REAL TIME SPECTRAL ANALYSIS—TAKING THE MYSTIQUE OUT OF THIS VALUABLE MAINTENANCE TOOL

by

Jon E. Palm

Application Engineer
Spectral Dynamics Corporation
San Diego, California

Jon E. Palm is an Applications Engineer with Spectral Dynamics Corporation of San Diego. His concern is with field applications and training in the use of analysis instrumentation.

He received an AA degree in Electronics in 1960 from Fullerton College, Fullerton, California.

His past experience includes work in the dynamics test laboratories at Aerojet General Corporation and Rocketdyne Division, North American Rockwell, as Test Engineer responsible for vibration and shock testing, application of measurement instrumentation and test data analysis.

He is a member of the Institute of Environmental Sciences and currently serves on the local Chapter Board.

A new "yardstick" for measuring rotating machinery vibration is seen in the real time spectrum analyzer. This paper presents some actual case history data that was analyzed using a real time spectrum analyzer. The object in doing so is to present the reader with a better understanding of the capabilities obtainable through use of this hybrid analyzer for monitoring vibration. Some theory of operation is also presented to describe how this tool works so that its application can be better understood.

WHY ANALYZE MACHINERY VIBRATION?

The object in performing a vibration analysis is to be able to identify the condition of a running machine. The best way to submit the findings of an analysis is to graphically describe the machine's condition. Often we can see, hear and feel machinery vibration, but we cannot always trust these senses to be accurate. We cannot always rely on them to give us a day-to-day comparison so that a trend can be established. We have been trained to understand numbers. A listing of numbers, representing vibration readings taken at sampling intervals, is something that we have learned to have confidence in. If a trend does exist, it can be recognized in the listing of numbers.

A graphical presentation of numbers could consist of a list of readings from the meter of a typical overall vibration monitor. This paper is primarily concerned with a graphical presentation that looks beyond the overall vibration level. Such a graphical presentation is obtained by interrogating the vibration signal to determine where (in the frequency range) the energy comprising the signal exists. A simple analogy to this might be to consider the overall vibration level being similar to

looking at a scene over the horizon with a wide angle lens in a camera. By switching to a zoom-in lens and viewing the horizon in segments, much more detail is suddenly realized. This is similar to the detail that can be realized with a vibration analyzer that uses a narrow filter for analysis, similar to the zoom lens, to interrogate the overall vibration level for its fine detail.

Figure 1 shows what could be considered a typical graphical presentation of the vibration of a shaft in a bearing on a running machine. The vertical axis is calibrated in mils with 1 mil being full scale. The vertical scale then represents amplitude or energy that exists. The horizontal scale is calibrated in segments of cpm. The frequency spectrum range, in this case, is up to 10,000 cpm. This type of graphical presentation is an X-Y plot. This plot could have been made by recording the results of a typical hand-tunable vibration analyzer, or by the automatic plotting capability provided in the newer type high-speed spectrum analyzers. The major advantage in the latter type of analyzer will be discussed in the forthcoming text. For the moment, let's look more closely at what could be learned by this plot.

This typical plot could be representative of the baseline signature of the particular point on the machine.[1,2] It shows a level of 1 mil at approximately 2400 rpm, undoubtedly the running speed. It shows a second component with an amplitude of 0.2 mils at approximately two times running speed. There is also evidence of minor vibration activity below running speed and again up at the higher end of the spectrum. A series of these plots, taken at different sampling intervals, would establish whether or not any trend existed in the behavior of this machine. For example, if at one of these data sampling intervals, the vibration peak at two times running speed had suddenly increased to 0.3 or 0.4 mils, the machine should certainly be monitored closer and the cause for this sudden change determined.

A LOOK AT WHAT IS MEANT BY SPECTRUM

The most familiar example of a spectrum is one that occurs in Nature—the color spectrum. There are other associations attached to spectrum. Instrumentation manufacturers and researchers in the electronic field have identified spectrum with frequency. A spectrum display or plot refers to the results of an analysis over a specified frequency spectrum range; i.e., from 0 to 10,000 Hz.

Figure 2 shows three types of classical signals and the respective spectrum display for each one. For the mechanically oriented reader, this may help establish a better understanding of the terminology and characteristics associated with signal analysis. The first signal shown in the column under "Time Domain" is representative of a typical sine wave signal. The vertical axis
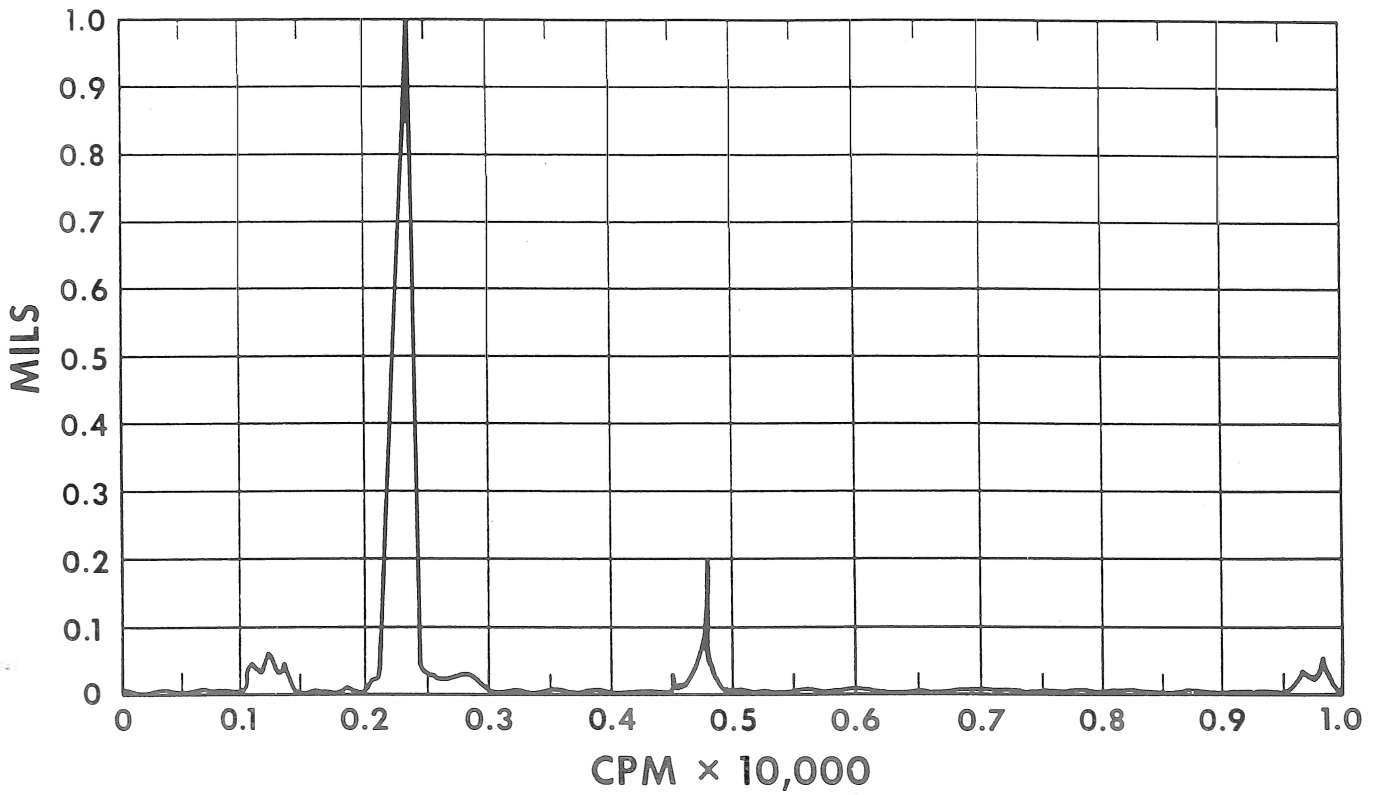
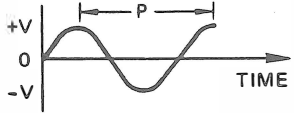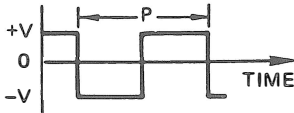Figure 1. Typical Amplitude vs Frequency Spectrum Display
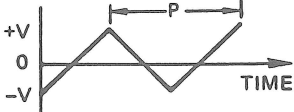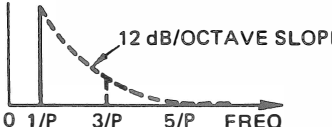
Figure 2. Classical Signal Time vs Frequency Domain Characteristics

associated with this drawing is amplitude and the horizontal axis is time. One cycle of the sine wave is completed in the time marked "P," representing one period. The next column shows this same signal in the "Frequency Domain." The vertical axis again is amplitude; however, the horizontal axis is frequency. The amplitude peak exists in the frequency spectrum at a frequency of 1 P.

Notice that the amplitude vs frequency, or spectrum display of the square wave and triangular wave, are similar. The only difference is that the amplitude of the fundamental (1 P) and each odd multiple frequency or odd harmonic have different amplitude values.

UNDERSTANDING THE REAL TIME SPECTRUM ANALYZER

The real time spectrum analyzer will show identical displays if these classical signals are applied to its input for analysis. The same information would be observed by using a hand-tunable analyzer except that the analysis would take longer. Such an analyzer uses one filter to perform the analysis. This filter is positioned throughout the frequency spectrum range by the front panel dial. Due to the operational characteristics of a filter, there is a required time that the filter be allowed to examine a signal before moving the filter to a new dial position. This is characteristic of all filters and is referred to as "filter response time." The filter response time is related to the width of the filter. A wider filter responds faster than a narrow filter; however, the wider filter does not do as discrete an analysis as does the narrow filter.

One technique that could be utilized to speed up the analysis process would be to use more than one filter. A battery of filters, lined up like a picket fence, covering a desired spectrum range for analysis, seems an obvious technique. A relatively simple detector and sampling circuit could be used to measure the energy at each filter location to provide an output display on an oscilloscope or an X-Y plotter. This would allow for an instantaneously updated display, providing one form of a real time analyzer.

This technique of multi-filters is extremely costly due to the number of filters that would be required. The same effect could be achieved if a single filter could be very rapidly moved, or stepped, to specific points in the frequency spectrum to simulate a battery of filters. This technique of stepping a single filter is the technique utilized in the real time spectrum analyzer.

But, what about the filter response time? It is impractical to step the filter slowly. An additional concept to stepping the filter is to increase the speed of the data. If the data can be recorded at a slow speed and then played back at a speed, say 500 times faster, a filter whose bandwidth is 500 times wider than what is desired could be used for the analysis. This relatively wider filter would have a fast response time, hence satisfying the requirements for performing an extremely rapid analysis. The real time spectrum analyzer uses digital circuitry to achieve data signal speed-up. The technique is referred to as "digital time compression."

Figure 3 shows a simplified block diagram of the real time analyzer concept of operation. Four of the key functions are shown: the digital time compression section, the analysis or filter section where multiple contiguous narrowband filters are synthesized, the detector and output amplifier section, and the central timing section that provides careful control of the other three functions.

The time compression section of the real time spectrum analyzer incorporates digital techniques because the digital circuitry is reliable, economical, requires little space and provides the fast speed-up rates. This section of the analyzer basically consists of an analog-to-digital converter, a cyclic digital memory and a high-speed digital-to-analog converter. The incoming data signal (analog signal) is sampled at precise intervals and converted to a digital "number" in the analog-to-digital converter. The memory is capable of cycling hundreds of these digital numbers at a very rapid rate. Typically, 1500 digital numbers are cycled once each 100 microseconds, or 10,000 times each second. Data leaves the digital memory through a high-speed digital-to-analog converter. As illustrated in Figure 4, the first sample is taken at a point in time designated by the first dot on the input sine wave signal. The digital number is loaded into the cyclic memory. Here that digital number will be cycled 500 times, in the case of a 500:1 speed-up, at which point in time the second sample is taken and the second number is loaded into the cyclic memory directly behind the first sample.

This process is continued until the memory is full of digital numbers. Once full, the "oldest" sample is discarded as a new sample is taken to replace it, thereby always keeping the cyclic memory full with the latest data samples. The high speed digital-to-analog converter reads each one of the digital numbers each memory cycle, as opposed to once each 500 cycles. By so doing, the analog signal that exits the high-speed digital-to-analog converter is a time compressed output; a high-speed replica of the input signal wave.

A relatively wide constant frequency bandwidth filter is stepped through the time compressed frequency range at a constant rate that satisfies the filter response time requirements for an accurate analysis. When a new analysis range is selected on the front panel of the real time spectrum analyzer, only the input analog-to-digital sampling time and data loading time changes. The analysis time is fixed by the fixed cyclic time of the memory so selection of different analysis frequency ranges only results in different speed-up ratios and different relative narrow filter bandwidths. The analysis time is always the same and is separate from the data sampling or data loading time. Because of this, the requirements for the analysis section are simplified, yet allow the real time spectrum analyzer to work over a wide number of frequency ranges.

In addition to the fixed operating frequency ranges that are selectable on the front panel, a technique of Signature Ratio® analysis allows the operating range to be continuously variable relative to an externally applied reference signal. Signature Ratio refers to an analysis technique that adds clarity and continuity to frequency information when speed changes are incurred. The technique is covered in several written references so no further attention will be given it here.[3]
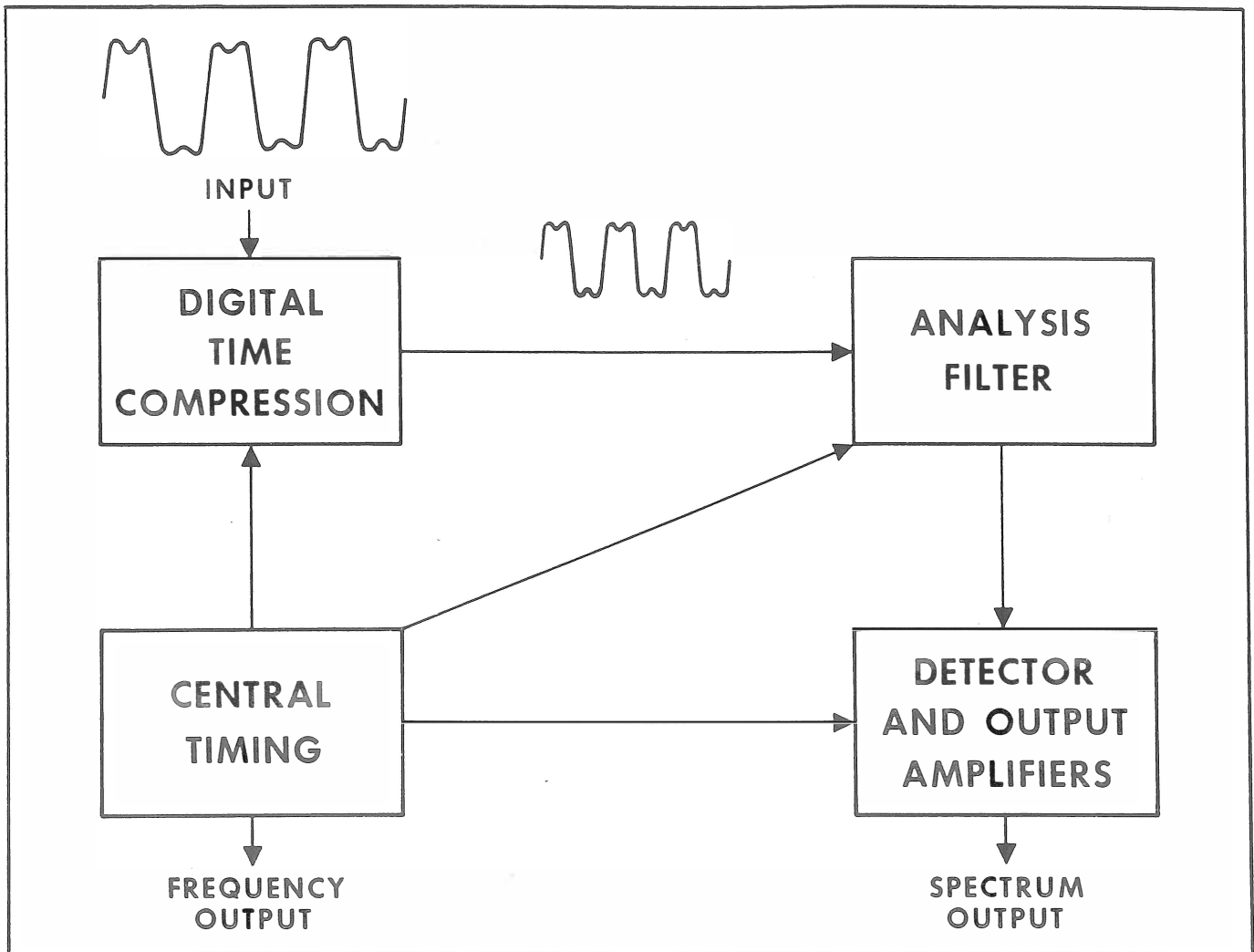
Figure 3.   Simplified RTSA Block Diagram

BENEFITS OF A NARROWBAND FILTER

In the case of a typical 500-line analyzer, which synthesizes 500 contiguous filters, each filter is spaced at 1 Hz (60 cpm) intervals when the 500 Hz (30,000 cpm) range is selected for analysis. The filter spacing on such an analyzer is always equal to 1/500 x the upper range selected for the analysis. The relative bandwidth of each filter is 1.5 x the filter spacing on each range. (On the 500 Hz range, the filter spacing is 1 Hz and the filter bandwidth is 1.5 Hz.) Narrowband filters in this realm are necessary for the type of resolution required to achieve an accurate analysis over a wide amplitude range typical of that exhibited by machinery. Early warning signs of incipient failures must be distinguishable at minute amplitude values in the order of less than 1/100th of the highest amplitude level that might be observed.[4,5,6]

An example of the interrogation capability of an analyzer with narrowband filters of the magnitude just discussed is shown in the X-Y plot in Figure 5. The horizontal axis here is frequently with an upper limit of 100 Hz (6,000 cpm). The vertical scale in this case is calibrated in logarithmic divisions rather than linear. A microphone was used to obtain this data. The unit being analyzed was a small feed pump driven by an electric motor rated at 3600 rpm. The microphone was placed near the casing of the motor. The highest peak is at 60 Hz (3600 cpm) and represents the acoustic effects of stator vibration. The very close peak just to the left of the hghest peak is running speed and was measured at 58.3 Hz indicating a small percentage of slippage. Without this ultra narrowband capability for analysis, it would have been impossible to accurately identify running speed. It is critical to know running speed to accurately identify the higher order frequency information that exists. At higher order frequencies, the percentage difference becomes an increasingly large number and can make interpretation of the spectrum data confusing.

In this case, the higher order information that was critical turned out to be five times running speed and was due to vane passage frequency of the impeller. Being able to precisely identify running speed eliminated the possibility of mistaking this vibration with the fifth order of the stator vibration frequency. In the case of this unit, the five times running speed frequency happened to coincide with a piping system resonance that produced an unbearable sound level. Accurate identification of the real problem resulted in the most effective corrective action.
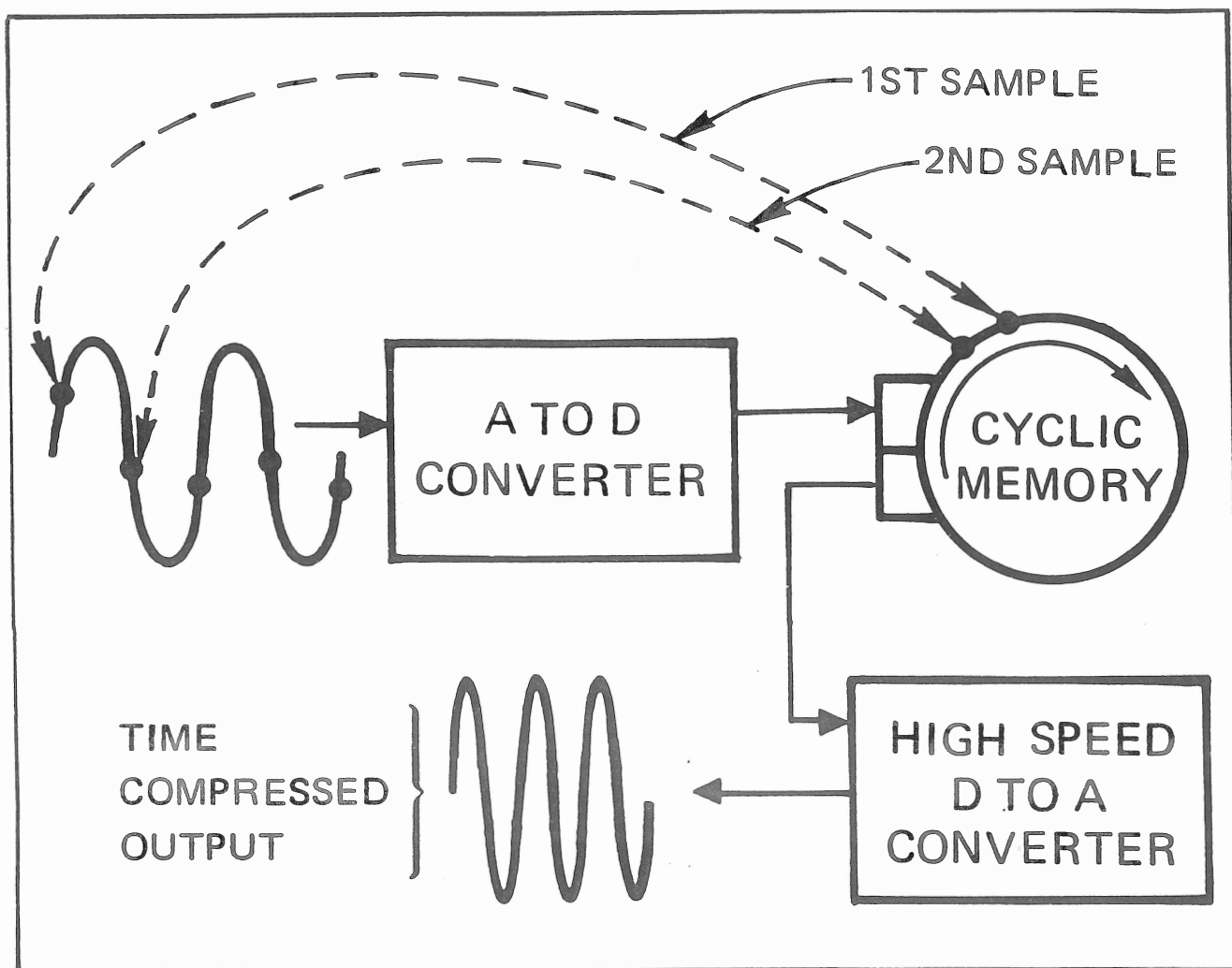
Figure 4. Simplified "Time Compression" Block Diagram

SPECTRUM AVERAGING

An averaging process was used in conjunction with the real time spectrum analyzer to add enhancement to the data shown in Figure 5. When a microphone is used for the data signal source, high background noise is typically picked up along with the constant frequent sounds. This noise, generally speaking, consists of randomly varying amplitudes and frequencies that tend to mask the constant frequency signals. The averaging process adds smoothing to the spectrum display that brings out the constant frequency tones and has the effect of washing out the random background noise.

A spectrum averager can be a separate accessory to a real time analyzer or can be built in and provided as a standard feature. The spectrum averager also has a digital memory and several operational modes that are very useful when looking at various types of machinery data signals. For example, a Peak Hold mode allows for monitoring peak vibration signals during machinery startup and also allows for capturing transient vibration phenomena.

RESONANT WHIRL CASE HISTORY

One of the biggest advantages in the real time analysis capability is seen with dynamic data. That is, when the vibration characteristics are such that a spectrum peak appears and disappears and then reappears, etc. It may not be easy to recognize these phenomena with a manually-tuned vibration analyzer. These phenomena could be misinterpreted. Take the case where a signal appears to be coming and going and is, instead, changing frequency so that it is moving away from the frequency where the manually-tuned filter is positioned. The effect would appear the same as if the amplitude were changing rather than the frequency. Or, even more confusing, is the case where it changes both frequency and amplitude in a continuous manner. By observing the oscilloscope display of a real time spectrum analyzer, the vibration characteristics are clearly revealed. A typical example of dynamic vibration data exists when a machine begins to surge for whatever reason. Such is the case in the following case history that was experienced by the Turbomachinery Engineering Service Division of Dow Industrial Service, Dow Chemical Company.

ELECTRIC MOTOR DRIVEN PUMP ASSEMBLY
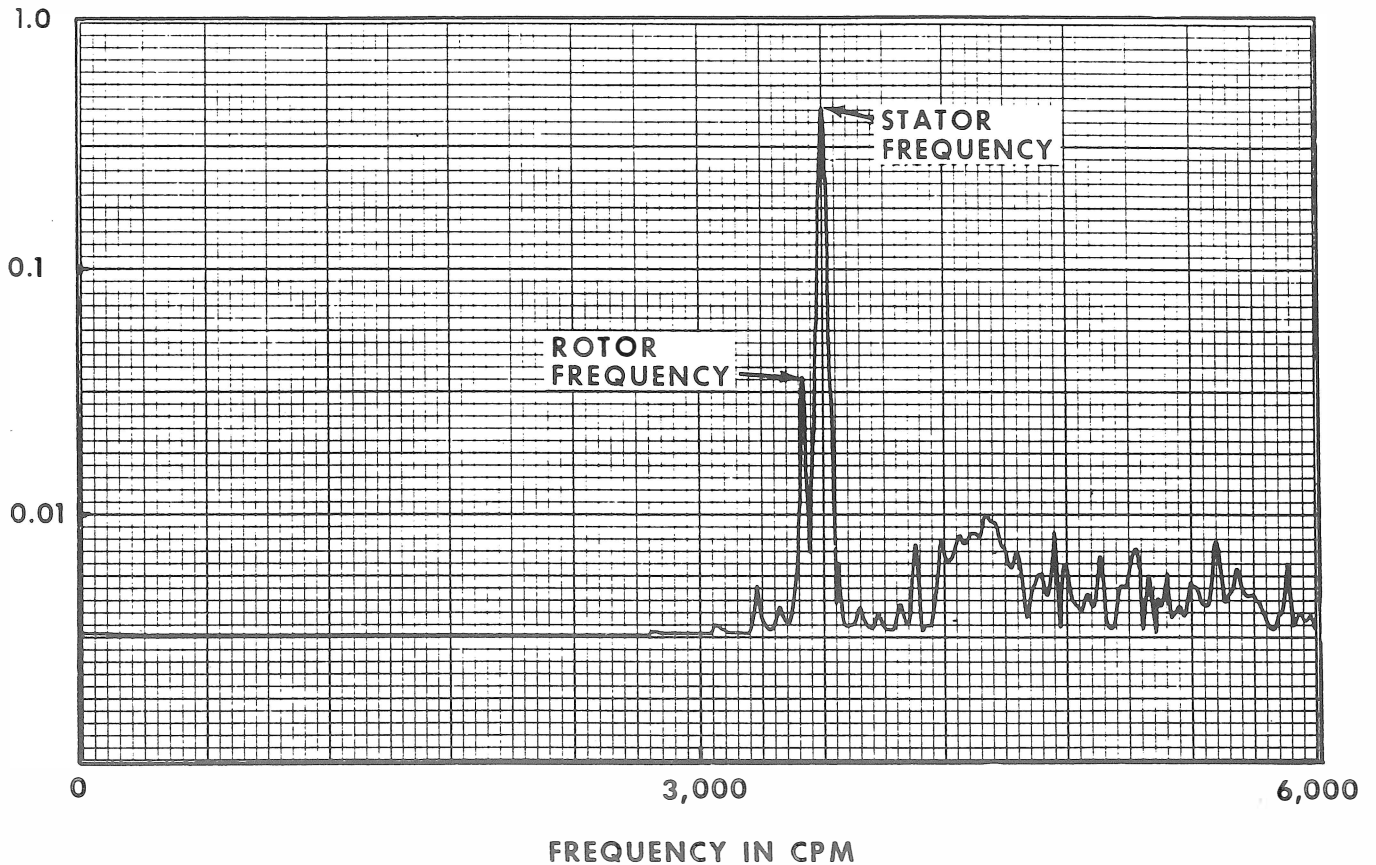## ACOUSTIC ANALYSIS

*Figure 5. X-Y Plot Illustrating Narrowband Analysis Capability*

The following four figures illustrate an experience associated with an ammonia syngas compressor. The vibration transducer was a displacement measuring probe that was located on the low stage inlet and near the bearing assembly to measure shaft vibration in the vertical direction. A tape recorder was being used to monitor the signal. The tape recorded data was later played back using a real time spectrum analyzer to obtain the photographs shown.

Figure 6 shows a steady running condition with a relatively low vibration level. The real time spectrum analyzer was set to the 500 Hz (30,000 cpm) frequency range for analysis. Full scale in the vertical range represents 10 mils of vibration. The display shows that most of the energy existed at running speed, shown to be slightly above 30% on the frequency scale, or above 9,000 rpm. Also shown is some evidence of activity below running speed as well as some energy at two times and three times (2nd and 3rd harmonic) running speed.

Suddenly, the unit began to surge. Figure 7 shows the change in the vibration spectrum display. Basically, two spectrum peaks exist, one at the previous running speed and one indicating a slightly higher running speed. When viewing the analyzer display during the playback of the tape-recorded data, it can be seen that both speed and amplitude continuously changed. The Peak Hold mode of the spectrum averager was used to capture the peak vibration amplitude that existed over this relatively short period of time. Figure 7 shows the results of this peak capturing mode of operation and allows this segment of the event to be stored for closer observations. (Both the frequency and amplitude scales on Figures 7 and 8 are the same as Figure 6.)

Note also that other vibration phenomena are revealed in this display. The below running speed, or sub-harmonic, vibration information was verified as resonant whirl vibration. It grew to a damaging level almost instantaneously. The unit ran under this high-vibration condition for several seconds. Figure 8 shows the over-whelming vibration peak that occurred. The over-vibration protective devices were activated and the unit did automatically shut down. Upon inspection, severe damage was found. The highest vibration level that occurred is only approximated due to the fact that overloading of the tape recorder existed, thereby preventing an accurate measurement. This entire event occurred in such a relatively short period of time that no time existed to attempt to decrease the resonant whirl vibration, let alone remember to change ranges on the tape recorder. The overloaded tape recorder condition produced some of the peaks on the spectrum display that are harmonically related to the resonant whirl frequency. In spite of the
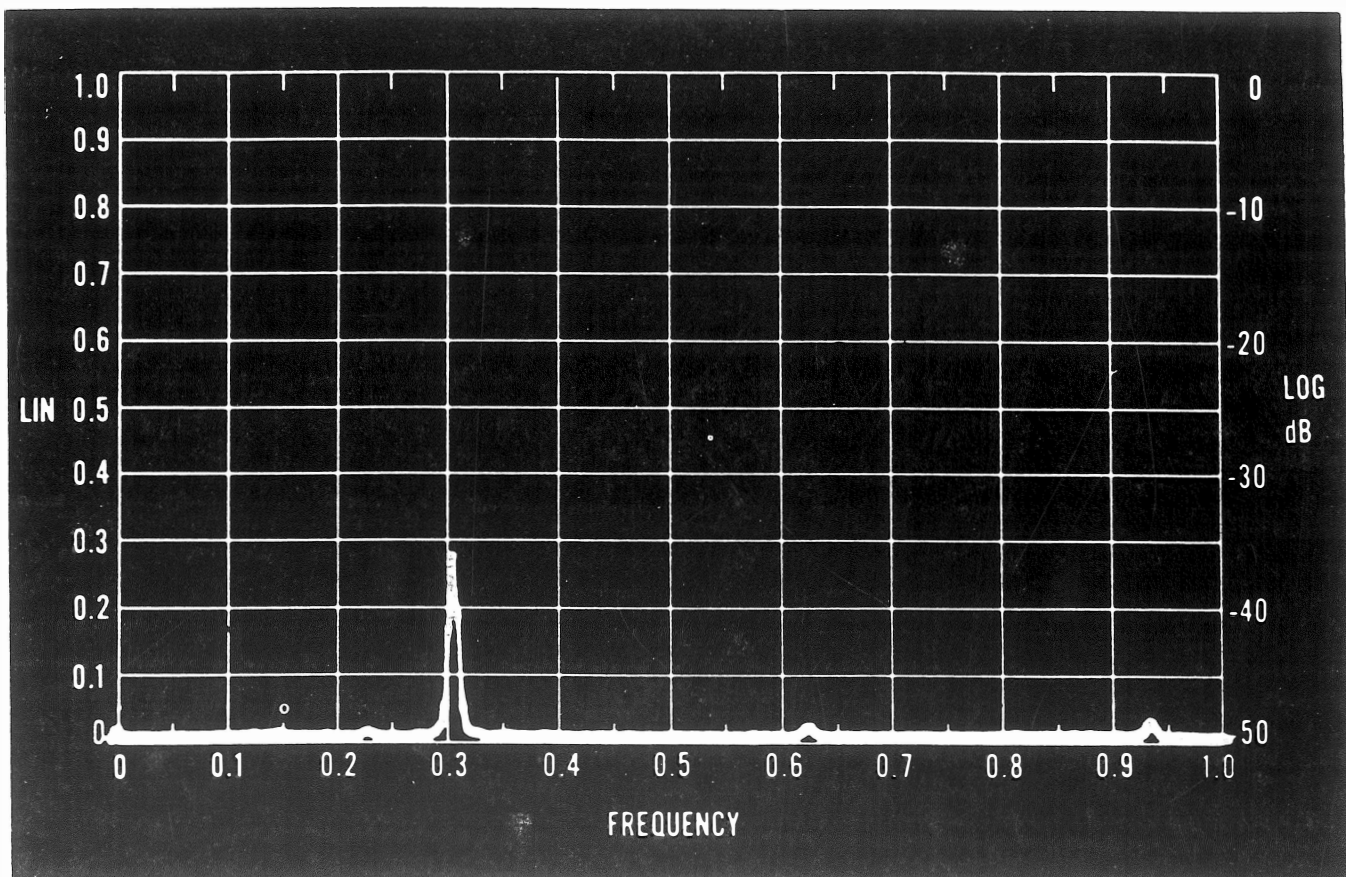
FREQUENCY — 30,000 CPM FULL SCALE
AMPLITUDE — 10 MILS FULL SCALE
BOTH SCALES ARE LINEAR

*Figure 6.   Scope Photo Showing Smooth Compressor Operation*

tape recorder overloading, a good lesson can be learned by the analysis of this event.

Figure 9 shows a technique whereby the entire time history of the vibration event is recorded providing this permanent record. The device that produces this type of record is a mechanical drive recorder that has a rapidly scanning stylus that electronically burns a specially treated paper. The special purpose recorder is locked to the scan rate of the real time spectrum analyzer. The stylus scans at a rate of 20 scans/second and burns the paper only where vibration amplitude peaks occur. This gives a 3-dimensional display that resembles a topographical map. The broadest dark marks represent the highest amplitude or, in this case, the highest vibration level. Frequency information is shown from left to right with 500 Hz (30,000 rpm) being at the right-hand edge. From bottom to top represents time which, in this case, is approximately 1½ minutes. Frequency markers were inserted with the data at the beginning (bottom) and end (top) of the record. The real time spectrum analyzer generates ten frequency markers, nine of which are

shown on this display representing 50 Hz (3,000 cpm) intervals.

The short straight line that exists just past the third marker indicates steady running speed of the compressor. The two times and three times running speed frequencies are also shown to be steady up to the point where speed is shown to increase. Paying close attention to the resonent whirl frequency region, notice that a high amplitude appears and then disappears and then finally appears continuously, growing higher in amplitude as time progresses. Higher multiple orders of the resonant whirl vibration are also shown on the display. Notice that after approximately 40 seconds, this multiple of the resonant whirl frequency (approximate center of the display) gets to be very large. This is the area where the tape recorder began to overload and, undoubtedly, caused this effect.

Looking again at the running speed trace, notice that once it became unstable, it gradually worked its way back to a stable frequency while the resonant whirl vibration increased. Following this trace, notice that after approximately 1 minute, the trace immediately changes
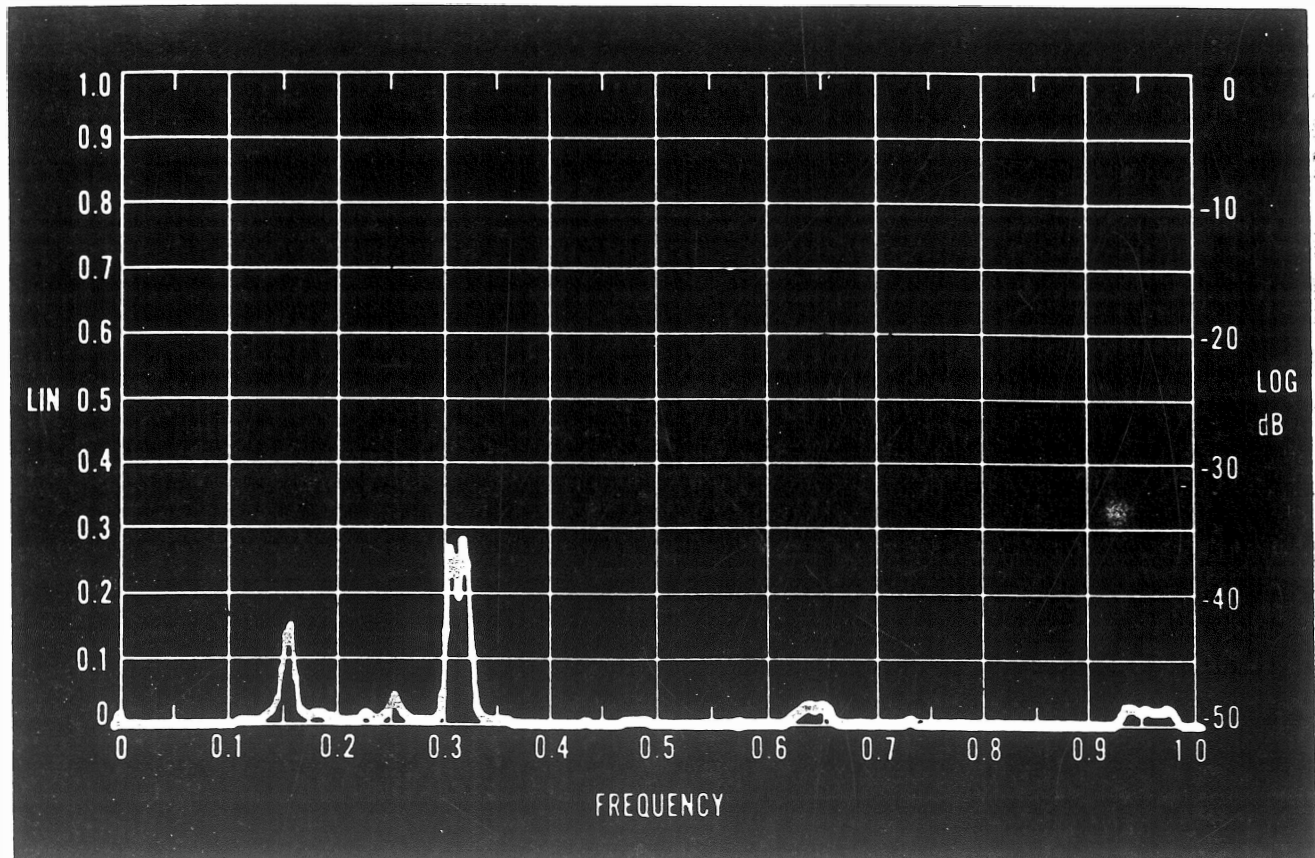
FREQUENCY – 30,000 CPM FULL SCALE
AMPLITUDE – 10 MILS FULL SCALE
BOTH SCALES ARE LINEAR

*Figure 7. Scope Photo Showing Surging and Start of Resonant Whirl*

direction. This is the point at which the vibration protective devices tripped the unit and it began to coast down in speed. It is interesting to notice that the amplitude of the vibration at running speed increased as it passed through this frequency range where the resonant whirl vibration existed. Focusing attention on the point at which the machine tripped, it is also interesting to notice that the high resonant whirl vibration continued even after the machine's speed began to decrease. The resonant whirl vibration finally subsided after running speed decreased to a point where the forcing energy had been taken away. The other traces that appear moving from right to left after the resonant whirl vibration subsided are multiple harmonics of running speed frequency. The harmonically related information that disappeared when resonant whirl subsided is obviously related to that frequency.

A real time spectrum analyzer was not on the job when this catastrophic failure occurred. That is not to say that had an analyzer been on the job, this event could have been prevented. This entire event took place in less than 1½ minutes. A point to consider here is

the fact that perhaps there were some early warning indications of this problem. Hopefully, the data that was recorded prior to this event showed some early warning signs that will provide a basis for predicting and, perhaps, preventing similar failures from occurring in the future.

Many users of real time spectrum analyzers are reporting successes in preventing outages due to the increased analysis capability. In many cases, the real problem is accurately and rapidly identified allowing temporary corrective action to be taken and, thus, allowing continued operation through a critical production period. In many cases, the temporary fix amounted to changes in oil temperature or oil pressure. The important thing here is that the problem was rapidly identified and continuously monitored while attempts to correct the situation were evaluated. The real time analysis capability allows for immediate observation of the effect of a change as corrective action attempts are implemented. Most cases are unlike the case history just reported in that a catastrophic failure does not occur so suddenly. This extra time is a blessing in such cases because corrective action attempts can be made and evaluated.
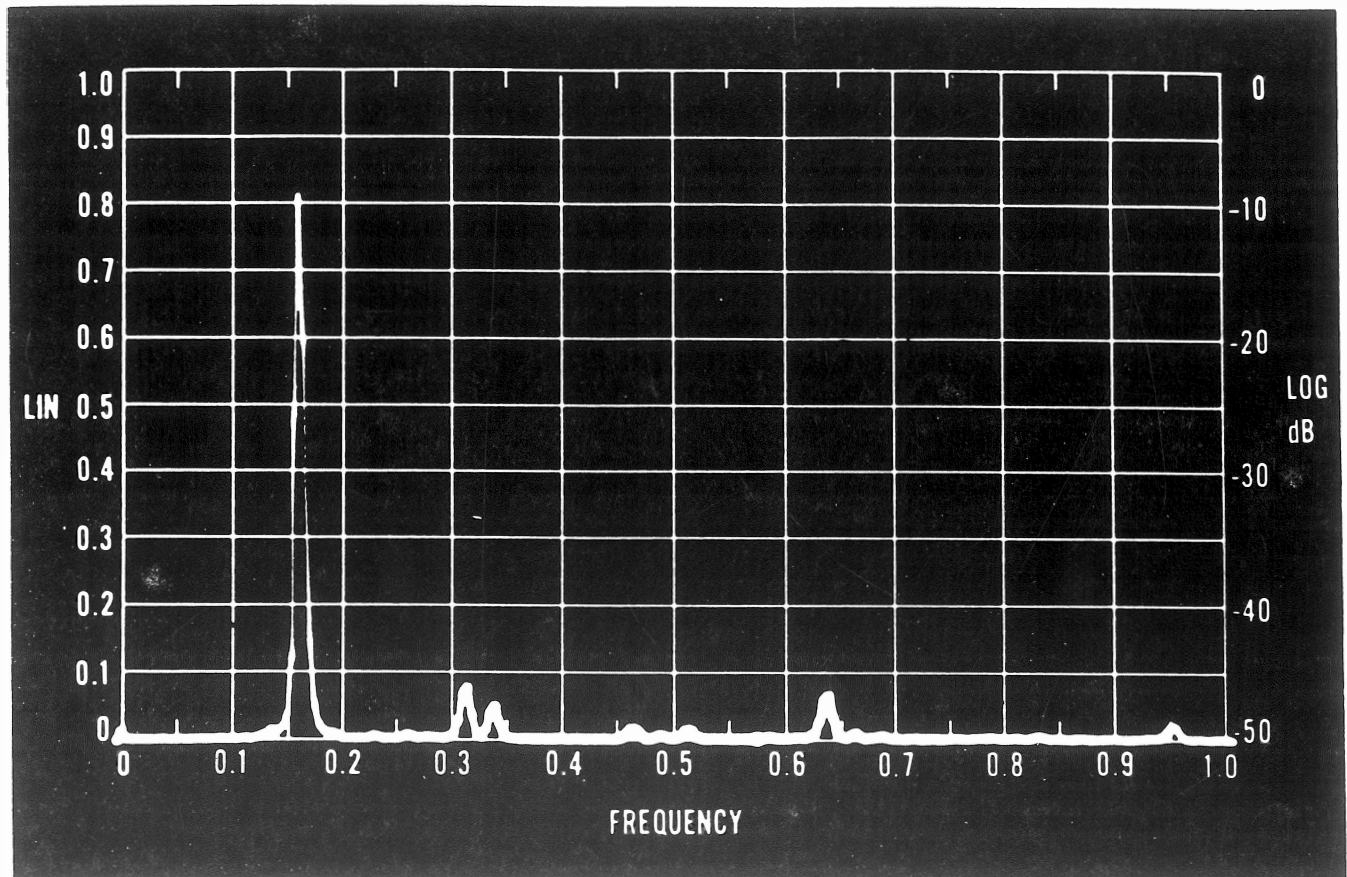
FREQUENCY – 30,000 CPM FULL SCALE
AMPLITUDE – 10 MILS FULL SCALE
BOTH SCALES ARE LINEAR

Figure 8. Scope Photo Showing High Resonant Whirl

ADDITIONAL ANALYSIS CAPABILITY

When planning new installations or when upgrading existing capabilities, the use of an accelerometer should be considered. There are many discussions of the benefits of an accelerometer in recent papers, so little will be devoted to that here.[5] Use of an accelerometer is not in place of, but rather, in addition to use of displacement probes and velocity transducers. For example, in the previous case history, perhaps the real indicator of incipient failure could have been seen by a casing-mounted accelerometer. The failure might have been prevented.

The vibration signature shown in Figure 10 is an example of the type of information that can be seen using an accelerometer. Full scale frequency on both plots is 20,000 Hz (1,200,000 cpm). The vertical scales are linearly graduated in gravitational units of acceleration —G. Full scale for the compressor section spectrum analysis is 8 G and 3.5 G is full scale for the turbine section spectrum analysis.

Each of the critical vibration peaks has been identified and related to the mechanical characteristics of the turbine and compressor. This data makes an ideal baseline signature analysis that can be used as a reference to compare with other signature analyses taken at data sampling intervals.

Normally, baseline data is taken when a machine is new or just overhauled. Certainly valid baseline information can be obtained from a machine that has been on line as long as it has shown steady-state operational characteristics.

All aspects of behavior should certainly be obtainable in the case of the jet engine shown in Figure 11. It illustrates the application for the various types of measurement devices that are best suited to obtain the most beneficial data. A wide assortment of techniques will bring about the vibration monitoring program with the best results.

ANALYSIS PROGRAMS TODAY AND TOMORROW

Great strides are being reported every day by people using a real time spectrum analyzer for measuring machinery vibration. This is a new and exciting field that
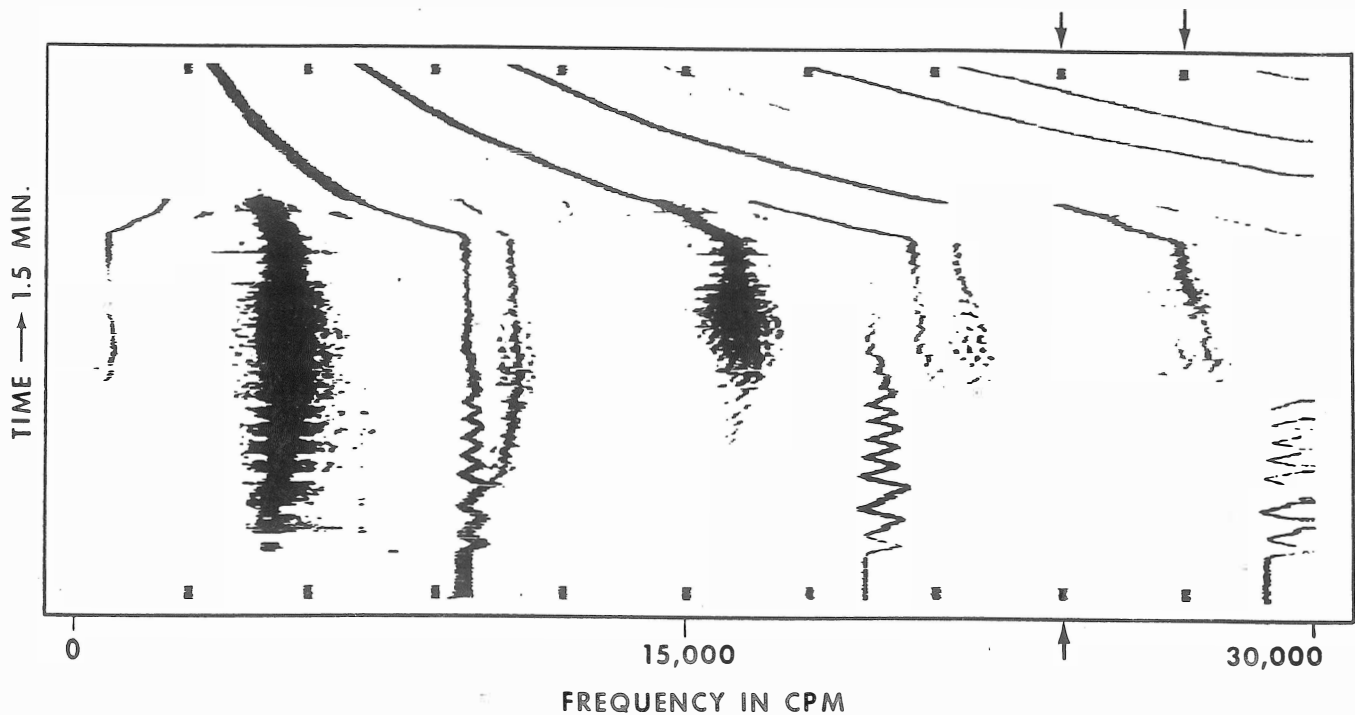
CONTINUOUS RECORD OF VIBRATION AMPLITUDE VS. FREQUENCY VS. TIME.

FREQUENCY MARKS ARE SUPERIMPOSED WITH DATA AT START AND END OF RUN AS SHOWN WITH ARROWS.

Figure 9. Time History of Compressor Failure Events

shows encouraging results for predicting failures, etc. Looking back for a moment, measurement of machinery vibration has been going on for a long time. The state of the art has not kept pace with the advancements made in the machinery field. Machinery has become more complex and is also running at higher speeds. The real time spectrum analyzer idea is an old one that was made marketable only about five years ago due to advancements in the electronic field. Only in the past few years has a portable unit been available for field use at a reasonable price.

A capability that is available today is illustrated in Figure 12. All machinery vibration and other data signals throughout a plant are transmitted to a central location for close observation. Correlation of all of the data can perhaps unfold a machine's characteristics very clearly. For example, correlation of an increase in vibration at two times running speed together with an increase in temperature reveals something different than what could be suspected if only one of these parameters were identified.

It may not be practical to have all vibration signals transmitted to a central location. In these cases, a portable instrumentation quality tape recorder or a portable analyzer can be taken to the machinery locations. The same results can be achieved.

The eye shown in this sketch is very important because it is symbolic of a company philosophy. That is,

how much is a company willing to invest in a machinery monitoring program. A manpower investment may have to be made as well. Naturally, the size of the plant and the nature of the process or product are influential in determining requirements for the objective in a monitoring program. In the simplest form, an analysis program might consist of just the addition of a hybrid analyzer. The benefits here would be in the time saved for making a vibration survey, plus the fact that a more discrete analysis would result. No additional manpower would be required.

The eye in Figure 12 is shown to be observing and establishing what relationships or trends exist in the data gathered. A case history file is being established. Soon a library of records will back up decisions made, based on the data observed.

The addition of a mini-computer at a future date would make the data acquisition and correlation task automatic. This concept is shown in Figure 13. Such a system would result in automatic trend monitoring, based on comparing vibration spectrum data with pressure, temperature, flow, etc., data. The vibration spectrum data information, in addition to the overall vibration level data, will result in a more accurate trend based alarm capability. A more accurate and automatic diagnostic capability could be expected as well.

One cannot expect miracles from such a computer/analyzer based system. That is, these benefits potentially
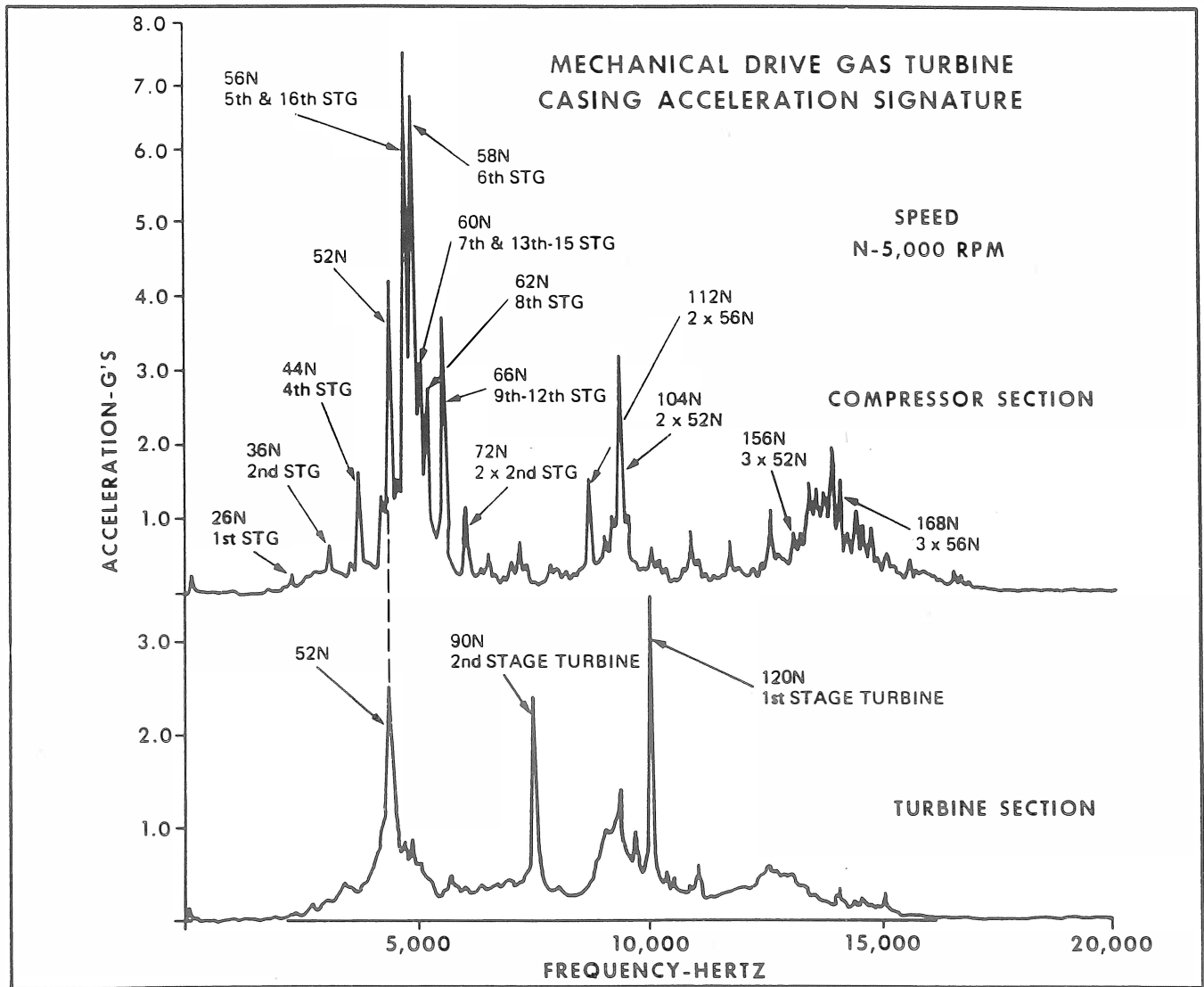
Figure 10. Typical of Analysis Capabilities Using an Accelerometer (Courtesy Dow Industrial Service)

exist, but it will take time to implement them. The automatic trend based alarm capability can be expected soon after installation, but a diagnostic capability needs case history data for reference. Here again, the investment in capital equipment and manpower are in direct proportion to the results that can be expected.

SUMMARY

The advancements made in turbomachinery technology in recent years certainly justify taking a look at new tools to meet vibration monitoring requirements. There is no magic associated with the use of a real time spectrum analyzer. It simply analyzes the input signal in accordance with the instructions given it via the front panel controls.

Some of the benefits are:

1. Faster and more accurate vibration data gathering capability;

2. Changing or dynamic data can be quickly understood;

3. Discrete analysis is more powerful than measuring overall vibration level alone;

4. Vibration spectrum trends can be correlated with other trends, establishing a better understanding of individual machine characteristics;

5. Expansion to semi-automatic or automatic monitoring systems for trend based alarms and diagnostic capabilities are natural next steps.

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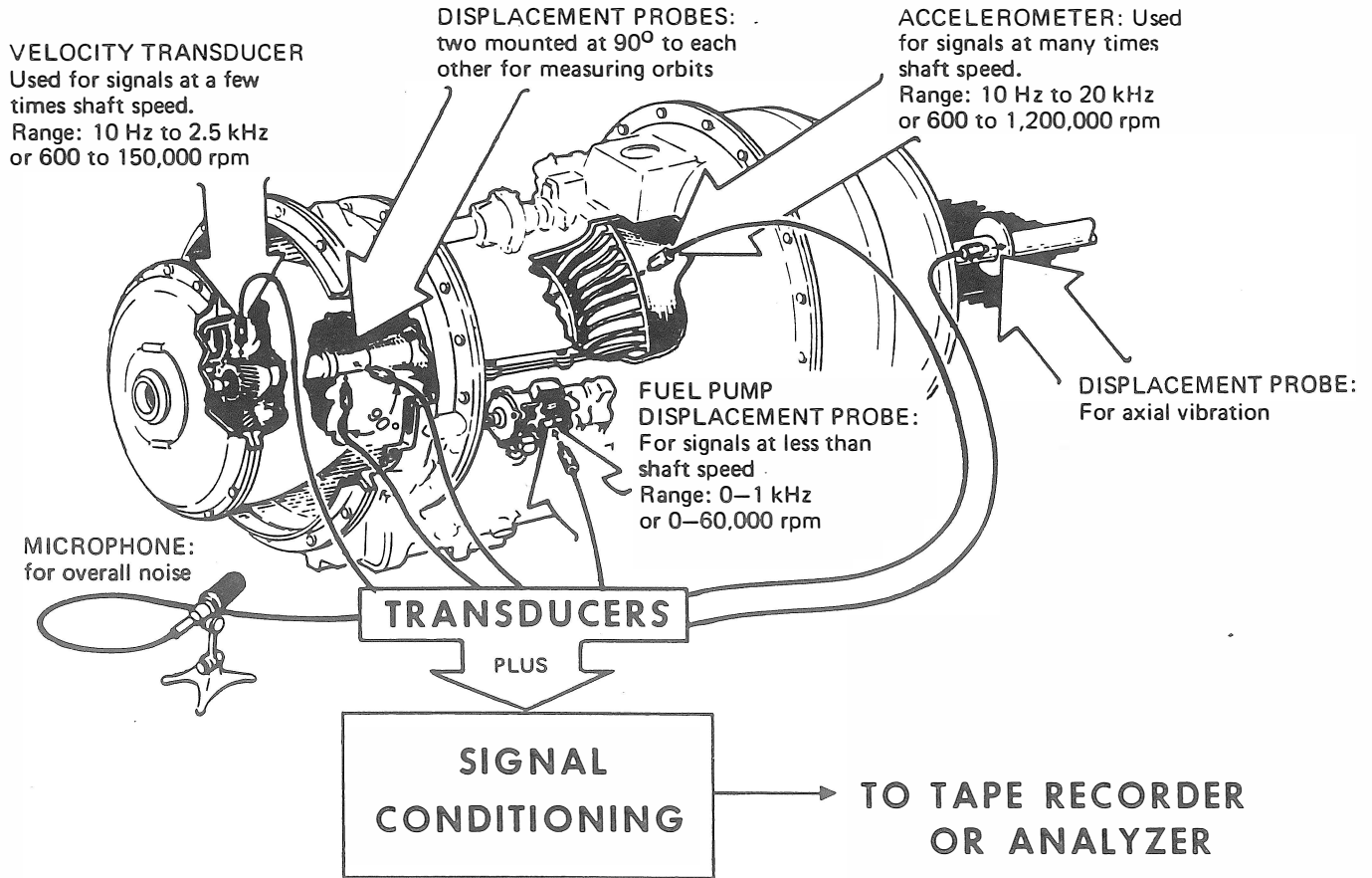
VELOCITY TRANSDUCER
Used for signals at a few
times shaft speed.
Range: 10 Hz to 2.5 kHz
or 600 to 150,000 rpm

DISPLACEMENT PROBES:
two mounted at 90° to each
other for measuring orbits

ACCELEROMETER: Used
for signals at many times
shaft speed.
Range: 10 Hz to 20 kHz
or 600 to 1,200,000 rpm

FUEL PUMP
DISPLACEMENT PROBE:
For signals at less than
shaft speed
Range: 0—1 kHz
or 0—60,000 rpm

DISPLACEMENT PROBE:
For axial vibration

MICROPHONE:
for overall noise

TRANSDUCERS

PLUS

SIGNAL CONDITIONING

TO TAPE RECORDER OR ANALYZER

Figure 11. Considerations for Vibration Transducer Capabilities

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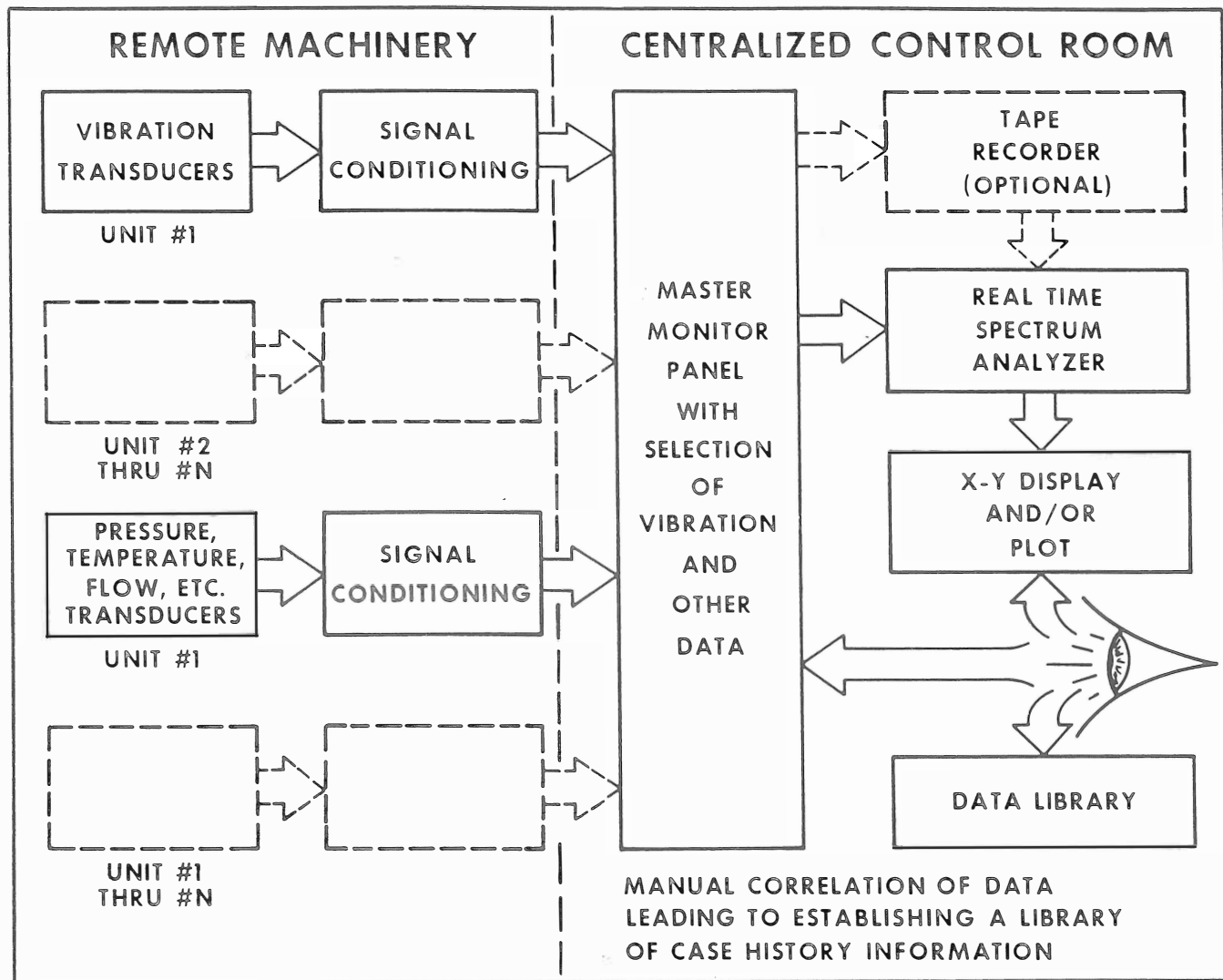6. Mitchell, L., "Origins of Noise," Machine Design, May 1969.

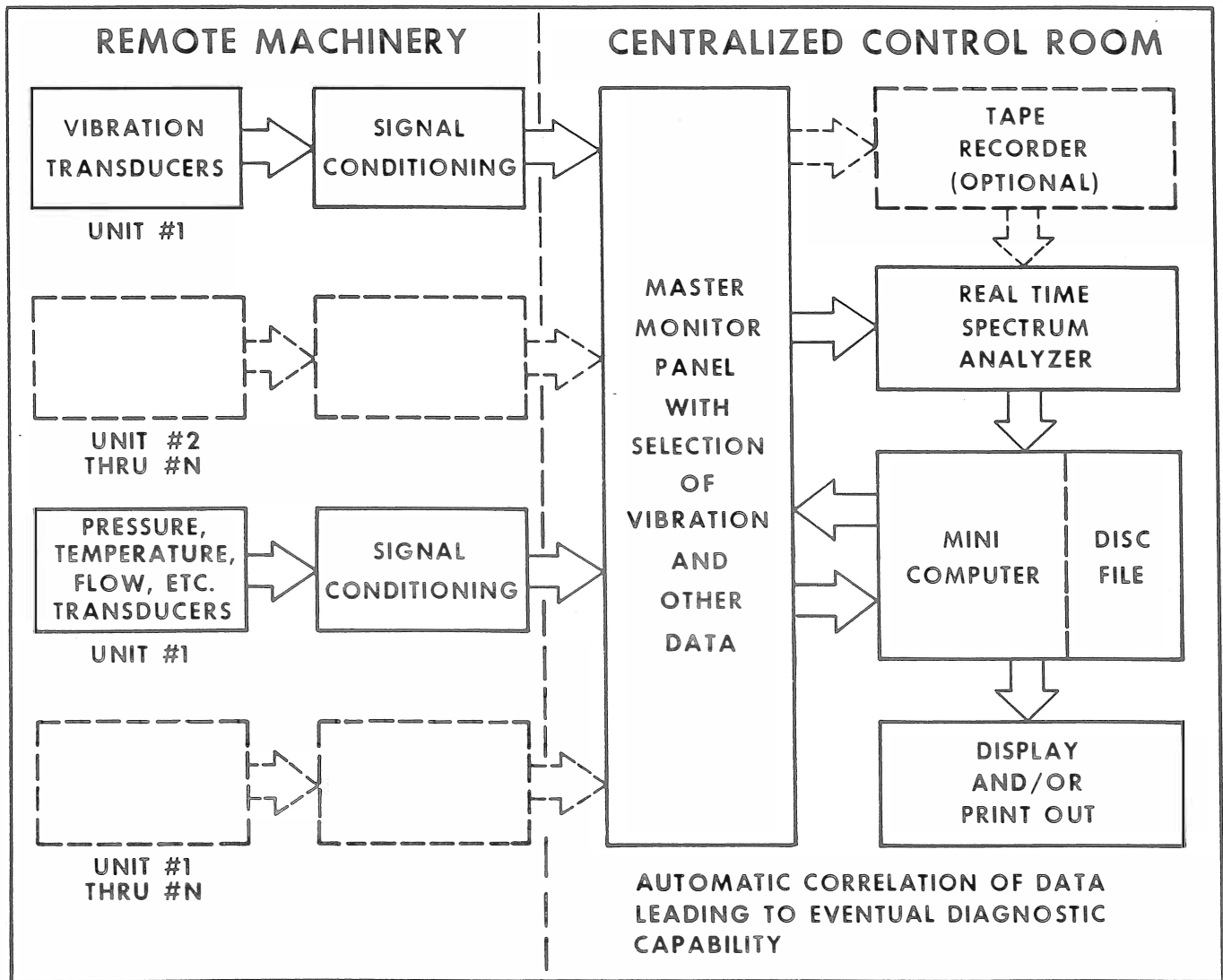*Figure 12.   Semi-Automatic Plant Monitoring Block Diagram*

Figure 13.   Expanded Automatic Plant Monitoring Block Diagram