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**High-Vibration Detection
Using Motor Current
Signature Analysis**

K. N. Castleberry

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Instrumentation and Controls Division

**HIGH-VIBRATION DETECTION USING MOTOR CURRENT SIGNATURE
ANALYSIS**

K. N. Castleberry

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OAK RIDGE NATIONAL LABORATORY
Oak Ridge, Tennessee 37831-6285
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ABSTRACT

Motor current signature analysis (CSA) has been used for several years as a diagnostic tool for electrical problems in ac induction motors. Personnel at Oak Ridge National Laboratory have found that CSA can also provide information about system vibrations and imbalances similar to the information provided by an accelerometer. As a result, CSA techniques for monitoring the status of the equipment, such as pumps and compressors, driven by induction motors have been developed and used in dedicated monitoring systems. In this work, researchers have found that CSA responds proportionately to imbalances in rotating equipment and can be used to detect the high-vibration conditions that can result. This report describes how vibration monitoring with CSA can be implemented and presents test data to support that use.

1. INTRODUCTION

During the past several years, numerous technical papers and journal articles have discussed the ability of motor current signature analysis (CSA) to detect electrical problems in both single-phase and multiphase induction motors. Personnel in the Instrumentation and Controls Division of Oak Ridge National Laboratory (ORNL) have followed these developments closely while also developing additional CSA techniques for identifying problems and abnormal operating conditions in motor-driven equipment, such as pumps and compressors. In this work, CSA has been shown to be useful in the diagnosis of many conditions not normally thought to be observable by examination of the motor current, and many load-related problems have actually been found to be more easily detected with CSA than with any other single-sensor means.

Part of the ORNL work has involved studies of motors and compressors used in the United States Enrichment Corporation's (USEC's) processing facilities located at Portsmouth, Ohio, and Paducah, Kentucky. These plants employ cascades of many hundreds of gas-compressor stages driven by motors ranging in size from 100 to 3300 hp to enrich uranium in the form of uranium hexafluoride. In the monitoring of such equipment, CSA has demonstrated the ability to provide information that not only includes detection of motor problems and compressor-aerodynamic instabilities but also diagnosis of certain coupling misalignments.¹

During 1995, monitoring systems demonstrating the application of automated CSA were installed on 80 compressor stages at each of the USEC gaseous diffusion plants (GDPs).² These systems, known as Unit Monitors, had been designed to assist process operators in controlling the GDP cascade by providing operational information that had not been previously available from installed instrumentation. Since their installation, the system's software has been upgraded several times to improve detection capabilities and to add new functions. In addition to stage-by-stage status monitoring, the systems record and archive hourly stage status and daily event information that can be used in after-the-fact examination of an equipment failure. Particular interest has been shown in the potential of these systems to also provide an inexpensive method for detecting high-vibration conditions in the monitored stages.

¹ S. F. Smith and K. N. Castleberry, "Advanced Techniques in Current Signature Analysis," pp. 63-75 in *Proceedings of the 46th Meeting of the Mechanical Failures Prevention Group, Virginia Beach, VA, April 7-9, 1992*.

² K. N. Castleberry, *Distributed Monitoring System for Electric-Motor-Driven Compressors*, ORNL/TM-13127, Oak Ridge National Laboratory, January 1996.

2. GDP VIBRATION MONITORING

In the late 1970s, vibration monitoring systems were installed at each of the GDPs covering essentially all of the axial-flow compressors. Within a few years after installation, a large percentage of the installed accelerometers had failed, and many were not replaced because of a combination of high cost and worker safety concerns. In the place of many of the failed accelerometers, the use of geophones became common at the Paducah Gaseous Diffusion Plant because of lower cost and longer operating life. Geophones, however, were not used at the Portsmouth Gaseous Diffusion Plant (PORTS) because of concerns about their lack of sensitivity at low frequencies in addition to their cost. Personnel at both plants have recently been concerned that in the near future the U. S. Nuclear Regulatory Commission may require dedicated vibration monitoring on all active process stages in the GDPs. As a result, a program has been underway to gradually restore the monitoring systems to coverage of all cascade compressors. The cost of restoration and maintenance of the existing vibration monitoring systems is high, so personnel at both plants have been especially interested in the possibility of using CSA as a possible alternative to using dedicated accelerometers or geophones. This interest stems from the fact that a CSA system can be installed for less than half the cost of an accelerometer-based system and subsequently requires very little maintenance.

There is another point of concern at the GDPs even with fully restored vibration monitoring. The existing systems employ a single compressor-mounted accelerometer or geophone for each monitored stage. This configuration provides good sensitivity to compressor vibration, but the sensitivity to drive-motor vibration is low. As a result, a stage-motor vibration can reach a dangerous level before it is detected by the present system. When used to monitor vibration, CSA does not detect vibration directly at any physical point but instead is sensitive to the torque variations occurring in both the motor and the driven load. Many of these torque variations result from the same equipment imbalances that cause vibration, so CSA can actually provide a composite vibration picture of an entire drive train.

With all of the research that has gone into developing uses of CSA, no one has until now attempted to document the fact that CSA can provide a dependable means for detecting and alarming high-vibration conditions. Part of the recent work by ORNL for the USEC has been devoted to the acquisition and analysis of data that will show that such monitoring is not only possible but practical.

3. EARLY OBSERVATIONS

The link between equipment vibration and frequency components in the drive motor current was noted several years ago in laboratory experiments. In that original investigation of the use of CSA for machine analysis, a correlation was established between standard accelerometer-derived vibration information and data obtained by analyzing the motor current driving a typical small-capacity vacuum pump. Acquisition of the pump electrical input was accomplished with an ordinary current probe such as those available as accessories for a standard multimeter. The probe signal was amplified and fed to an amplitude-demodulator circuit, which extracted the load information from the 60-Hz carrier as if it were a radio carrier. The resulting motor-load signals along with the signal from an accelerometer mounted on the pump were subsequently analyzed with a spectrum analyzer. The spectra from the accelerometer and current probe are compared in the plots of Fig. 3.1. In each plot, the pump (P), motor (M), belt (B), and the motor slip-related (S) peaks and their respective harmonics are identified. Note that the motor current signal shown is not yet demodulated and still includes the large 60-Hz line frequency. Although there is a frequency range difference between the AM-demodulated current-probe signal (Fig. 3.2) and the accelerometer plot (Fig. 3.1), they compare very well up to a frequency of about 30 Hz. The attenuation of frequencies above 30 Hz in the AM spectra is due to postdetection filtering used to remove potential high-frequency artifacts caused by signal aliasing in the demodulation process.

Fig. 3.1. Vacuum pump vibration versus motor current spectra.

From these data, it can be seen that the motor current responds to load variations that are directly related to the mechanical vibrations in the motor and pump. Examination of this and other data subsequently led to the conclusion that the amplitude of modulation components in the motor current typically occurs in proportion to the intensity of the related vibration. In the case of the motor speed or running speed (RS) component, there is not only a measure of the rotational speed of the motor but also an indication of how smoothly the rotation occurs.

Fig. 3.2. Vacuum pump AM-demodulated motor current spectrum.

4. VIBRATION FREQUENCY

The frequency content of the vibration from any piece of equipment is usually unique to that particular equipment type. GDP compressor vibration, for example, is composed of a collage of vibrations from several sources that include gas-flow noise, blade resonances, compressor-housing and piping vibrations, rotor imbalance, and floor vibration. Normally, the amplitudes of most of these vibrations are dependent on the gas load or power level of the stage with some additional effect from adjacent equipment. Stage-motor vibration is a little less complex and is usually only a combination of floor vibration, rotor imbalance, and alignment. Improper motor, compressor, and coupling alignment, of course, affects the vibration of the motor and the compressor. Of the sources mentioned, only rotor imbalance or improper alignment have the potential to cause dangerously high vibrations. As a result, the main frequency involved in any high-vibration situation occurs at the RS of the equipment. For 000-size, GDP-stage equipment, the RS vibration occurs at or just below 20 Hz.

When vibration measurements are made, the frequency bandwidth of the measurement is typically limited to some predetermined range. The vibration measurement is then a composite reading of all vibrations that occur in the selected frequency band. For the measurement of GDP stage vibrations, a 200-Hz bandwidth is typically used for the composite reading, although the main contributor to a high-vibration condition is always the RS frequency. Since the effect of RS vibration naturally appears as an RS component in the related motor current, this report will compare the magnitudes of that frequency in both the vibration and the motor-current spectra. By ignoring the contributions from other sources, the sensitivity to equipment imbalance or misalignment is increased.

To demonstrate the effect of RS vibration on the total vibration, Fig. 4.1 shows the size of the RS component compared to the contribution of all other miscellaneous vibration frequencies for 19 stage motors measured in June of 1996. From the plot, it can be seen that the percentage of the miscellaneous components in the total vibration is only significant at very low vibration levels. Figure 4.2 shows the same comparison for the stage compressors. As expected, the miscellaneous components, such as gas-flow noise, contribute a larger percentage to the total, but as vibration velocities increase above 0.1 in./s, the RS portion always dominates.

Fig. 4.1. Comparison of component contributions to total motor vibration.

Fig. 4.2. Comparison of component contributions to total compressor vibration.

5. SINGLE-PHASE MOTOR TESTS

In order to provide additional evidence that the RS component in a motor current actually responds to the amount of imbalance and therefore vibration in a rotating system, a series of laboratory tests was conducted. The tests employed two 1/20-hp, 110-Vac single-phase motors mounted on rubber supports coupled with a flexible metal coupling to a 110-Vdc. Power was applied to one motor, and the other was used as a mechanical load. Vibration measurements were obtained with a vertically mounted accelerometer that was magnetically attached to the load bearing of the drive motor, and the motor current was sampled, as usual, with a standard current probe. A CSI Model 2110 Machinery Analyzer was used to process the accelerometer signal and provide vibration velocity readings directly in inches per second. The motor current signal was sampled and analyzed with hardware and software similar to that used in the installed Unit Monitors. Since the size of the RS component also varies in proportion to the amplitude of the motor current, it was normalized by dividing by the amplitude of the 60-Hz component to remove this effect. The resulting measure of the RS component was in the form of a modulation percentage.

After the motors were set up, baseline measurements were made, and then the imbalance was increased by adding weight to the coupling. This process was repeated several times, gradually increasing the vibration level in each step. As the test progressed, it soon became evident that several factors were adversely affecting the acquired data. Because of less than perfect alignment between the motors, the stiffness of the coupling was contributing a significant torsional load in relation to the power and mass of the motors. This torsional load appeared as an RS modulation, just like an imbalance. Then when weight was added to the coupling to increase the imbalance, it could, depending on the angular location of the weight, counteract the effect of the coupling and initially reduce the RS component even though the vibration level increased. This effect was evident only at low vibration levels and seemed to have only a limited impact on readings taken at higher levels, but to eliminate the complication, the second motor was decoupled.

With the second motor removed, it was then determined that regular amplitude variations were occurring in the vibration signal as a result of motor and table resonances. This was really only a problem because the vibration and motor current data could not be acquired at exactly the same time because of differences in required sampling periods. To overcome this, an averaging approach was adopted where several readings from the vibration and the CSA signals were obtained and averaged before comparisons were made.

The data resulting from the drive motor and attached coupling are shown in Table 5.1. Since both the measured vibration level and the resulting CSA-RS modulation varied over time, five readings for each parameter were taken at each of the four vibration levels and presented as levels one to four. The average of each set of readings is presented in Table 5.2. The plot of the data (Fig. 5.1) shows a clear dependence of the RS amplitude on the vibration level although insufficient data were taken to determine the linear or nonlinear nature of the relationship. Most of the nonlinearity shown in the plot may have been eliminated by acquiring more data points to improve the average at each vibration level.

Besides demonstrating the presented relationship, two important observations were made during this series. The first was that the vibration and RS-modulation dependence was not very predictable at low vibration levels because of interactions between system members. The second was that system resonances in both rotating and nonrotating members apparently caused variations

variations over time in both the vibration levels and the RS-modulation amplitude. These phenomena would become even more evident as data from operating GDP stage equipment were analyzed.

Table 5.1. Motor vibration versus RS modulation

Level	Vibration velocity (in./s)					CSA-RS modulation (%)				
1	0.086	0.096	0.088	0.09	0.081	0.044	0.048	0.05	0.043	0.045
2	0.237	0.225	0.313	0.278	0.27	0.078	0.065	0.07	0.073	0.07
3	0.623	0.497	0.593	0.65	0.515	0.085	0.086	0.097	0.087	0.09
4	0.854	0.679	0.838	0.649	0.75	0.096	0.1	0.123	0.109	0.105

Table 5.2. Average motor vibration versus average RS modulation

Level	Vibration average	RS average
1	0.0882	0.046
2	0.2646	0.0712
3	0.5756	0.089
4	0.754	0.1066

Fig. 5.1. Single-phase motor vibration versus RS modulation.

6. GDP STAGE DATA

The project to develop a CSA-based monitoring system for 000-size GDP stage equipment was started in August of 1994. One of the goals of the project was to demonstrate the use of CSA for monitoring stage vibration levels and for generating appropriate alarms. Although in preceding years hundreds of CSA measurements had been made on GDP stage equipment, there had been no definitive attempt to document the apparent relationship between equipment vibration levels and the RS component in the associated motor current spectra. It therefore became necessary to build a vibration-versus-CSA database for GDP stages that could be used to statistically quantify the expected dependence.

The first attempt to acquire simultaneous vibration and CSA data on a large scale from GDP stage equipment took place in September of 1994. From previous experience with cascade equipment, it was known that most stage compressor vibration levels were relatively low while motor-vibration velocities ranged from low to as high as 1.0 in./s. Since the weights of the motor and compressor rotors are in the 6,000- to 7000-lb range and since their effect on the amplitude of the RS modulation should be about equal, a strategy to center the correlation study on stage-motor vibration velocities was initially adopted. It was found, however, that in many cases the compressor vibration does produce a significant effect and must be considered.

6.1 SEPTEMBER 1994

This data series was taken from 22 stages in Units 4 and 5 of Building X-333 at PORTS. Since it was not possible with available instrumentation to record the motor current and the vibration signals at exactly the same time, it was assumed that stage power levels and therefore stage vibration levels would not change significantly during the day that the data were recorded. Vibration readings were therefore taken in a morning session, and matching motor current signals were recorded during the afternoon of the same day. Vibration was measured in both horizontal and vertical axes on each compressor-load bearing and on each motor-load bearing, and readings were recorded on paper. The motor current signals were recorded on digital audio tape (DAT) by sampling control room ammeter loops with a current probe.

A stage-by-stage comparison of motor and compressor vertical-vibration velocities is shown in Fig. 6.1. As expected, compressor vibration levels were generally low while motor vibration varied significantly from stage to stage, with motor horizontal velocities as high as 0.65 in./s observed. Subsequent analysis of the motor currents revealed that the amplitude of the RS component varied over a three-to-one amplitude range on many of the recorded stages. Such a large variation was not anticipated, and it implied that the vibration amplitudes also experienced larger perturbations than were noticed during the acquisition process. To account for the variations in the CSA component, an average of five consecutive readings taken 20 s apart was used for each stage. The vibration measurements, however, could not be averaged because multiple readings had not been recorded.

Figure 6.2 shows the single reading of the horizontal-axis vibration from each of the motor-load bearings plotted against the averaged RS modulation for that stage. Although the plot shows significant data scatter because of the inability to average vibrations, an included trend line, which was calculated as a least-squares fit, shows the approximate rate at which the RS modulation

Fig. 6.1. Vertical motor and compressor vibration versus stage location.

Fig. 6.2. Motor load bearing, horizontal vibration versus RS modulation.

increases with increasing vibration. The vertical-axis vibration readings were all lower than the horizontal velocities, but when the vertical velocities from the stage motors and compressors are added together and plotted against the stage RS modulation (Fig. 6.3), the results continue to support the relationship. Several other combinations of the measured parameters were also examined, and in all examined cases data scatter was a major problem. Since variation in each stage-vibration level was apparently responsible for much of the scatter, it was determined that additional data were needed.

Fig. 6.3. Motor plus compressor vertical vibration versus RS modulation.

6.2 JANUARY 1996

Because of other project commitments, it was over a year before more vibration and motor current data were recorded in X-333-4 at PORTS. Vibration data from 23 stages were obtained in the same way as in the previous data, except in this set four vibration readings spaced in time about 40 s apart were obtained at each position and axis checked. Because of the increased number of measurements, only vertical vibration readings were recorded for the compressors, and mainly horizontal readings were recorded on the motors. By this time, the Unit Monitor demonstration system had been installed and monitoring the 80 stages in X-333-4 for several months. All of the motor current signals for the unit were easily accessible on the multiplexer in the area control room basement, so for stages from which vibration data had been obtained earlier in the day, vibration signals were recorded to DAT directly off of the multiplexer cabling.

The initial analysis of these data produced very confusing results until it was later discovered that wiring errors in the Unit Monitor installation had caused the wrong CSA data to be paired with some vibration measurements. Subsequent reorganization of the data resulted in elimination of matching measurements for several stages but greatly improved the results from

remaining data. A plot of the average velocity of the horizontal motor vibrations versus the average RS modulation for 14 stages (Fig. 6.4) again shows a strong correlation between the two parameters. Comparison of the plotted data points with the included least-squares-fit trend line shows that averaging has reduced the data scatter, especially at the higher vibration velocities. It should be noted that the range of vibration amplitudes measured was significantly lower than in the previous data set because the stages were operating at reduced power.

Fig. 6.4. Average horizontal motor vibration versus average RS modulation.

The data scatter, which was a major problem with the previous data, appears to have been reduced but not eliminated by the measurement averaging used in this set. Averaging of more measurements over a longer period could have reduced scatter even further, but it probably would not have eliminated it. It is believed that part of the remaining scatter, evident especially at the levels below 0.2 in./s in Fig. 6.4, is caused by interaction between the motor, compressor, and coupling as observed in the small motor tests described in Sect. 4. The imbalance and torsional load variations from the various stage components apparently act like rotating vectors, which combine to cause variation in both the vibration and the CSA signals. The vectors can add or subtract from the total at any given instant depending on their relative vector phases. As a result, the small interaction that is causing much of the remaining scatter cannot be eliminated or quantified based on available data.

6.3 APRIL 1996

The third set of data was taken from the compressors and the motors in 20 stages in X-333-4 and concentrated on vertical vibration measurements. Five vibration readings spaced about 40 s apart were taken at both of the measurement locations on each stage. These

measurements were also recorded before the Unit Monitor wiring problem was discovered, so the required data reorganization resulted in the loss of readings from several stages. As in the January data, below-normal building power resulted in low vibration readings, so most of the 14 stage points in the plot of the average vertical velocities (Fig. 6.5) appear below 0.1 in./s. Although significant data scatter is still evident, the few points above 0.1 in./s appear to fit the expected relationship.

Fig. 6.5. Average vertical motor vibration versus average RS modulation.

6.4 JUNE 1996

The fourth data set again involved only vertical vibration velocities for 16 stages in X-333-4 and one stage each from units 3, 5, and 8. Vibration levels were still generally lower than those observed in September of 1994, and only four cells in X-333-4 were operating. As a result, it was again difficult to find stages with relatively high vibration levels, so a walk-by inspection was conducted for running cells in units 3, 4, and 5. Of the three stages included from outside of unit 4, two were found by the walk-by inspection, and one in unit 8 was recommended by the PORTS vibration specialist. Measurements were acquired as described in previous sets except the multiple RS-modulation readings for the unit 4 stages were calculated automatically by the Unit Monitor and written to a disk file, which was subsequently imported into Microsoft Excel for analysis. The plot of the vertical vibration velocities in the region of the motor-load bearing versus the stage RS-modulation level (Fig. 6.6) looks very much like the plots from previous sets. Data scatter may have actually been reduced somewhat by allowing the Unit Monitor to derive the RS modulations, but it appears that one of the two points above 0.25 in./s in Fig. 6.6 may be in error. Both of these points represent a modulation level of about 0.18% but at significantly different vibration velocities. The discrepancy occurs in stage 8.8.7 and results from significant compressor vibration, which is also contributing to the modulation reading. When the data are plotted again

with the stage compressor readings added to the motor velocities (Fig. 6.7), the discrepancy has disappeared, and the two suspect points are almost superimposed.

Fig. 6.6. Average vertical motor vibration versus average RS modulation.

Fig. 6.7. Motor plus compressor vertical vibration versus RS modulation.

6.5 ALARM IMPLEMENTATION

Each of the four data sets demonstrates how the RS component in the motor-current spectra increases roughly in proportion to increases in stage vibration. It should therefore be possible to use this relationship as the basis for high-vibration detection without using dedicated accelerometers. The old vibration-monitoring system in X-333 employs, as described, a single accelerometer mounted vertically on the load-bearing assembly of some stage compressors. The system compares each vibration signal against a warning and an alarm threshold. The warning level is set at 0.377 in./s, and the alarm level is set at 0.754 in./s. When considering thresholds for vibration monitoring with CSA, it is probably appropriate to select thresholds that are slightly higher since the CSA-RS component represents a composite reading for the entire drive train.

At this point, it should be noted that although horizontal-plane vibration readings were often recorded and have been presented in previous figures, the remaining discussion will be limited to vertical-plane vibration. This restriction will simplify the task of relating the new vibration and RS readings to the old accelerometer thresholds. Selection of acceptable thresholds for vibration monitoring with CSA requires consideration of the combined vibration effects of both the motor and the compressor. To assist in making this judgment, Fig. 6.8 depicts the combined motor and compressor vertical-vibration velocities from the September 1994 data set with a least-squares trend line extending to a velocity of about 0.9 in./s. This is the data and trend line that was originally used to set the vibration alarm thresholds for the Unit Monitor software. For a total stage-vibration warning at around 0.5 in./s, Fig. 6.8 would indicate an RS modulation threshold of 0.2%. For a high alarm at 0.8 in./s, a 0.3% threshold would appear to be appropriate. A comparison of these thresholds can be made with the June 1995 data set. Figure 6.9 depicts the data plotted in Fig. 6.7 with the addition of the extended trend line. In this plot, it appears that the thresholds of 0.2% and 0.3% will be exceeded by roughly the same vibration levels that were estimated from Fig. 6.8. Assuming that the data scatter is also present at the higher vibration levels, a stage-to-stage error band can be expected for any alarm threshold. The error band will be roughly equal to the amount of data scatter present at the alarm setting. From the Fig. 6.9 trend line and data scatter, it can be estimated that a 0.3% alarm threshold would result in actual stage alarms in the range of 0.65 to 0.85 in./s, which is a ± 0.1 in./s error band.

With suitable thresholds and an error band determined based on the presented data, it is necessary to explain that these threshold values are not used by the installed Unit Monitors. The RS modulation average calculated by a Unit Monitor is actually a weighted average in which the most recent reading is half of the average. This averaging method allows the Unit Monitor to respond more quickly to an abnormal event and results in RS numbers that can vary from the averages presented in the figures by 20% or more. The Unit Monitor thresholds are therefore set about 25% higher than the presented data might indicate. As a result, a setting of 0.25% is used for a 0.5 in./s warning, and 0.375% yields an alarm level of about 0.75 in./s.

Fig. 6.8. September 1994 data with extended trend line.

Fig. 6.9. June 1996 data with extended trend line.

7. CONCLUSIONS

Evidence has been presented that shows how CSA can be employed as an effective alternative for detecting high-vibration conditions in GDP stage equipment. Since the range of the acquired data was limited to normal or near normal operation, linear extrapolation was used to estimate appropriate alarm thresholds. Such estimates can be adversely affected by small errors in the subject data, so vibration measurements in the desired alarm range will ultimately be needed to conclusively establish threshold settings for warnings and alarms.

If GDP management determines that CSA should be pursued as a possible alternative to dedicated vibration monitoring with accelerometers, steps should be taken to ensure that opportunities to record data from stages experiencing high vibration are not missed. This could be accomplished by site personnel using existing, manually applied vibration instrumentation to obtain measurements for comparison with CSA readings that are automatically recorded by an installed Unit Monitor. For stages that are not covered by a Unit Monitor, a portable DAT recorder with a compatible current probe could be used for recording the motor current signal from the affected stage ammeter loop. This data could then be subsequently analyzed and compared to the related vibration readings.

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