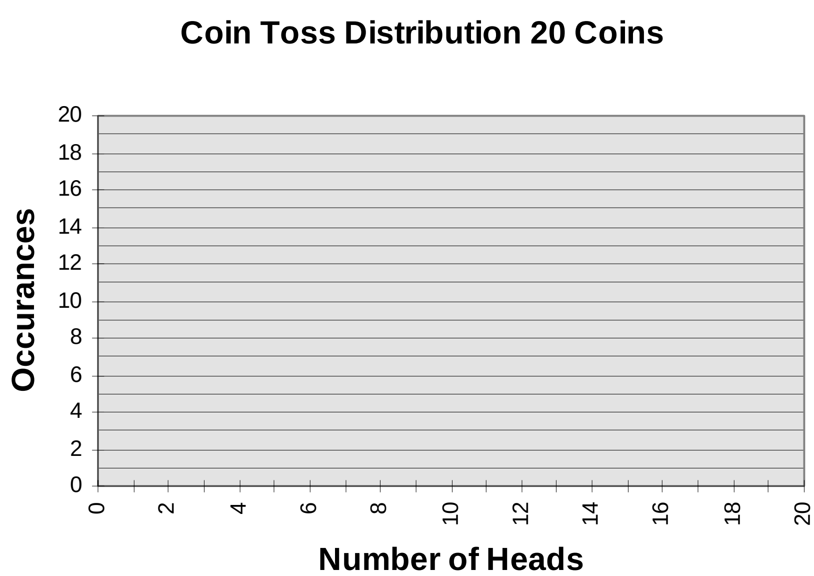


Figure 2

The standard deviation and coefficient of variation for this group of numbers are ____ and ____ respectively. Multiply the standard deviation by 3 and add it to the average to determine the UCL (Upper Control Limit) for this group of numbers. To obtain the LCL (Lower Control Limit) for this group of numbers, multiply the standard deviation by 3 and subtract it from the average. Enter the value for both control limits LCL _____ and UCL _____ and draw the limits on Figure 2.

Now I need to set alarm limits that will determine if the coin is fair. Probability shows that 99.74% of the samples generated using fair coins will fall between 4 and 16 inclusive. Only one try in 400 attempts will produce numbers outside that range. So I now have a simple test for fair coins with control limits. I have set my limits to discard one good coin out of 400 tests to ensure the fairness of the remaining coins.

How many people can make a living flipping coins? So the coin flip exercise was fun, but you make your living taking vibration readings. Well good news, statistics does not care what process is used to generate the data. Any type of data can be evaluated statistically.

Let’s review the application of overall vibration alarm levels as established by the International Standards Organization. Table 1 contains the alarm data from ISO Standard 2372. The machinery is classified by this Standard as follows:

- Class 1 Individual machine components integrally connected. I.e. motors < 15 kW
- Class 2 Medium sized machines. I.e. motors 15 kW to 75 kW
- Class 3 Large prime movers on heavy, rigid foundations
- Class 4 Large prime movers on relatively soft, light weight structures

| | ISO 2372 | | | |
|---|---|---|---|---|
| Vibration Severity Ranges | Class 1 | Class 2 | Class 3 | Class 4 |
| 0.01 IPS | | | | |
| 0.02 IPS | Good | | | |
| 0.03 IPS | | Good | | |
| 0.04 IPS | Satisfactory | | Good | |
| 0.07 IPS | | Satisfactory | | Good |
| 0.11 IPS | Unsatisfactory | | Satisfactory | |
| 0.18 IPS | | Unsatisfactory | | Satisfactory |
| 0.28 IPS | | | Unsatisfactory | |
| 0.44 IPS | Unacceptable | | | Unsatisfactory |
| 0.71 IPS | | Unacceptable | | |
| 1.10 IPS | | | Unacceptable | |
| 1.77 IPS | | | | Unacceptable |

Table 2

The Entek IRD “General Machinery Vibration Severity Chart” is shown in Figure 3. This Chart has been used by vibration analysts for the last 30 years to set vibration alarm levels. I have evaluated vibration databases that have the alarm level for every point on every machine set at 0.157 IPS.

ENTEK IRD

**GENERAL MACHINERY VIBRATION SEVERITY CHART**

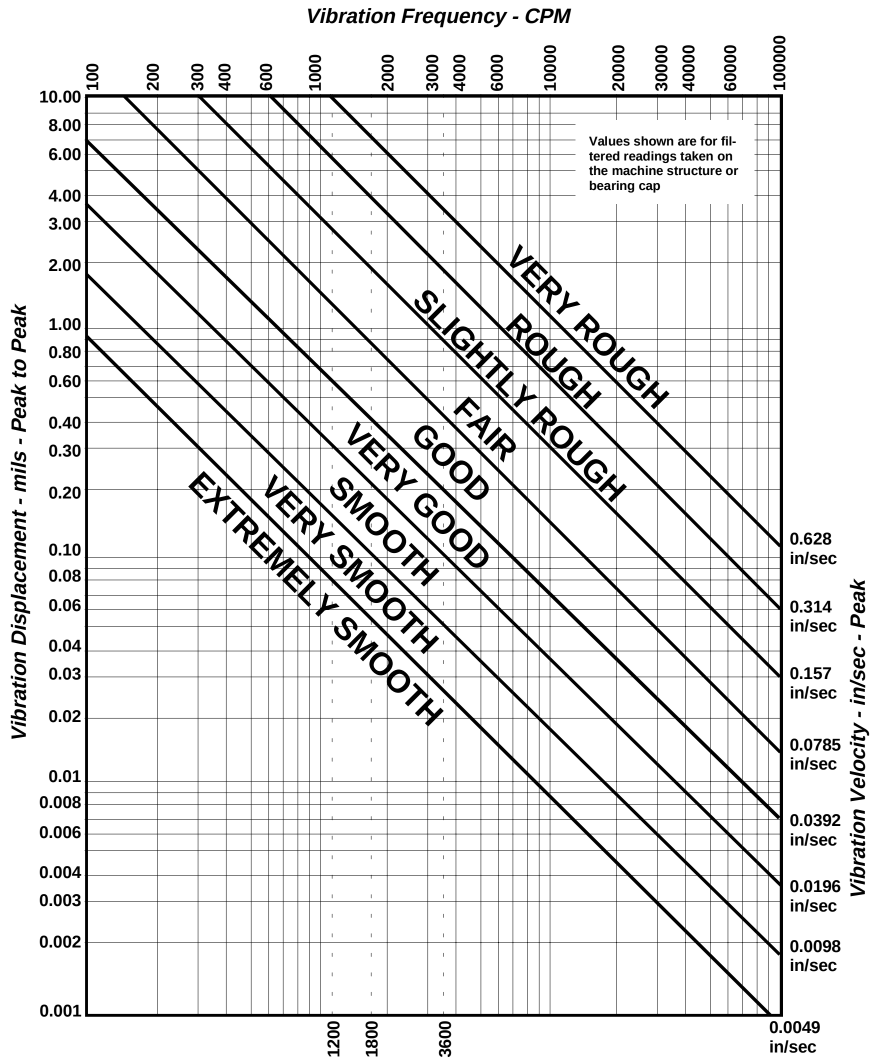


Figure 3

Another method for setting alarm levels is to monitor the percentage change in overall vibration and alarm on a 50% increase.

Finally, some analysts use alarms that are generated statistically. Analysts either swear by or swear at statistical alarms. Most analysts fail when trying to use statistical alarms, because they don’t understand the true nature of statistics.

Figure 4 contains 15 points of vibration data obtained from point H03. The average and overall vibration readings are shown in green and blue respectively.

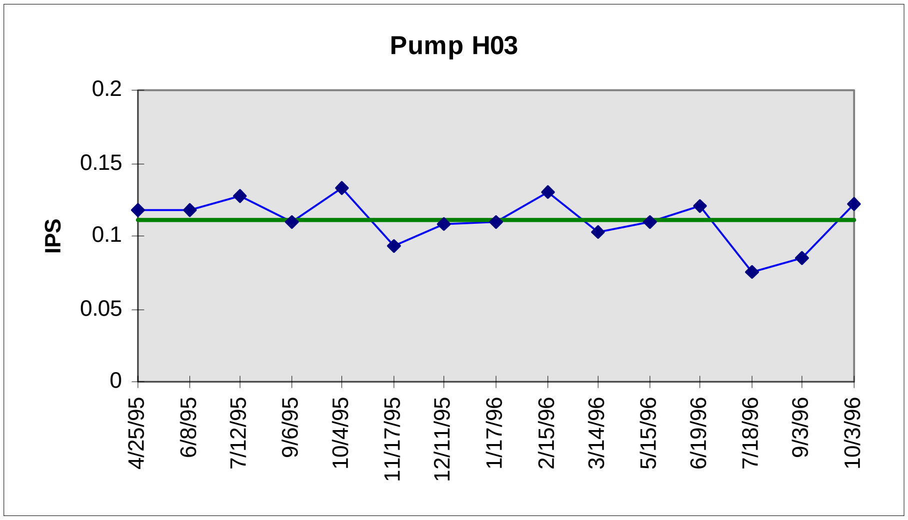


Figure 4

The mean of the data in Figure 4 is 0.1108 IPS. A standard deviation value of 0.0163 results in a coefficient of variation equal to 0.1471. I find that whenever **the coefficient of variation is below 0.33** the dispersion of the readings is acceptable. The pattern of the data points looks good to me, so I think alarm values can be set. The question is where do I set the alarms if I am willing to tolerate a 1% missed call rate?

Before we set alarm limits, we should develop tests that generate values indicating the data quality. Then the computer can recognize out of specification data and screen the vibration information for us. Tests 1 through 4 were published in the Western Electric Quality Control Handbook in 1956. They are able to identify data "Instability". The Handbook referred to the Instability tests as the most important unnaturalness tests.

There are three basic characteristics of a natural or random pattern: (1.) most points occur near the centerline (average), (2.) a few points occur near the control limits and (3.) only rare points exceed the +/- 3 Sigma limits. The following tests look for these characteristics to determine the randomness of the data.

Figure 5 contains the same information shown in Figure 4. Red limit lines have been added at the mean +/- 3 Sigma. Unnaturalness Test #1 looks for a single point outside the +/- 3 Sigma Limits. The population of data points in Figure 4 passes this test since no data points occur outside the 3 Sigma Limits.

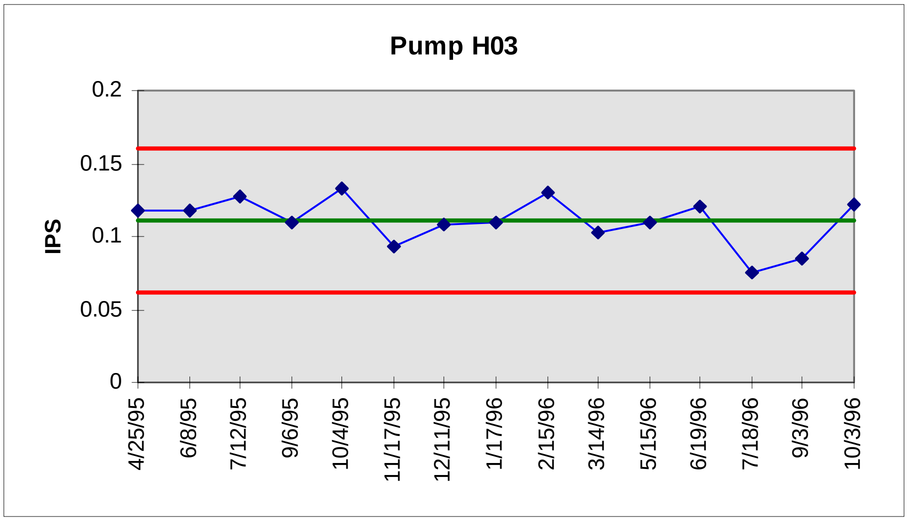


Figure 5

Figure 6 contains the raw vibration data from Figure 4. Red limit lines have been added at the mean +/- 2 Sigma. The average and data values are shown in green and blue respectively.

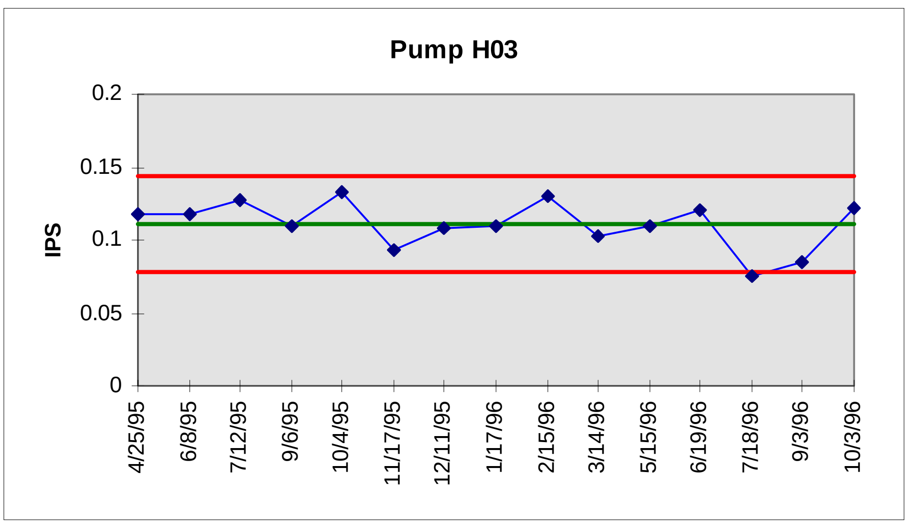


Figure 6

Test #2 from the Western Electric Quality Control Handbook identifies when two out of three successive data points occur outside the +/- 2 Sigma Limits. I only found one data point outside the +/- 2 Sigma Limits (7/18/96) in Figure 6. Therefore, the data passes the second test.

The vibration data from Figure 4 is shown again in Figure 7. Red limit lines have been added at the mean +/- 1 Sigma. The average and data values are shown in green and blue respectively.

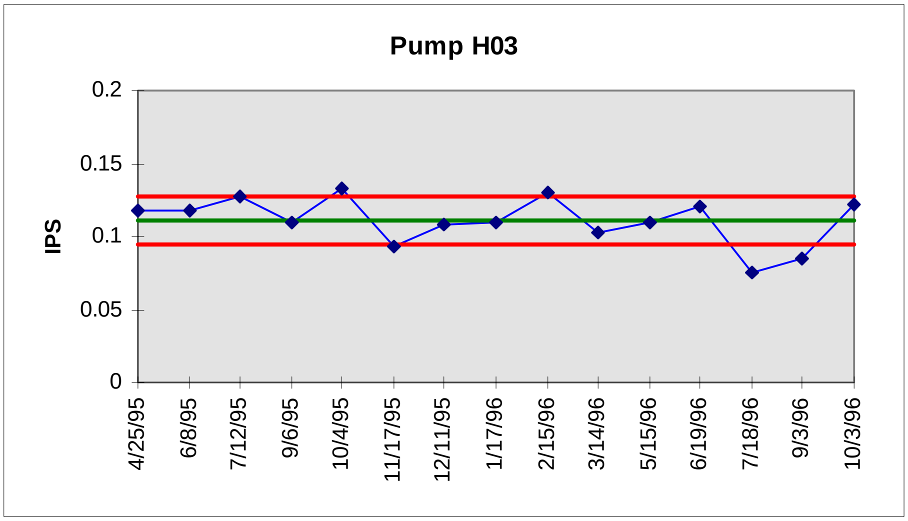


Figure 7

During Test 3 the vibration data is inspected for the presence of four out of five successive points outside 1 Sigma. The data shown in Figure 7 easily passes this test.

A final Instability Test, that we will refer to as Test #4, checks for the presence of eight successive points on one side of the mean. The data shown in Figure 7 has a maximum of three consecutive points that occur on one side of the mean. This test also indicates that the data is random.

The probability of failing the four "Instability" tests is shown on Table 3. The "Total Probability of Failure" is calculated by adding the probabilities of failure for all tests. Only 1.88% of the data evaluated will actually fail these tests. So the vibration data shown in Figures 3, 4, 5 and 6 is part of the 98.12% that passes this test.

| Test # | Probability of Failure |
|---|---|
| 1. | 0.26 % |
| 2. | 0.30 % |
| 3. | 0.54 % |
| 4. | 0.78 % |
| Total Probability of Failure | 1.88 % |

Table 3

Figure 8 contains a distribution curve for the vibration data contained in Figures 4 through 7. Notice, the shape of the curve approximates the normal distribution of data we observed during the coin tossing exercises. The normal shape of this curve confirms the results of the Instability Tests. The shape of this curve can be expressed as a number called the coefficient of variation. Remember the coefficient of variation for this data was 0.1471.

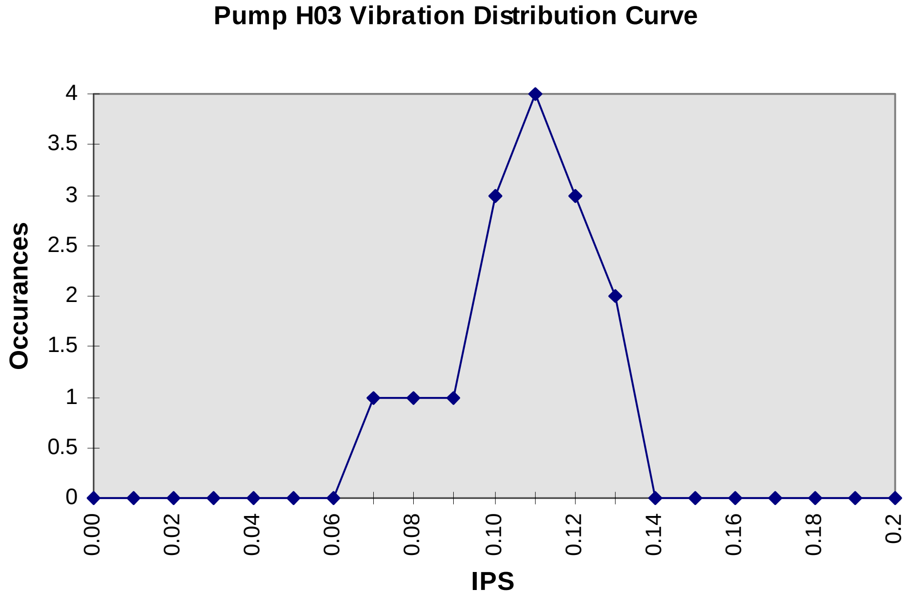


Figure 8

Another type of common unnaturalness test checks for the presence of trends in the data. When a trend is present in the data it tends to create a flat topped distribution and a wider disbursement of data points. To fail this test the data must either increase or decrease over five consecutive data points. The probability of failing this test based on five points is 3.1%. Notice, that this failure is three times higher than Tests 1 through 4 combined. If the number of points required for failure is increased to 6 the failure rate is decreased to 1.56%. I prefer to base the trend test on 7 points that reduces the probability of failure or false alarm rate to an acceptable 0.76%.

The tests have failed to detect any of the following unnatural patterns: cycles, trends, freaks, mixtures, grouping, sudden shifts in level, gradual changes in level, instability, stratification, interactions and systemic variations. Therefore alarm limits can be set.

Pump H03 would be classified as a Class 2 machine by ISO. The alarm according to the ISO Standard would be 0.18 IPS. The alarm limit according to the Entek IRD "General Machinery Vibration Severity Chart" should be 0.157 IPS. If I use percentage change alarms, set at 50%, the upper alarm and lower alarms would be 0.166 IPS and 0.055 IPS. The alarm limits for Pump H03 can also be set at +/- 3 Sigma. The values of the Upper and Lower Control Limits are 0.1597 IPS and 0.0619.

Notice, that the same general alarm limits are being generated by many different techniques. I prefer to have protection if the vibration level increases or decreases, so I would set an **upper alarm at 0.16 IPS and a lower alarm at 0.06 IPS**.

Figure 9 contains 20 points of vibration data obtained from Centrifugal Pump H03. The average and standard deviation of this group of vibration readings are 0.0651 IPS and 0.04787. The coefficient of variation is 0.735. This is well above my 0.33 limit and indicates **excessive dispersion** in this group of vibration readings. This pump was not repaired during the time period shown.

Compare the pattern of overall vibration shown for Pump H03 (Figure 7) and Centrifugal Pump H03 (Figure 9). There are some visual indications that the data from Centrifugal Pump H03 is not random or reliable. How would you determine the alarm values for this data and where would you set the alarm values?

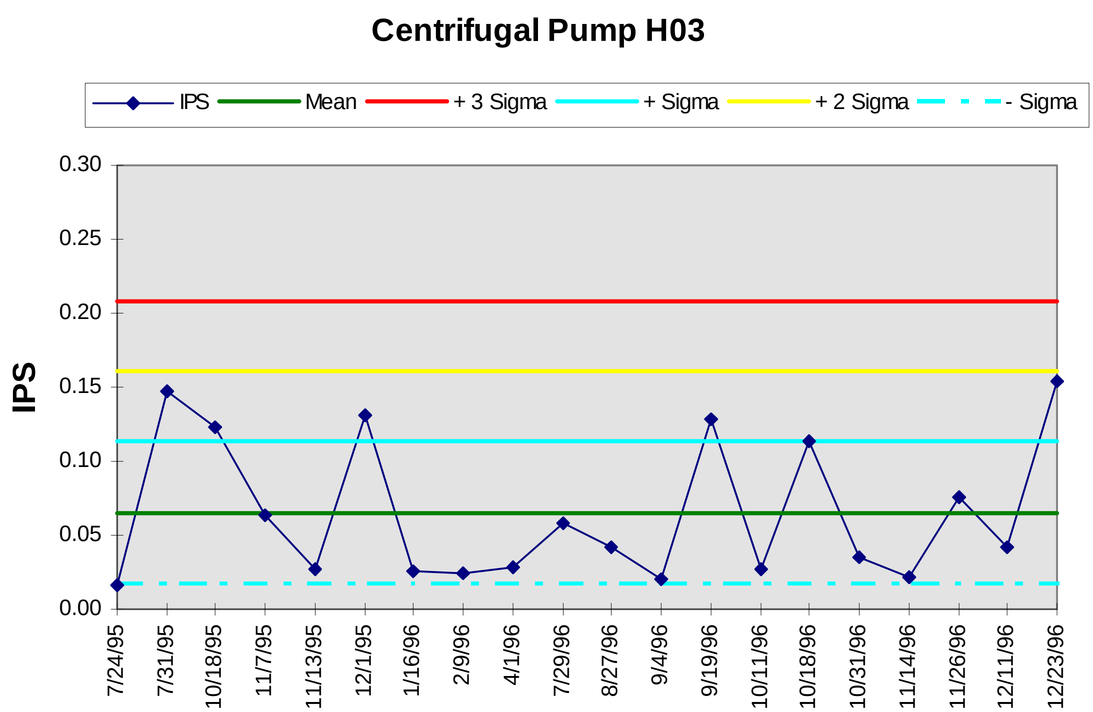


Figure 9

The five statistical tests that we ran earlier can be applied to the vibration data shown in Figure 9. The results of this test would be:

- Test 1 would pass because no points exceed the 3 sigma limit.
- Test 2 would pass since no points exceed the 2 sigma limit.
- Test 3 passes because the condition where four out of five successive points are outside the +/- sigma limits does not exist.
- Eight consecutive points cannot be found on one side of the mean so the data passes Test 4.
- The data passes Test 5 even if five consecutive points are used to check for a trend.

So far the data from the Centrifugal Pump H03 has passed five statistical checks for randomness. Can we set alarm limits for this data and to what vibration levels would the alarms be set?

If I wanted to set fixed alarm values I could use the ISO alarm limit for Class 2 machines 0.18 IPS, but this is 300% of the average vibration level. My experience tells me that this alarm value is too high. According to the guidelines shown on the Entek IRD "General Machinery Vibration Severity Chart" the alarm should be set at 0.157 IPS. This alarm value is 250% of the average vibration reading. Experience tells me that this alarm value is still too high.

If I use Percentage Change Alarms I would normally set the upper alarm to detect a 100% change in vibration level. The low side alarm would be set to detect a 50% change in vibration. This alarm setup will generate alarms on 60% of the data points. The excessive number of alarms makes this alarm setup unacceptable.

Finally, statistical alarms may give us better alarm values. The average and standard deviation values for this data are 0.0651 IPS and 0.04787 IPS. If the alarms are set at +/- 3 sigma the lower alarm is below 0 IPS and the upper alarm is 0.2087 IPS. The lower alarm is nonexistent and the upper alarm value is over 300% of the average vibration level. Neither of these values seems correct. Alarms set at +/- 2 sigma would set the lower alarm below 0 IPS and the upper alarm at 0.1608 IPS. The lower alarm is nonexistent and the upper alarm is approximately 250% of the average vibration level. These values still seem excessive. If I set the alarms at +/- sigma the lower alarm would occur at 0.172 IPS and the upper alarm setting would be 0.113 IPS. These settings will cause alarms to be generated 30% of the time. This will result in excessive maintenance costs and a loss of confidence in the analyst's repair recommendations.

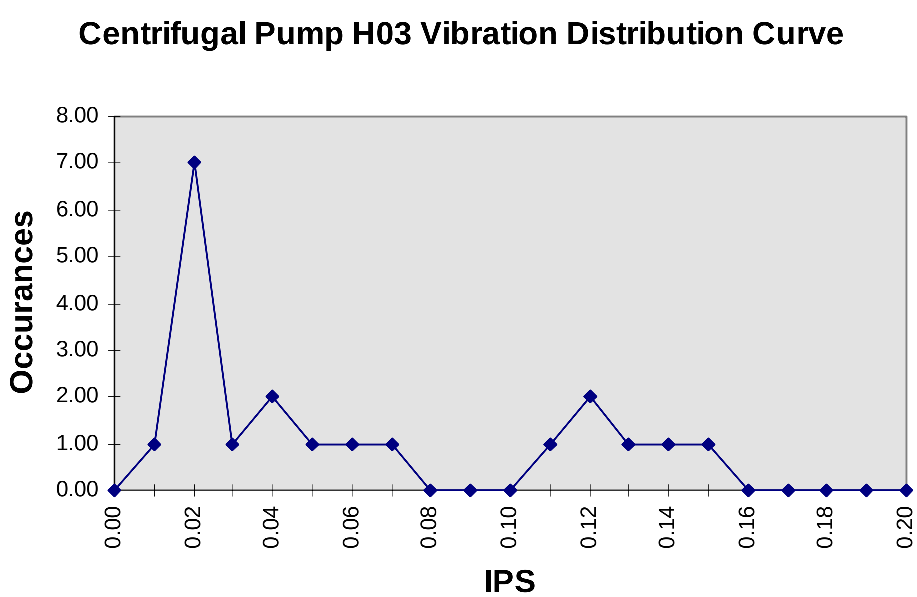


Figure 10

I am uncomfortable setting any type of alarms for this data. My reasons for not wanting to set alarm values should be defined. If I say alarms can't be set because "The data just doesn't look right" I will have to visually review all future data. I need a reason for not setting alarms that can be quantified so the computer can sort this data for me.

Figure 10 contains a distribution curve for the vibration data on Centrifugal Pump H03. This curve is dissimilar to the coin toss and Pump H03 distribution curves shown in Figures 1 and 8. When information lacks a normal distribution alarm values cannot be set. This is true for all methods of setting alarm values. The alarm method is not to blame for the poor alarm results. A lack of normal data distribution is the real problem.

The "Coefficient of Variation" that I have been referring to is a measurement of the dispersion or shape of the data distribution. I have found that a coefficient less than 0.33 indicates a data condition that can accept alarms. When the coefficient exceeds 0.33 accurate alarm values cannot be set.

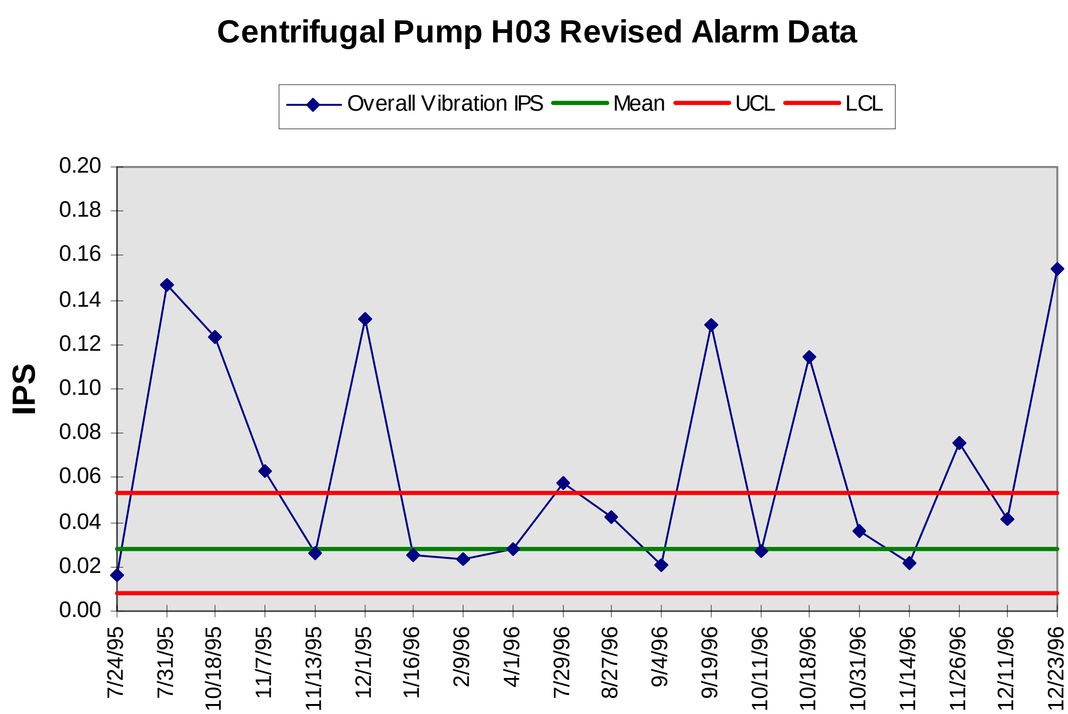


Figure 11

The vibration data from Centrifugal Pump H03 has been displayed in Figure 11 with new UCL, LCL and mean values displayed. The points that are outside the alarm limits are called freaks. Freak measurements are the result of special causes. The freak measurements may be the result of changes in machine loading or speed. They may also result from variation induced by the measurement process.

Whenever a chart contains freak readings the cause must be temporary. First, the analyst needs to identify the source of the change in vibration. Second, the analyst must determine if the temporary increase or decrease in vibration is normal to machinery operation. Finally, the analyst must make the repairs or procedural changes required to eliminate. This may involve taking vibration readings within a specific range of machine speeds or loads. Since a process has no measurable capability unless it is in statistical control, if the freak measurements cannot be eliminated the vibration data is not worth collecting..

The special cause of variation in vibration data from Centrifugal Pump H03 involved changes in pump loading. The solution to this problem involved installing a discharge pressure gauge and setting up a data collection procedure that avoided data acquisition when flow was restricted. The results of this effort are shown in Figure 12. Notice the change in distribution for data taken in 1997. Within two sets of readings the vibration data has stabilized and reflects the true condition of the pump. Let me stress that this pump did not require repairs. The data collection procedures needed to be changed.

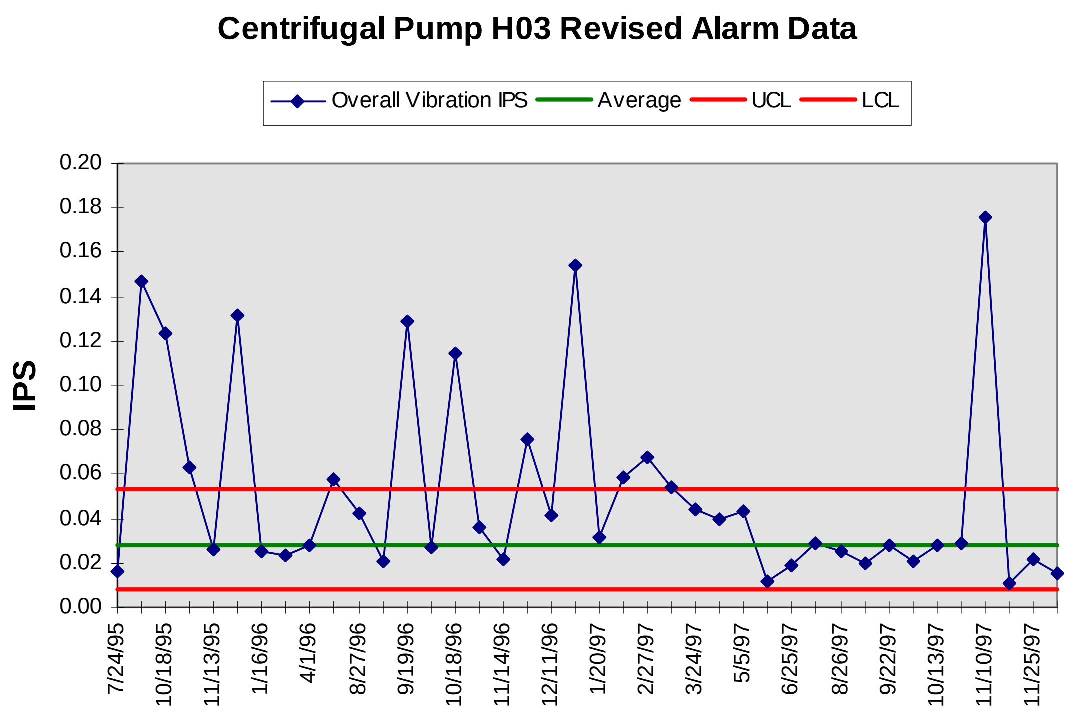


Figure 12

The only freak reading after March 1997 occurred on 11/10/97. The initial reaction to this alarm was to take an additional reading on 11/17/97. The new vibration data was within the alarm limits allowing the analyst to determine that the previous data was a statistical freak. The most likely cause for the freak reading on 11/10/97 was an analyst collecting data when the head pressure was excessive.

Another data pattern that appears often is the "sudden shift in level". The data in Figure 13 contains a sudden shift in vibration level. The green and red lines represent the average (0.0665 IPS) and +3 sigma limit (0.1349 IPS) respectively. The coefficient of variation is 0.3422. Where would you set the alarm limits?

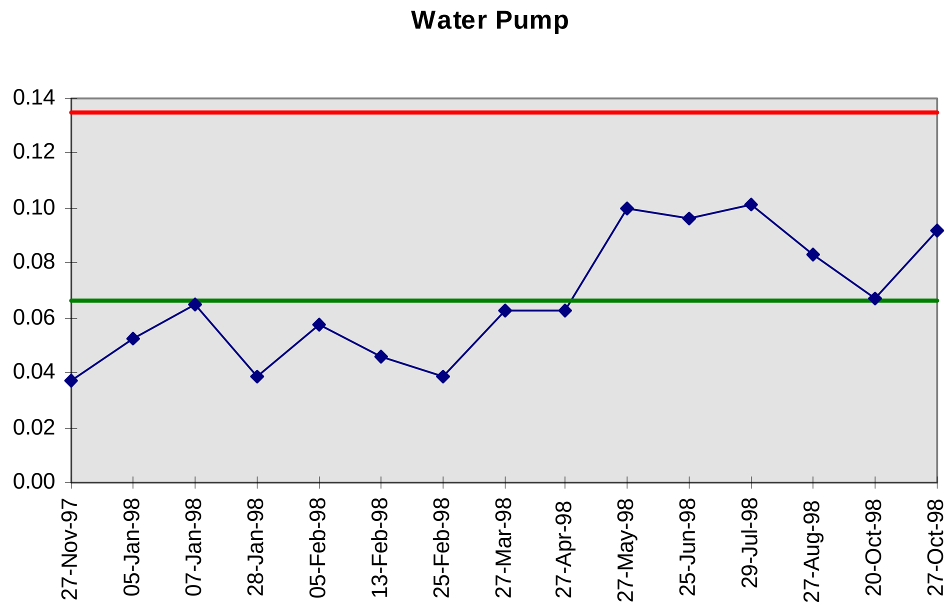


Figure 13

A shift in vibration level started in March 1998, but is not apparent to the analyst until May 1998. Unlike freak readings sudden shifts in level remain until the source of additional vibration is removed. In retrospect the source of this increase in vibration appears in all readings taken after March 1998.

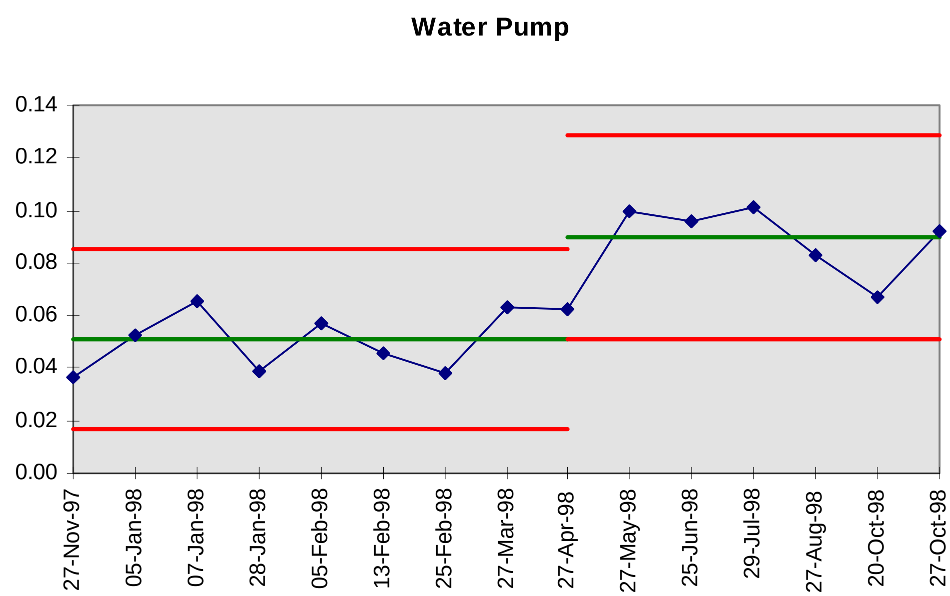


Figure 14

The same basic vibration information is displayed in Figures 13 and 14. The presence of two distinct data populations has been accentuated by displaying both averages (green lines) and the four control limits of the original and shifted vibration data populations.

Statistical alarms should be set during the machinery baselines. Sudden shifts in vibration level are the best reason for not updating statistical alarms monthly. The average vibration level in Figure 14 changes from 0.05 IPS to 0.09 IPS. This 80% increase will remain undetected if the statistical limits are changed monthly.

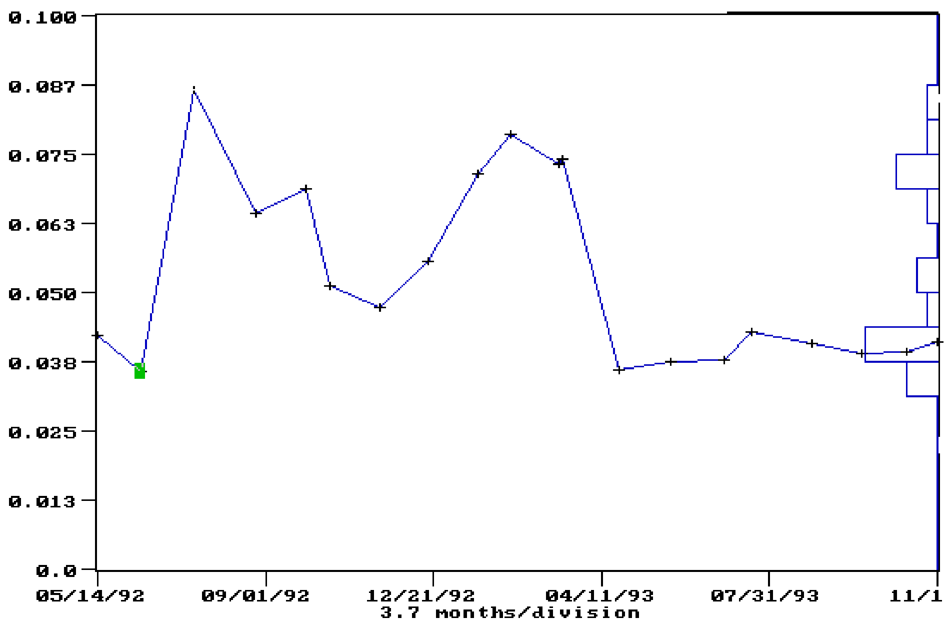


Figure 15

Figure 15 contains the data from a gearbox on a 10,000 hp mill drive. The ISO Standard suggests 0.18 IPS. The Entek IRD "General Machinery Vibration Severity Chart" suggests 0.157 IPS. Neither of these standards would detect a problem in this vibration data. Percentage change alarms set to detect an increase exceeding 100% or a decrease exceeding 50% would have alarmed at data points 3 and 13. Finally, statistical alarms based on this entire data population would not have alarmed. The maximum overall vibration reading is less than 0.09 IPS. Where would you set the alarm levels?

Notice the data distribution shown on the right vertical axis of this plot. Is this a normal distribution like the coin toss or an unnatural population of data. The data seems to be bimodal or has the presence of two systems of vibration. The first vibration system is a composite of all the normal sources of gearbox vibration. The second vibration system is the source of additional vibration that started at data point 3 and continued to be present until data point 13.

Notice the increase in vibration variation that starts at data point 3 and continues until point 13. The historical data from this machine indicates that a spalled bearing was removed between data points 12 and 13. After point 13 the data becomes consistent and returns to the level of vibration seen before point 2. When a special cause of vibration is eliminated from the machine the vibration should return to baseline level. The spalled bearing was the special cause responsible for the elevated overall vibration levels. This demonstrates how vibration data reacts when the special cause of vibration is taken away.

In Figure 16 the UCL, Mean and LCL have been marked for the vibration data collected after point 12. The alarm values form a tight alarm window around the data. The readings taken with a spalled bearing are above the Upper Control Limit and readings taken without the spalled bearing are within the limits.

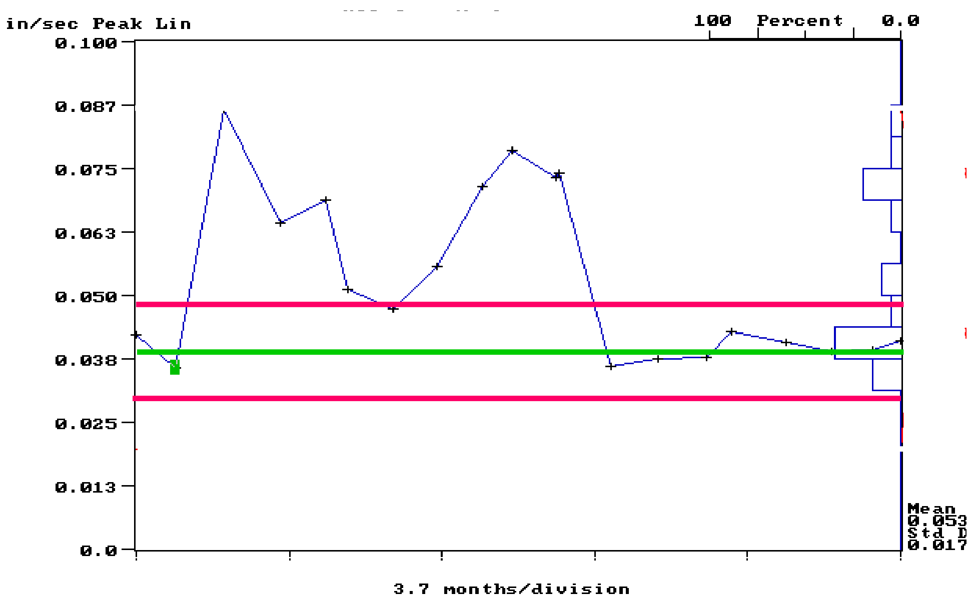


Figure 16

**There is no true value of anything. There is, instead, a figure that is produced by application of a master or ideal method of counting or of measurement." W. Edwards Deming**

I have presented information on data validation tests used in statistics. If the historical vibration data does not pass these tests it is unusable for machinery condition decisions. In order to set legitimate baseline vibration alarms the historical data must:

1. be without special causes of vibration.
2. pass the four tests for randomness.
3. pass a test for trends.
4. exhibit a normal distribution.
5. have a coefficient of variation less than 0.33.

Analysts searching for a universal vibration alarm limit will be disappointed. The comparative vibration data that is processed should be evaluated with statistical tests to determine the current data quality. Afterall, there are only two times when a machine down. When you are expecting a failure and when you are not expecting a failure.