USING MODIFIED ACOUSTIC EMISSION TECHNIQUES FOR MACHINERY CONDITION SURVEILLANCE

by

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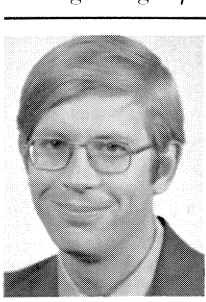

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ABSTRACT

Acoustic emission is the release of high frequency sound energy in a material under strain. It is the result of microscopic changes in material structure and is associated with deformation and defect growth.

Until about 1973, acoustic emission technology was primarily employed in the non-destructive testing of such structures as pipelines, heat exchangers, storage tanks, pressure vessels, and coolant circuits of nuclear reactor plants. However, the applicability of this technique to the detection of defects in rotating equipment bearings was recognized and the results of prototype testing were published in 1973. These tests led to the development of a plant-wide, computerized acoustic incipient failure detection (IFD) system which was leased from a major aerospace contractor in 1975 and evaluated until early 1977.

In late 1977, advanced, second generation IFD systems were employed. These systems incorporate features which greatly enhance component reliability and usefulness to plant operators. Automated acoustic emission sensing has proven to be indispensable for dependable surveillance of machinery condition.

Design concepts and field experience with advanced, second generation acoustic IFD systems are described and many actual incipient failure warning events illustrated in detail.

INTRODUCTION

Most machinery surveillance systems attempt in some way to provide the earliest possible indication of impending equipment failure. The benefits of early warning are significant [11]: corrective action can be taken in a well-planned fashion and the problem may even be averted entirely. Furthermore, adequate pre-warning may allow accurate problem identification and therefore continued operation with minimum risk of catastrophic failure.

High frequency acoustic emission technology has been shown to be more effective in this regard than the popularly used low frequency vibration and sound techniques [4, 5, 6]. In fact, high frequency technology has become commonly referred to as IFD, or incipient failure detection, to emphasize this ability to detect failure in its early stages.

The basic premise of acoustic IFD monitoring is that the presence of defects in machinery and mechanical structures is characterized by corresponding abnormalities and changes in the acoustic signature. For early identification of failure, these defects must be detected when they first develop and are quite small; however, the amount of detectable energy released from a small defect is usually negligible in comparison to normal machinery operating noise. Fortunately, operating noise tends to be concentrated in the low frequency range of vibration while defect-originated energy extends to much higher frequencies. It is this frequency separation that accounts for the success of IFD technology.

The problem of failure prediction remains nevertheless quite complex and many factors are normally involved. A very fundamental objective can be achieved by the simple goal of presenting measured parameters in a form that allows an immediate determination of their significance. This is best accomplished by graphically plotting data in a trend display covering a fairly long operating period. This powerful diagnostic tool gives perspective and simplifies failure prediction. When done manually, the procedure would require painstaking data collection which cannot generally be justified on a plant-wide basis.

Therefore, computerized data acquisition was introduced very early in the development of practical large scale IFD systems [2, 3]. Further refinements have more fully utilized the processing power of the computer to implement the operator-interactive features of graphic displays.

The material presented illustrates the features and the use of these systems as they are presently implemented. It must be emphasized that these systems are not prototypes — they are fully functional and produce continuing results typical of the valid technology on which they are based.

BENEFITS AND COSTS

Understandably, any machinery surveillance program must first be justified by weighing the expected benefits against costs. This simplifies the budgetary decision-making process somewhat, even though a high benefit-to-cost ratio does not guarantee acceptance and use of a system. Still, the process of estimating the benefits is a necessary first step in planning an adequate program.

Since IFD technology was relatively novel when the program began, justification was more difficult because of limited data base and unfamiliar technology. Only because of very dramatic results from a small test program [16] was a medium scale trial program approved that generated a great amount of data on benefits [14, 17], these results are summarized in Table I.

As can be seen, a sizeable number of events occurred in which IFD monitoring was credited for giving advance warning and better problem understanding. In addition, although no direct credits were taken, it was most encouraging to note how the IFD systems effectively assisted process operators in recognizing flow starvation and cavitation in pumps, product unbalance in centrifuges, excessive ice formation in cold process vessels, etc. Also, equipment engineers often used the IFD systems to determine when *not* to remove equipment, although conventional low-frequency instrumentation and audible noise indicated marginal mechanical condition.

The tabulated credits indicate savings totaling approximately $265,000 based on 500 sensor years of experience. Since the three IFD systems mentioned in Table I were only leased on a trial basis, and since much of the equipment in the plant was still not monitored, these cost credits became the basis of purchasing five upgraded systems that implemented a total of 1200 sensor points. [14] With an approximate price tag of $500 per point, it can be seen that these systems should pay for themselves in one year, based on the original conservative credit analysis.

It must be noted that in nearly all cases mentioned IFD instrumentation was the only instrumentation being used, so that the relative merit of IFD as a machinery surveillance tool is not directly illustrated. This factor has been examined elsewhere [5, 16] and is not at issue. What is significant is that the credits claimed by IFD are similar to those claimed by more conventional vibration monitoring systems [11, 12, 18], yet IFD technology has still not been fully exploited as an early warning system. Projected benefits indicate a 50% reduction in channel cost with at least twice the savings in maintenance and equipment downtime.

This is not to say that current IFD systems are intended to replace conventional MVSA (machinery vibration signature analysis) techniques. The capabilities of MVSA systems are well documented [11, 12, 13, 20], and in fact, some features have been implemented in IFD systems. MVSA makes use of the fact that vibration produced by a machine contains a great number of discrete frequencies, some of which can be tied directly to the operating dynamics of particular elements within the machine. When the amplitude of a specific frequency or pattern of frequencies changes, it represents a change within the machine and possibly a deteriorating condition. IFD analysis on the other hand makes use of only a narrow band of high frequencies that is sufficiently removed from background vibration to make even small changes readily apparent. This represents a very effective simplification of MVSA that results in significant cost savings.

TABLE I. IFD SYSTEM BENEFITS AND CREDITS (Reference 14).

System 1 (Jan. 75 - June 75)		
No. of sensors	268	
Incipient failure events	8	
Projected Payout	1.5	years
System 2 (August 75 - July 76)		
No. of sensors	280	
Incipient failure events	23	
Projected Payout	1.5	years
System 3 (Feb. 76 - July 76)		
No. of sensors	156	
Incipient failure events	6	
Projected Payout	1.3	years
6 Channel Monitor (Jan. 75 - July 76)		
No. of sensors	6	
Incipient failure events	4	
Projected Payout	0.6	years
1 Channel Monitor (June 72 - Jan. 75)		
No. of sensors	1	
Incipient failure events	10	
Projected Payout	0.5	years
Portable Test Equipment (June 72 - July 76)		
No. of tests (approximate)	25	
Projected Payout	0.4	years

DESCRIPTION OF SECOND GENERATION IFD INSTRUMENTATION

The basic structure of the IFD Systems being discussed in this paper is essentially that of a data acquisition system. Acoustic signals are detected, measured, processed, and stored in a standard manner even though much of the processing is highly specialized. In fact, one of the significant differences between first and second generation IFD systems is the much greater simplicity and modularity of the newer systems.

The system block diagram, as shown in Figure 1, illustrates the fundamentally straightforward nature of IFD processing; Table II lists the specific characteristic of each of the five systems in use. As can be seen, there are three types of measurements that can be acquired: high frequency acoustic, low frequency vibration, and high frequency pulse count. There is no provision made for processing additional variables such as temperature and flow since other systems can handle these measurements much more efficiently.

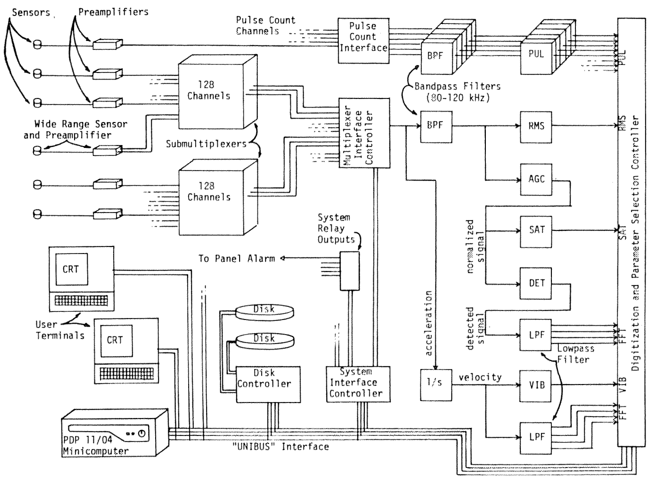


Figure 1. IFD System Block Diagram.

Each acoustic incipient failure detection system acquires both high and low frequency vibration data from rotating machinery by means by piezo-electric sensors attached to appropriate points on centrifuges, pumps, motor compressors, turbines, extruders, gear boxes, turbochargers, compressor headers, and lateral piping. The output of each transducer is fed to a solid state pre-amplifier located near the machine being monitored which boosts the signal so it can be transmitted over cabling. Low voltage DC power to the pre-amplifiers is supplied from the submultiplexers or central stations over the same cabling that carries the acoustic data signals.

The pre-amplifier outputs are connected to the central processing station by means of direct wiring or through field mounted submultiplexers which sample data from each point. The field mounted submultiplexers are accessed by controllers located at the central stations under command from a digital computer. The amplified sensor signals are conditioned by hardware processors located at the central stations. There are three basic types of processors: high frequency acoustic processors for multiplexed channels, low frequency vibration processors for multiplexed channels and pulse count processors for non-multiplexed channels. The processors operate on the amplified sensor signals to provide information used to determine machinery condition and digitize this information for input into a digital computer system.

A minicomputer is used in the central station to control system operation, store and display data, and process spectral parameters from incoming signals. Specialized interfaces are used to connect the computer to the signal processing and multiplexing circuitry.

Other computer peripherals incorporated into the system are two disk storage devices for storing programs and data, a graphic display terminal with hard copy capability and keyboard to present output data and to provide operator control of the system.

The organization and function of the hardware elements of the system are provided by the software. There are two basic software packages: the operating system and the application programs. The operating system controls and monitors the computer and its peripherals to provide an environment in which the application programs can operate. It also provides services in areas such as application program development, file and system management, startup and diagnostics. The application programs determine and control the operating functions of the system, including data acquisition and storage, comparison of current data with programmed alarm thresholds, output of alarm messages if thresholds are exceeded, data averaging, trend plotting, and spectrum analysis.

Sensors and Amplifiers

One of the specialized developments involved in the IFD system design was a low cost ($40-$100) high frequency acoustic sensor. Since most commercially available acoustic emission transducers are priced at over $200, simple economics would limit the application of the system even though a plantwide system was intended. However, with absolute accuracy not needed in a system based on trend analysis, a very simple transducer could be used. In essence the typical IFD sensor simply consists of a single piezoelectric crystal bonded in a low-cost case; a picture of this construction with some typical transducers is shown in Figure 2.

Two significant features of these transducers as used in the second generation IFD systems are the integral armored cable and the intrinsically safe design. Early transducers were found to have two weak points: the miniature connector and the small unprotected lead wire. The use of an integral armored cable added very little to the cost of the sensor but has increased the durability considerably. The intrinsically safe design of the sensor has always been a requirement since many sensors are used in a potentially explosive atmosphere, or Class I Division I environments as defined by the National Electric Code. Ideally, the sensors should be certified by a national testing agency as to their intrinsic safety, but this requirement was relaxed since adequate data was provided to indicate suitability in the specific installation.

The amplifiers (Figure 3) used in the IFD systems are also specially designed to be low cost ($100-$200) and intrinsically safe. An additional feature was needed to keep costs low: The amplifiers draw their electrical power over the same cabling that carries the acoustic high frequency signal, so that only a single coaxial cable is needed. Where low frequency vibration is monitored, however, this is not possible, so in these cases, a

TABLE 2. IFD SYSTEM CONFIGURATIONS.

System	Number of Multiplexers	Number of Terminals	Number of Channels SAT/RMS	VIB	PUL	Number of Machines
1	3	2	219	9	32	102
2	4	1	295	12	0	84
3	4	3	250	21	0	90
4	3	1	206	3	0	83
5	3	1	205	4	0	58

Note: This data represents actual *installed* features. Sufficient *spare* capacity was included to allow 3 terminals on all systems and 80% more channels.

Figure 2. IFD Sensors: (l. to r.) Crystal Mounting, Boeing Design (N/A), Metrix Wide Range, HERCO, Acoustic Emission Technology.

special dual preamplifier was used which "piggybacked" a low frequency amplifier on the power supplied to the high frequency amplifier.

As can be seen from Figures 2 and 3, there are several vendors currently making the low cost sensors and amplifiers. The large number of these components required by IFD systems of medium to large scale dictates that they must be inexpensive. In fact, they are one of the major factors contributing to the cost effectiveness of second generation IFD systems.

IFD Signal Processing

The key feature in the processing of signals in computer-based IFD systems is the use of signal multiplexing before parameter measurement. This allows the use of only one channel of processing circuitry since only one channel is sampled at a time. The amount of custom electronics in the central console is thus simplified and system costs dramatically reduced (Figure 4).

The principal function of the multiplexing system is to selectively switch one of a number of analog signals onto a single output. In addition, a non-switched DC voltage must be provided to each high-frequency input line as a power source for the pre-amplifier driving that line. The multiplexing system is subdivided into "submultiplexers" which are located remotely from the central control unit but near the signal sources.

A number of submultiplexers are located in strategic locations classified Class I, Division II or less throughout the plant to reduce the number of cables required. These submultiplexers are housed in general purpose enclosures and require a source of 110 volts 60 Hz single phase AC power at less than 2 amperes. The submultiplexers sample acoustic data from each antifriction bearing or gear transducer and transmit this information to the central stations over a single cable for processing and analysis.

As shown in the block diagram (Figure 1), there are basically four parameters that can be measured and analyzed by current IFD systems: high-frequency acoustic energy (RMS), high frequency signal-above-threshold (SAT), high-frequency pulse count (PUL) and low-frequency vibration (VIB). These parameters have been discussed in detail elsewhere [1, 5, 14, 17], but are summarized briefly below.

Frequency Band

As has been discussed and justified in previous reports [3, 5, 6], high-frequency acoustic channels encompass a bandwidth from 80 kHz to 120 kHz because this frequency range is sufficiently removed from the background noise typically

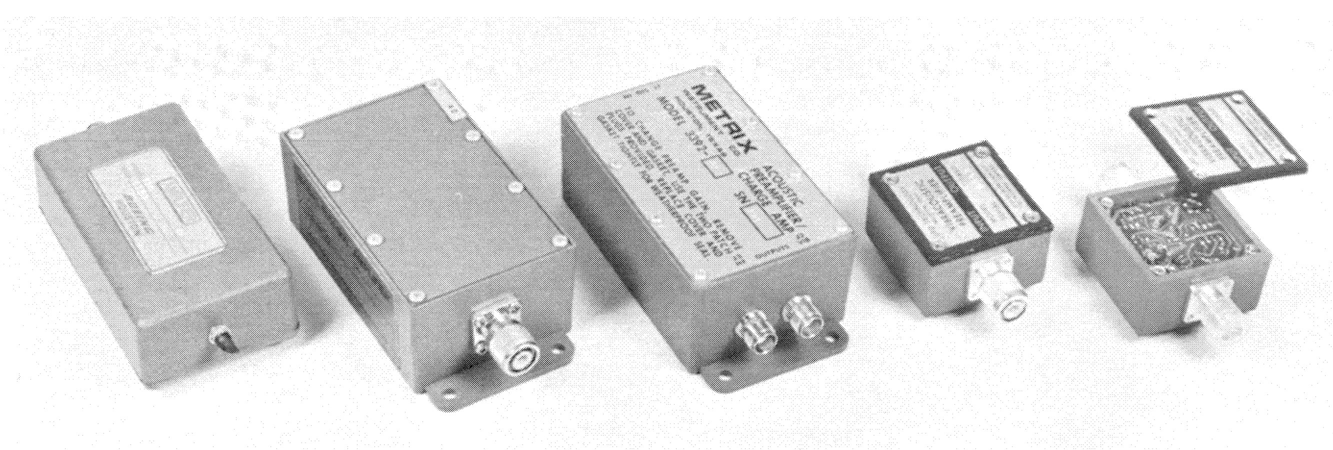


Figure 3. IFD Preamplifiers: (l. to r.) Boeing (N/A), HERCO, Metrix Wide Range, IFD Technology, Gain-Changing Jumpers.

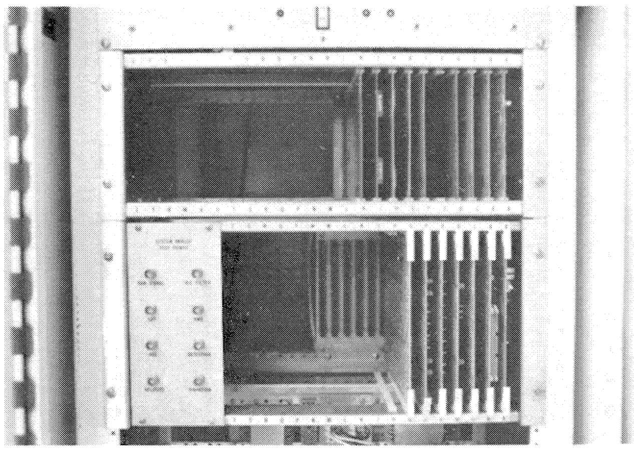


Figure 4. Main Processing Circuits in IFD Central Console.

encountered in an industrial plant environment. Low-frequency vibration channels use the same 10 Hz to 1 or 2 kHz bandwidth customarily found in handheld vibration meters.

RMS Parameter

The RMS parameter provides an indication of the overall amount of ultrasonic energy generated by a rotating machine. This is generally equivalent to the "smoothness" of mechanical contact since the energy emitted is examined at a frequency high enough to discount the effects of rotational energy. RMS is normally described as "friction noise" and was found to represent confirmation of internal bearing defects.

SAT Parameter

The signal above threshold (SAT) represents the total value of the signal energy above a set threshold in a given time period. Where RMS is mostly a measurement of random noise, SAT is a measurement of abnormal signals of high amplitude that have a specific cause: the sudden release of energy due to mechanical impact or fracture. SAT is generally directly related to defects present in the bearings and contact surfaces of rotating equipment, and consequently provides the earliest indication of failure.

PUL Parameter

Crack propagation in piping and vessels produces abnormal signal bursts of high amplitude; consequently failure may be predicted by counting the number of these bursts in a given time interval and monitoring their rate of increase. These signal bursts are related to the growth of cracks and the surface-to-surface movement around them [7, 8].

Two facts should be noted about this parameter as used in second generation IFD systems. First, it is not used in rotating equipment monitoring where it has been replaced by the SAT measurement. Second, it is not multiplexed, as are the other acoustic signals. In general, pulse count measurements are still somewhat experimental when applied to on-line monitoring of piping and vessels.

VIB Parameter

Vibration in inches per second (IPS) is a well-known parameter used to identify immediate problems such as rotor unbalance and gross bearing defects. Inclusion of this parameter in the system allows for instrumentation of machines which are highly susceptible to those problems, such as centrifuges and reciprocating compressors.

Other Parameters

The remainder of the processing circuitry used in the IFD systems performs a function normally seen in conventional machinery vibration signature analysis (MVSA) systems [13, 19]: frequency spectrum analysis is done by means of a fast Fourier transform (FFT) algorithm implemented as a special purpose program in the computer. The filtering and detection circuitry shown in Figure 1 is necessary for preprocessing and also for "carrier detection" of the high-frequency signal to allow it to be analyzed for low-frequency information [5]. This capability of the system provides a means of evaluating the high-frequency or vibration signal in terms of machine operating frequencies and permits the identification of the root cause of defects detected by other parameters.

The Computer System

First and second generation IFD systems differ primarily in the extent to which computer power is used to simplify data acquisition. Where first generation systems scanned measurements at slow rates and saved results on paper printouts [2], second generation systems scan rapidly and save data on a large disk memory unit. Presentation of this data in many different formats then becomes a user-demandable function. Interactive features such as prompts and messages are also used to make it easy to access this information. Other features such as spectrum analysis, alarm limit checking, data scaling and channel "name" association are also implemented to overcome the limitations that made first generation systems difficult to use.

In summary, many of the features which make it possible to use IFD technology on a large plant-wide scale are the result of computer - assisted monitoring. The vast amount of data analysis needed to provide adequate surveillance of 1200 sensor points would simply be impractical otherwise. Whereas second generation IFD systems are cost-effective primarily because of multiplexing and low-cost sensors and amplifiers, they are powerful and useful because of the computer.

OPERATION OF SECOND GENERATION IFD SYSTEMS

As has been stated, most of the differences between first and second generation IFD systems center around the operating details. The most obvious feature of the newer systems is of course the computer terminal which allows simple user interaction with the system. There are, however, other features that deserve careful description: The scanning procedure, the alarm checking procedure, and the historical data storage.

Automatic Scanning

As shown in Figure 5, current IFD systems use a 90-second cycle to scan and measure the four basic parameters. The most significant feature of this 90-second cycle is that the number of measurements made on a given parameter depends on the parameter. First generation IFD systems attempted to measure *all* parameters on a given channel before stepping to the next channel. This forces the system to operate on the scan rate of the slowest parameter (SAT) which required an average time of 30 seconds to settle to a stable value.

This scan cycle time was a severe limitation of the early systems. A typical 200-channel system only measured parameters on a given channel once every 100 minutes and thereby missed many sudden changes on short-term problems. Plant operators could not correlate startup with an IFD alarm an hour later when the system finally monitored the equipment being started. In fact, several sudden equipment failures did

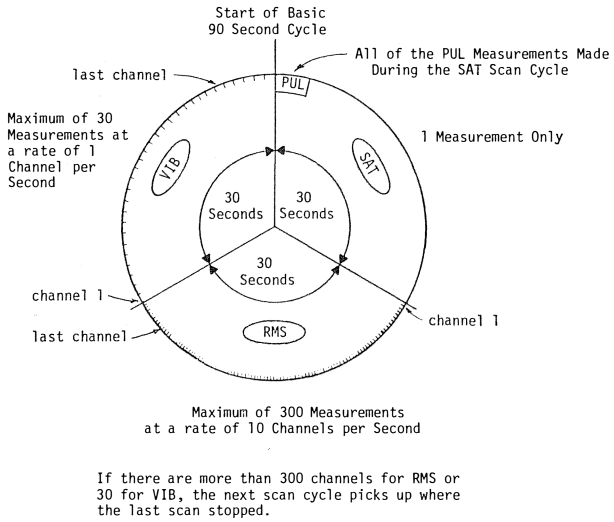


Figure 5. Scan Cycle for Parameter Processing.

occur without IFD warnings simply because the system was busy scanning other channels.

Breifly put, IFD technology is intended to give early warning but in a general purpose machinery surveillance system it must also provide continuous monitoring. Experience indicates that while some failures occur slowly and can be predicted days in advance, many occur very rapidly and require "tight" surveillance even to detect. One of the outstanding benefits of second generation IFD systems is that they provide both capabilities.

In order to achieve this, the newer systems automatically scan each parameter at its maximum practical rate, as described on the following page.

1. RMS is measured at the fastest scan rate and at the most frequent intervals since it may be rapidly acquired, yet is a highly reliable parameter of machine operation. Every 90 seconds a rapid (10Hz) scan is made of the high-frequency channels and RMS data is collected. This portion of the basic 90-second interval lasts 30 seconds; if all high-frequency channels cannot be scanned, the scan sequence continues in the next scan interval.
2. SAT is measured at the slowest scan rate since the SAT integrator requires a relatively long interval to accumulate meaningful data. Every 90 seconds only one high-frequency channel can be scanned for SAT over an interval of 30 seconds.
3. VIB (vibration) is measured slowly due to the required settling time for this parameter; every 90 seconds a scan of vibration channels at a rate of 1 Hz is begun which lasts 30 seconds. As for RMS measurements, if all channels cannot be scanned in 30 seconds, the scan sequence continues in the next 90 second cycle.
4. PUL (pulse count) may be acquired in an independent time frame since it is continuously available and does not have to be scanned; however, the basic time interval should be controlled for meaningful measurement of count rate. Therefore, all channels of pulse count are scanned once each 90-second cycle during the SAT interval.

As mentioned previously, the current IFD systems also are capable of spectral analysis by means of the FFT algorithm. This analysis also fits into the 90-second cycle when it is requested by a user; it simply displaces scanning of the other parameters beginning with SAT. Normally, *only* the SAT interval is needed for an FFT analysis.

Alarm Checking

As with any data acquisition system, all parameters are checked when measured against stored limits to determine out-of-limit or alarm conditions. However, the technique of alarm incrementing was developed on first generation IFD systems and was found to be very useful. This feature allows an arbitrary increment to be specified for each alarm limit so that whenever a measurement exceeds its limit, the limit is automatically "bumped" by the amount of the increment. The RMS parameter was the primary factor in developing this concept; it was reasoned that a simple absolute limit would be inappropriate for a relative measurement of that type.

Two benefits result from the alarm incrementing feature. First, the severity of a problem can be judged from the number of alarms issued since it takes more increments to stabilize the alarm level for rapidly rising or large changes. Second, since alarm levels automatically "float up" to their normal level, they need not be carefully set initially. This greatly simplifies the process of system installation or channel calibration for an inexperienced user.

Further justification of alarm incrementing comes from the fact that the RMS parameter is a trend parameter and the alarm structure must be capable of handling it. That is, any level of RMS is theoretically acceptable as long as it is stable; high levels should cause alarms signifying an increase but should not remain in the alarm state if they level off. This is not a particularly useful concept for the other parameters but the feature may be used if desired or removed by setting the increment at zero.

Historical Data Storage

In order to display the data trends needed to evaluate the significance of alarms, long-term storage of parameter measurements is needed. As described previously, this data base is maintained on a disk memory unit under computer control. Figure 6 illustrates the structure of the historical data files and the data averaging used to "compress" long-term measurements into a small number of data points.

There are four basic grouping of data in this structure, classified roughly by the time period covered by each file of data: current (6 hours), daily (24 hours), weekly (21 days) and monthly (120 days). Each file represents successively less time resolution of RMS, PUL, and VIB data because several readings are averaged into one. For instance, the "weekly" file consists of 504 readings at one hour intervals; each reading represents 10 of the "daily" readings, or 40 of the "current" readings, averaged together. Only the "current" data represents actual measurements made on the 90-second cycle.

SAT data does not suffer from the averaging process, though, since it inherently has low-time resolution. Consequently, all SAT data is saved in one file containing 400 measurements at intervals determined by the number of channels in the system. For example, a system having 200 SAT variables on scan would take

$$200 \times 90 \text{ sec.} = 300 \text{ min.} = 5 \text{ hours}$$

to make a full scan. Although this slow scan makes it difficult to catch transient problems with SAT measurements, it is a natural result of the slow speed at which reliable data can be gathered from a single SAT processor with multiplexed inputs. This is not considered a problem because SAT is not intended

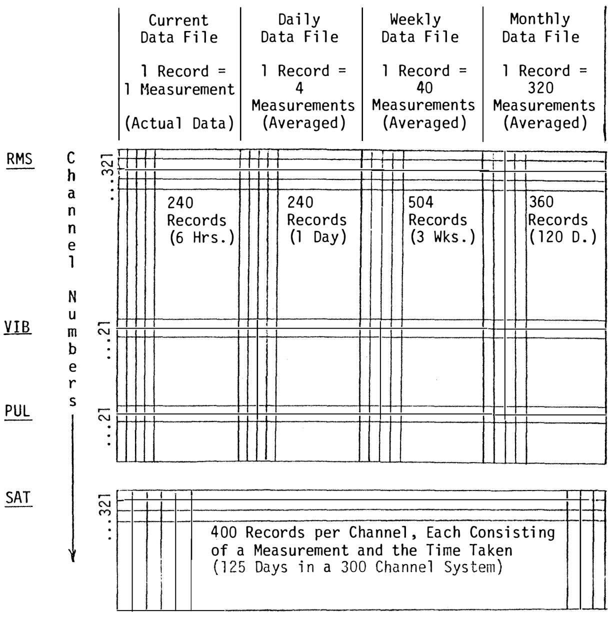


Figure 6. Historical Data File Structure.

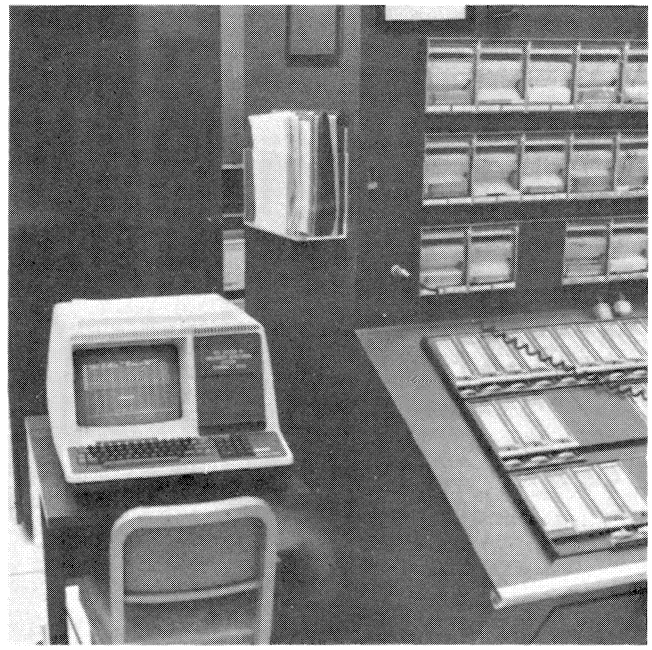


Figure 7. IFD System Terminal.

to detect transient problems; it is very definitely an early warning indicator.

The historical data base serves as the only record of system measurements since there are no periodic logs and in fact no printout devices, although the video terminal incorporates a hard copy printer and will permit an occasional copy to be made. Due to the averaging process the system does not preserve transient information; any data "older" than one file is only saved by being averaged into the next larger file. This means that it is impossible to determine the exact circumstances surrounding an alarm unless someone has made a copy of the high resolution "current" data file.

With historical data being averaged, retrieval of relevant quasi-instantaneous values requires a procedural solution, as will be described later: a log or trend plot of the data surrounding an alarm event must be printed out when the alarm is acknowledged. This inconvenience somewhat overshadows the advantages of the computer-managed data base, and will probably be solved in future systems by the addition of longer history files for "current" data and by automatic logging or storage of data surrounding alarm events.

The basic historical data file structure is nevertheless justified by the fundamental principle of IFD technology: failures take time to develop. If all failures were sudden, there would be no need for historical data or trend analysis. Simply because some problems take more time than others to develop, there is need to have both long-term, low-resolution data and short-term, high-resolution data. This is the purpose of having four data files which can characterize failures by the time required to see changes: a few hours ("current"), a day ("daily"), a few weeks ("weekly"), or a few months ("monthly").

Demandable Functions

The functions of second generation IFD systems described so far are automatic and are not as important to a user as those functions which are demandable from the system terminal. As shown in Figure 7, the system terminal is a CRT (cathode ray tube) device with a standard typewriter keyboard and an integral copier. In normal operation there are eighteen basic functions that may be called by entering a two-letter "function code." A typical display called the MENU (Figure 8) lists these codes; this display can be requested by typing in "??" or any combination of two letters that does not represent a valid function code. The purpose of the MENU is simply to show a user what functions are available and how they may be requested.

Some functions require entry of a verification code before they will begin; these are the *privileged functions* shown on the left of the MENU. They allow significant changes to be made to the data base of the system and so their use is restricted. All other functions are considered normal system functions.

Where remote terminals are used, the number of functions available is also restricted, as shown by the MENU display of a typical remote terminal in Figure 9. There are two reasons for this: first, remote terminals are meant only as alarm displays and, second, the limited power of the computer chosen does not allow all the features to be implemented.

```
DATE 30 - JUNE - 78    TIME 15:20:59    IFD SYSTEM 2          FUNCTION (MN)

MENU OF AVAILABLE FUNCTIONS

     PRIVILIGED FUNCTIONS               OPERATOR ENTRIES

     EN - ENTER CHANNEL NAME            HR - HISTORICAL TABULAR DISPLAY
     DN - DELETE CHANNEL NAME           DT - DISPLAY HISTORICAL TREND
     FF - FAST FOURIER TRANSFORM        AL - ALARM LIMITS DISPLAY
     CS - CHANGE SERVICE STATUS         AH - ALARM HISTORY DISPLAY
     SC - CHANGE SCALE FACTOR           DC - DISPLAY CHANNELS OUT-OF-SERVICE
                                        CA - CHANGE ALARM LIMITS
                                        IA - INHIBIT-ENABLE ALARMS
                                        BA - BASIC DISPLAY
                                        UA - UNACKNOWLEDGED ALARMS
                                        ?? - MENU
                                        OS - OUT OF SEQUENCE SAT
                                        FH - FUNCTIONAL HISTORY LOG
                                        LN - LIST CHANNEL NAME
```

Figure 8. "MENU" Display of Available Functions.

```
DATE 05-JUL-78  TIME  11:11:07      IFD SYSTEM  1      FUNCTION  (   )

MENU OF AVAILABLE FUNCTIONS

     OPERATOR ENTRIES

     DT - DISPLAY HISTORICAL TREND
     HR - HISTORICAL TABULAR DISPLAY
     IA - INHIBIT-ENABLE ALARMS
     UA - UNACKNOWLEDGED ALARMS
     ?? - MENU
```

Figure 9. "MENU" of Remote Terminal.

All of the functions available make use of prompting to simplify interaction with the system; that is, a user is always told what type of information the system is expecting. If the wrong entry is made, the system will either notify the user of this or else will terminate the function. Thus, the system is designed to be as simple to use and as foolproof as possible.

The following descriptions discuss the various functions in more detail.

EN, DN, and LN:
Accessing Channel Information

These three functions provide the means for defining, deleting and listing the points that the system monitors. EN is a privileged function that allows definition of all the characteristics of a channel; Figure 10 is an example of the prompting features involved in using this function. DN is also a privileged function that will completely delete a channel from the data base; LN (unprivileged) simply lists the characteristics of channels in the system.

As shown in Figure 11, each channel has several characteristics associated with it; the most important of these is the CHANNEL NAME, a six character identifier that is used throughout the system to call up information on a channel. The other characteristics are described as follows:

POINTER - a number indicating the position in the scan sequence

CHANNEL DESCRIPTOR - an 18-character description of the channel

TYPE - a description of the parameter being monitored on that channel; high-frequency channels, of course, have two parameters, RMS and SAT

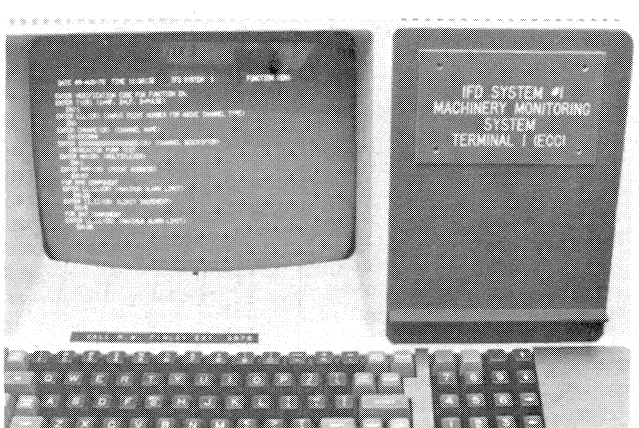


Figure 10. EN Function Prompting Sequence.

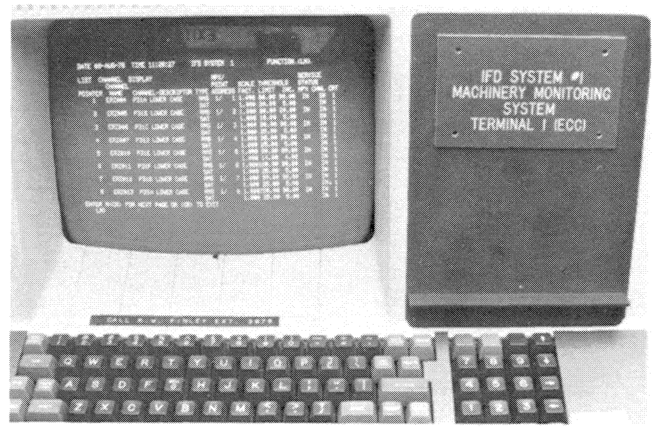


Figure 11. LN Function Display Showing Channel Characteristics.

MPX/POINT ADDRESS - the number of the multiplexer and the terminal to which the cable for the channel is connected

SCALE FACT - the scale factor is multiplied by the measurement to "fine tune" or calibrate readings when a channel is set up

THRESHOLD LIMIT - the alarm limit

THRESHOLD INC - the alarm increment

SERVICE STATUS MPX - whether the multiplexer is on scan

SERVICE STATUS CHNL - whether the channel is on scan

CRT - which terminal the channel is assigned to for alarm purposes

HR and DT:
Displaying the Data Base

These two functions are the key features of second generation IFD systems: they allow a user to call up the trend displays that permit easy evaluation of data patterns. HR (historical recall) provides a tabular listing of measurements from any one of the four historical data files, while DT (display trend) generates a plot of these values against a time axis. Both functions direct the system to recall, sort and display data from the extensive data base maintained on the disk memory.

A typical prompt sequence for the HR request is shown in Figure 12; the types of information requested from the user are explained as follows:

CHNAME - The six character "channel name" described previously

S or R - The user must specify whether SAT or RMS data is desired for a high-frequency channel, since only one parameter at a time can be displayed. For low-frequency (VIB) or pulse count (PUL) channels, only one parameter is possible and the user is not prompted.

C,D,WorM - The user can specify which of the four historical data files should be displayed. For SAT data, which is not stored in this way, the user is not prompted — all data available will be displayed.

Next Page - Since all the data from a given file cannot be shown on the screen at once, it is "paged" in groups of

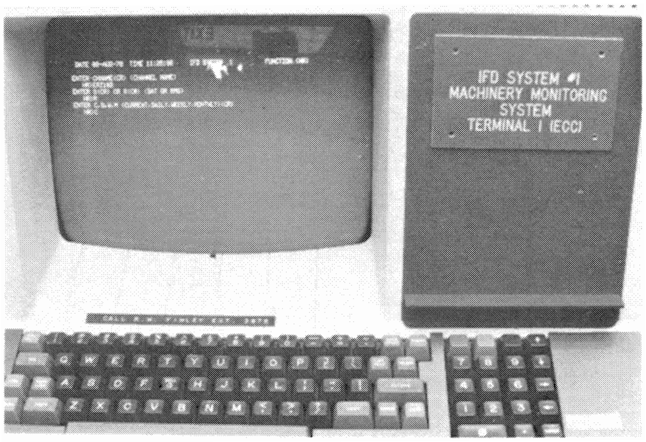


Figure 12. HR Function Prompting Sequence.

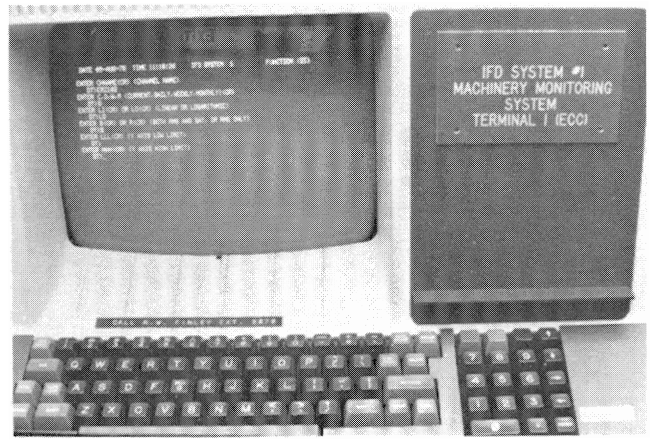


Figure 14. DT Function Prompting Sequence.

32 items. The user must request the next page if more data is needed.

<CR> - The user must transmit each entry to the computer by pressing the "carriage return" key on the keyboard. If no entry is made but <CR> is pressed, the function will be terminated.

A typical HR display of RMS data is shown in Figure 13. Notice that units of measurement are not given; data is simply displayed as a percentage of full scale. In actuality there is a relationship that links these measurements back to physical parameters, but for trending purposes only the relative percentages are important. Although this makes channel-to-channel comparisons difficult, it simplifies initial installation, as will be described later.

The prompting sequence for the DT function (as shown in Figure 14) is very similar to that of HR, except the user is also given the option of displaying *both* RMS and SAT and of setting the zero and full scale limits of the graph. A typical DT plot is shown in Figure 15.

UA, IA and AH:
Handling Alarms

Three functions are provided to allow a user to acknowledge, inhibit and list alarms that occur in the process of checking measurements against stored alarm limits. UA is the primary function since it provides a display of the alarms that are considered "active;" that is, have not been acknowledged (Figure 16).

As long as there are any such points, the system holds a relay closed to signal the alarm state to an external device such as a panel alarm. The IA function inhibits the activation of this relay but has no effect on the routine processing of alarm conditions. The UA function always clears the alarm relay by automatically acknowledging all active alarms.

Alarm conditions related to system faults are displayed in addition to normal overlimit alarms. In these cases, the display is similar except a message is presented instead of numbers for the alarm limit and the value exceeding that limit.

The system automatically stores all of the alarms in a data file once they are acknowledged, and this information is available to a user by means of the AH function. This display as seen in Figure 17 also allows judgment of the severity of an alarm because frequently occurring alarms are readily apparent. Figure 17 also shows the alarm incrementing feature already described; the alarm limit on point PFV069 obviously increases by .70 after each successive alarm.

Figure 13. HR Display (Typical).

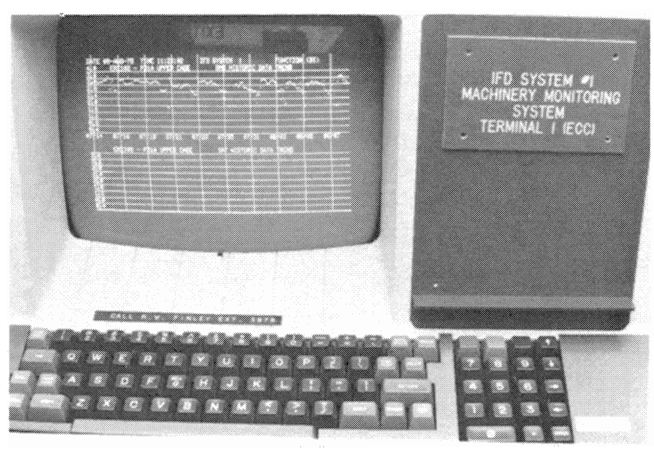


Figure 15. DT Display (Typical).

Figure 16. UA Display (Typical).

Figure 18. FH Display (Typical).

FH - System Activity Log

Several functions described so far obviously can significantly change the operation of the system; for instance, DN can completely destroy all records on a channel. In order to monitor these activities, the system automatically records the date, time and type of each transaction in a data file called "function history." A user may request a display of this information by simply requesting the function FH (Figure 18). Any questions regarding proper operation of the system at any given time can thus be resolved.

FF - Spectral Analysis

As discussed earlier, second generation IFD systems provide spectral analysis by means of instrumentation for prefiltering and via special programs that perform a fast Fourier transform (FFT). However, this is not a routine parameter measurement since it has been found to be primarily an analysis tool and, like SAT, requires a significant amount of processing time. This does not contradict the body of literature which documents the benefits of spectral analysis, both for high-frequency "detected carrier" signals [4, 5] and for conventional low-frequency MVSA [13, 19, 20]. However, the user expertise and system complexity necessary for implementation of continuous spectral monitoring were not thought to be justified for a general purpose system.

Consequently, FFT analysis is handled on demand by entry of the function code FF as shown in Figure 19. As can be seen this is a relatively specialized function that requires a knowledgeable user, so FF is classed as a "privileged" function. After entering the verification code, the user is prompted

DATE 08-AUG-78 TIME 11:00:22 IFD SYSTEM 1 FUNCTION (AH)

ACKNOWLEDGED ALARMS FOR CRT NUMBER: 1

DATE	TIME	NAME	DESCRIPTION	TYPE	ALARM LIMIT	ALARM VALUE
08/09/78	10:17:31	ERZ275	- FAN GEARBOX 5 BOT	RMS	10.00	13.58
08/09/78	00:32:34	ERZ342	- FAN GEARBOX 16 HS	RMS	15.00	15.19
08/09/78	00:16:04	ERZ331	- FAN GEARBOX 7 HS	RMS	35.00	35.37
08/09/78	00:14:33	ERZ331	- FAN GEARBOX 7 HS	RMS	30.00	35.71
08/09/78	00:13:03	ERZ331	- FAN GEARBOX 7 HS	RMS	25.00	35.91
08/09/78	00:11:33	ERZ331	- FAN GEARBOX 7 HS	RMS	20.00	36.15
08/09/78	00:10:04	ERZ331	- FAN GEARBOX 7 HS	RMS	15.00	33.56
08/09/78	00:08:33	ERZ331	- FAN GEARBOX 7 HS	RMS	10.00	33.71
08/08/78	15:17:37	ERZ050	- MA7E SHAFT HSNG	RMS	15.00	27.31
08/08/78	13:36:53	ERZ081	- MA8A SHAFT HSNG	RMS	20.00	42.46
08/08/78	00:20:20	ERZ102	- P31A UPPER CASE	RMS	210.00	214.95
08/07/78	11:50:19	ERZ010	- P31E LOWER CASE	SAT	10.00	12.35
08/06/78	00:40:11	ERZ270	- FAN GEARBOX 26 TOP	RMS	25.00	34.39
08/06/78	00:38:44	ERZ322	- FAN GEARBOX 26 BOT	RMS	10.00	12.31
08/06/78	00:38:40	ERZ270	- FAN GEARBOX 26 TOP	RMS	20.00	36.59
08/06/78	00:37:00	ERZ270	- FAN GEARBOX 26 TOP	RMS	15.00	24.52

ENTER N(CR) FOR NEXT PAGE OR (CR) TO EXIT
AH).

Figure 17. AH Display (Typical).

Figure 19. FF Function Prompting Sequence.

for the number of spectra to be averaged, the frequency range desired, and whether the display is to be linear or logarithmic. The resulting display is shown in Figure 20.

It should be noted that a spectral plot can be run for either a high-frequency or a low-frequency channel. In the case of the low-frequency channel, an FFT is taken from the actual velocity signal; for a high-frequency channel, the signal is both normalized and detected, as shown in Figure 1. The process of deriving low-frequency information from a high-frequency channel has been described elsewhere [5, 6] and need not be covered in detail. It is sufficient to say that the technique used simply determines the periodic characteristics of the abnormalities that may occur repetitiously in the high-frequency waveform.

As the display of Figure 20 illustrates, two spectra are actually presented: an "old" or baseline plot and the "new" or current plot. This permits a comparison to be made when the significance of a new plot is not immediately apparent.

CS, DC and OS: Altering the Scan Sequence

These three functions allow a user to take channels in and out of service, display those that are "off scan" and request a special out-of-sequence SAT measurement. CS is a privileged function since it inhibits monitoring of any channel or multiplexer, and this is not normally necessary. However, whenever

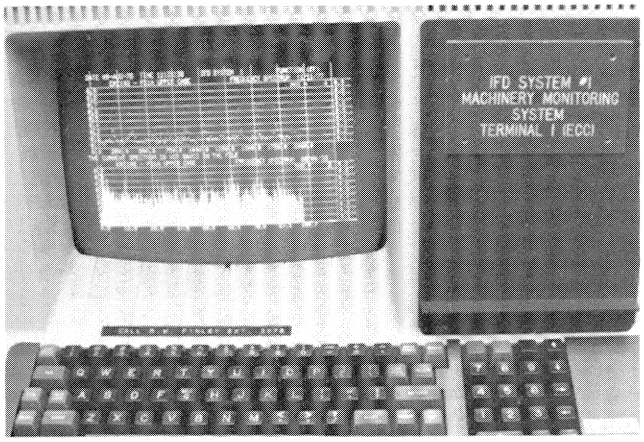


Figure 20. FF Display (Typical).

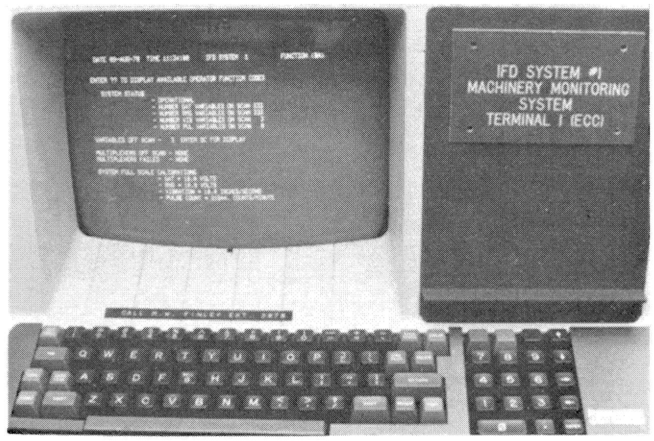


Figure 21. BA Display.

maintenance is being done, it is usually best to remove channels or multiplexers from service to prevent erroneous data from being collected. A user may always check to see which channels have been disabled in this way by requesting the DC function.

The OS function is a means of forcing the system to measure the SAT parameter for a given channel. This is necessary since otherwise a user only sees SAT data on a channel once every few hours even though it may be needed to analyze an immediate problem. Although an automatic out-of-sequence measurement could easily be triggered by an alarm, current systems only implement the user-demandable OS function.

CA and AL:
Accessing the Alarm Limits

These two functions permit a user to change alarm limits and increments (CA) as well as display them (AL) for any channel. Neither function was originally considered a privileged function although CA obviously affects system behavior, and any changes are logged in the function history. Despite the possibility of effectively disabling an alarm, it is still considered important that any user be able to set alarm levels if the need arises. For instance, although alarm limits are normally set at two to five times the normal running level, special circumstances may warrant setting them much closer to warn of slight changes in operation.

SC: The Scale Factor

Each parameter for a given channel in a system has associated with it a scale factor by which all incoming measurements are multiplied. Normally this factor is unity, but for special calibration purposes it can be set anywhere from .01 to 9.99 to compensate for differences in sensors, amplifiers, multiplexers and cable losses. For trending purposes, of course, absolute accuracy is not important, but for some measurements (mostly vibration) it is necessary. The SC function, which is of course privileged, permits a user to adjust the scale factor accordingly. As will be discussed later, a simple procedure of installation involves using the scale factor to normalize baseline data.

BA: The Basic Display

The BA function is the last of the 18 normal system functions available to the user; the display which results is shown in Figure 21. The purpose of this display is to provide a quick summary of system operation, including the total number of parameters on scan, disabled channels, multiplexers which have failed or are off scan, and full scale (100%) voltage equivalents for each parameter.

Special Features

In addition to all the normal system functions which are demandable by entering a two-letter "function code," there are four special features that may be requested by following more elaborate procedures. They are not normal functions because they involve operating the system out of the scan mode. Startup and shutdown, for instance, are two of the operations; the other two, the auto-FFT and the low-value scan, require special scan routines. All of the features except the auto-FFT require direct commands to the computer operating system.

The startup, also called "coldstart" or "boot," is of course the most important special operation. It basically allows a user to restart the system whenever a problem develops that cannot otherwise be corrected. The procedure consists of depressing a special "boot" switch on the computer console and then entering required information through the terminal, in particular, the proper time and date. A typical display is shown in Figure 22. Power failures cause an automatic restart, although the time will be in error and must eventually be reset by a special command to the operating system.

System shutdown could of course be accomplished by turning power off; however, an orderly shutdown consists of removing all active system programs. A special command was implemented with this in mind. The consideration was that a simple power down leaves data files on the disk memory in an undetermined state, and this is not desirable if disk cartidges are being replaced.

The low-value scan function and the auto-FFT both place the system in a special scan mode. In the case of the auto-FFT, the purpose is to compile a baseline spectrum for all channels in the system without having to run the FF function for each channel. The low-value scan causes the system to scan all high-frequency channels for RMS measurements which are lower

```
003062 002776 177450 004772
$DK

  RSX-11M V03 BL18   28K
>RED DK0:=SY0:
>MOU DK0:UNMOBJ
>@[1,2]STARTUP
>* PLEASE ENTER TIME AND DATE (HH:MM MM/DD/YY) [S]: 08:47 7/14/78
```

Figure 22. Startup Procedure Display.

than some preset limit. This is particularly useful in system installation since it simplifies finding "dead" sensors and improperly installed channels. A typical display is shown in Figure 23.

SYSTEM IMPLEMENTATION

The benefits of plant-wide incipient failure detection cannot be realized without effort in non-budgetary areas. Just as money doesn't usually buy happiness, a fat appropriation alone will not ensure the commitment of plant personnel to utilize IFD systems to the fullest extent possible. Neither will money alone buy the optimum specification document.

The initial experience with prototype computerized acoustic IFD led to the development of highly detailed specifications for the second generation systems described above. While the development of these or similarly satisfactory systems is judged well within the capabilities of a team composed of an experienced systems engineer and a similarly qualified machinery engineer, we would caution against entrusting the task to either a well-meaning electronics expert or to the machinery specialist alone. Unless detailed specifications are developed with the clear intent of satisfying the reasonable requirements of the electronic and mechanical engineering disciplines involved, the end product may not represent the optimum system at all.

We believe that the merits of detailed, jointly written specifications cannot be overemphasized. These specifications are the backbone of inquiries which should be discussed with — not just mailed to — potential contractors or systems vendors. A vendor must fully understand what he is asked to provide, how the system is envisioned to function, and how operators and technical personnel can best use the devices in their daily work. If this essential understanding is lacking, work execution may suffer from a variety of disappointing compromises ranging from cost cutting component execution to restrictive interpretation of software design.

An equally important facet of systems implementation involves obtaining operator input, concurrence and commitment at the earliest possible stage, usually well before releasing the specification to potential bidders.

Operations Management and operators themselves have to be shown what computerized acoustic IFD systems can do for them. They have to be convinced that the appearance of yet another "black box" in their control centers is not burdening them with additional tasks but, instead, facilitates their work,

```
 DATE 29-MAR-78  TIME 12:19:54     IFD SYSTEM 2           FUNCTION (DG)

LOW-VALUED CHANNEL DIAGNOSTIC                  MPX/             PAGE  1 OF 10
        CHANNEL                                POINT   CHANNEL
POINTER  NAME    CHANNEL-DESCRIPTOR     TYPE ADDRESS    VALUE   CRT   ERRORS
    1    PPS193  C402C PUMP OUTBD        RMS   1/   1    0.00    1  MUX-COMM
   85    PLY179  P4101A PUMP INBD        RMS   2/   1    1.95    1
   86    PLY185  P4101B PUMP INBD        RMS   2/   2    1.37    1
   87    PLY081  P4107A PUMP INBD        RMS   2/   3    0.24    1
   88    PLY075  P4107B PUMP INBD        RMS   2/   4    0.05    1
   89    PLY055  P4108A PUMP INBD        RMS   2/   5    0.05    1
   90    PLY049  P4108B PUMP INBD        RMS   2/   6    0.05    1
   91    PLY093  P4109A PUMP INBD        RMS   2/   7    1.66    1
   92    PLY087  P4111A PUMP INBD        RMS   2/   8    0.05    1
   93    PLY019  P4109B PUMP INBD        RMS   2/   9    1.07    1
   94    PLY013  P4111B PUMP INBD        RMS   2/  10    0.05    1
   95    PLY067  P4113A PUMP INBD        RMS   2/  11    1.17    1
   96    PLY061  P4113B PUMP INBD        RMS   2/  12    0.05    1
   97    PLY007  P4122A PUMP INBD        RMS   2/  13    0.05    1
   98    PLY001  P4122B PUMP INBD        RMS   2/  14    0.05    1
   99    PLY031  P4206A PUMP INBD        RMS   2/  15    0.05    1
ENTER N⟨CR⟩ FOR NEXT PAGE OR ⟨CR⟩ TO RESCAN
   DG⟩N
```

Figure 23. Low Value Scan Function Listing (Typical).

provides for the early identification of potentially troublesome equipment, and greatly enhances overall plant safety.

Both ease of operation and reliable design must be achieved before these users will be convinced of the value of acoustic IFD systems. While ease of operation can be achieved by pre-defining operator interactions in the design specification, design reliability must be verified by appropriate testing at the vendor's facilities before shipment is authorized. Excessive field troubleshooting will inevitably cast doubt on the usefulness of IFD systems and will undermine the credibility of the entire approach in the eyes of operating personnel.

Consequently, the vendor should also be required to fulfill a final acceptance criterion of extended system performance, and, in addition, should provide a long-term total warranty. Both requirements result in added incentive to produce a "solid" system and also simplify maintenance during the period of time that in-house personnel are becoming familiar with the system.

The second generation IFD system project at Baytown was implemented by following most of the guidelines mentioned, and much of the success is attributed to that factor. In addition, the previous experience with first generation systems was important in determining those features which make the newer systems easier to use. The combination of these design concepts and project execution methods for second generation IFD systems have resulted in a machinery surveillance program that stands entirely on its own merit.

Installation

The most difficult phase of the IFD project was the installation of the field components: sensors, pre-amplifiers, multiplexers, conduit and cable. Both plant personnel and contractors were unfamiliar with the novel instrumentation and careful attention was necessary just to keep the job moving. Problems were encountered that ranged from improper location of conduit to difficulty in selecting the proper pre-amplifier gain.

Experience with first generation systems indicated that a rugged field installation was critical for reliable operation. Cabling had to be given mechanical protection wherever there was risk of damage. General routing of conduit and pre-amplifier and sensor mounting locations were chosen so that machinery could be serviced or even removed without requiring excessive dismantling of field-mounted IFD components. We found it highly desirable to solicit the advice of field maintenance personnel before finalizing field installation details.

The last major hurdle in field installation was the problem of pre-amplifier gain selection and channel calibration. Instrumentation personnel had to be trained in the operation of sensors and amplifiers, particularly regarding the concept of high-frequency measurements. IFD technology, although straightforward, remains difficult to understand because it is unrelated to simple process measurements and can be affected by many operating variables. Consequently, it is very difficult to determine if an absolute measurement is "right."

Still, some guidelines are essential for installation if any meaningful data is to be obtained. For initial installation, it was decided to normalize baseline data by choosing pre-amplifier gains and scale factors such that the initial baseline RMS reading was 1%. The SAT parameter was automatically normalized by an automatic gain control (AGC), as shown in Figure 1; VIB of course could be calibrated against conventional vibration instrumentation; and PUL was pre-calibrated. The only problems, then, were to make sure that each channel could be set up with a 1% RMS reading and to troubleshoot those that could not.

This procedure was adequate for initial installation simply because IFD data is relative in nature. Even though it may be wrong to assume that the initial 1% reading represented "normal" operation, it at least is easy to evaluate the magnitude of further changes. Frequently, though, it has become necessary to modify the initial calibration to reflect known variations in machine performance. For instance, a pump reading higher than others in similar service should not be scaled down if the pump is under greater load.

Furthermore, it is generally desirable to have all similar sensor locations processed identically by having the same size amplifier and scale factor. In these cases, it is more important to know relative differences between channels than to normalize each channel independently. Still, it would be unwise to attempt to measure all channels on the same scale since experience has shown that variations of 1000 to 1 in "normal" levels are possible. Interpretation of absolute readings over such a range would be impossible since a normal reading on one channel might be catastrophic on another.

Thus, the basic procedure was to initialize all readings at 1% RMS and revise this setting later if necessary. Portable IFD instruments were frequently used to verify readings or to troubleshoot, and have also been used as standards for calibration. Even so, the process of channel installation remains somewhat arbitrary and time-consuming.

Training

Of particular importance to the success of the IFD project was the effort spent training field maintenance, operating, and supervisory personnel in areas pertinent to their work. Field maintenance forces were given an overview of the system, and sensor placement and removal were carefully explained and documented. Operating personnel required training in console operation and fault recognition. Presentations were made to supervisory and management personnel to explain what the acoustic IFD systems do and how they should be operated to derive maximum benefits.

In turn, the supervisors defined the reporting steps necessary to go from alarm event acknowledgment in the control center to problem analysis involving operators, mechanical work forces or technical staff personnel. The responsibilities for implementing corrective action had to be clearly assigned by management to the various specialists. At each step it was necessary to assure proper training of the people involved.

Of course, training is a continuing requirement since utilization is a direct function of familiarity. Most important, though, the proper discharging of responsibilities by all personnel involved must be monitored quite frequently. On the one hand the successes and probable cost savings by timely reaction to IFD alarms should be documented and credit given where due. Conversely, management followup and renewed emphasis on the merits of proper utilization of IFD as a cost reduction tool may be required if the defined responsibilities are not carried out with the proper degree of diligence.

Application

From the information presented thus far, it should be clear that second generation IFD systems have two basic functions: on-line machinery monitoring and special data handling for user analysis. In the case of the monitoring function, the primary user is the process operator, while the data handling feature was mainly intended for the equipment specialist. In either case, procedures were developed to explain the proper use and application of the system.

For the process operator, these procedures were written in a standard format for instrument systems that covered startup, shutdown, normal operation and alarm handling. The most important feature was the alarm handling procedure, and, as previously promised, is detailed below:

1. When the panel alarm is activated, request the UA function at the system terminal — this will clear the panel alarm;
2. Note the channel listed on the screen and request the DT function for that channel;
3. Check all operating conditions associated with the equipment in question and correct any abnormalities;
4. If there are no unusual process conditions or obvious equipment problems, determine how severe the DT increase appears to be and either notify the equipment specialist immediately or send a copy of the DT plot to him for later analysis;
5. If there are other indications of equipment problems, contact the equipment engineer or shut the equipment down;
6. If there are abnormal process conditions, correct them and note the occurrence in the unit logbook;
7. If new, yet acceptable process conditions have caused the signal excursion, no follow-up action needs to be taken.
8. In all cases, a copy of the DT plot should be saved for the equipment specialist.

As this procedure indicates, the equipment specialists play a major role, not only in analyzing data, but also in making decisions based on on-line alarms. For this reason, an extensive amount of material was prepared for the specialists which described system operation and use, and several orientation classes were held to discuss their role. Routine meetings bring this group together to communicate experience on the systems to further improve the ability to predict failure or even time-to-failure.

Other key individuals in this program are the systems engineer and the machinery engineer who developed the original specification. They provide continuity to the project and serve as focal points for continued application. Also, since they prepared the original justification, it is their duty to compile the data which confirms it.

Maintenance

The final element of system implementation is maintenance, which involves aspects of installation as well as troubleshooting. An effective maintenance program generally requires cooperation between the vendor, who can handle the more difficult problems, and in-house personnel, who are responsible for day-to-day operation and initial troubleshooting. Frequently, most of the maintenance can be done in-house, especially on a system which is properly designed and documented.

Second generation IFD systems were designed with modular elements and subsystems that can be easily replaced. Consequently, the key to effective maintenance and troubleshooting is to understand enough about system operation to isolate problems to a particular subsystem or module. With the aid of a tool called the troubleshooting flowchart (Figure 24), most maintenance can then be done in-house.

The vendor of course is responsible for all warranty work, and this normally covers an extended period (about a year) of system operation. After that period of time, maintenance by the vendor generally involves some sort of contractual agreement. In the case of the IFD project installation, maintenance is somewhat more sophisticated since various elements of the

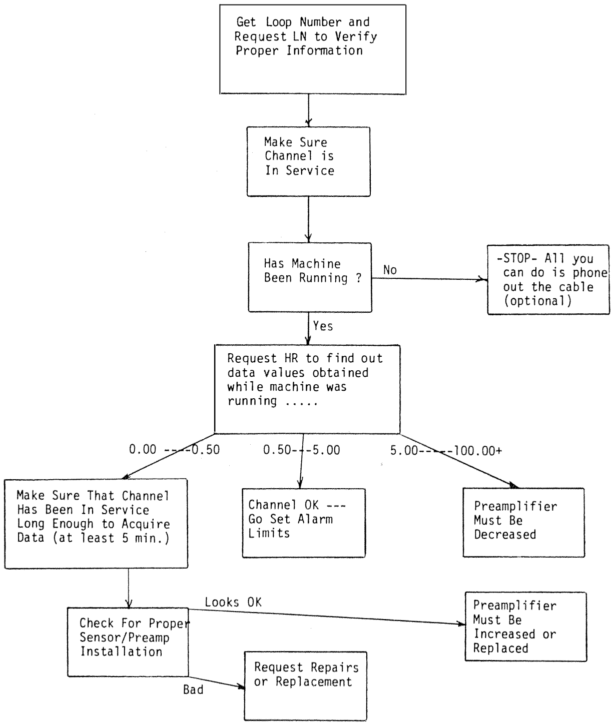


Figure 24. Troubleshooting Flowchart for IFD Systems.

system are covered in different ways: pre-amplifiers, sensors and cabling are maintained in-house, vendor-manufactured hardware and software is under warranty, and computers and peripherals are serviced on a time-and-material contract with the vendor. Potential users should be aware of the merits of each approach and not simply opt for a comprehensive (and expensive) maintenance contract with the vendor.

The optimum maintenance approach is to service the systems in-house after a learning period during which the systems should be fully warranted. The vendor should be required to provide training for in-house personnel and should also be capable of supporting service for special circumstances after warranty expires. It is also especially important that proper emphasis be placed on the coordination of the in-house program; knowledgeable people must always be available to answer questions and follow through on any maintenance problem. In many instances it is most practical to integrate the IFD maintenance program with the general instrument maintenance program.

At any rate, IFD system maintenance need not be a special problem; reliability overall is very good due to the simple structure, which also facilitates troubleshooting. Experience indicates that a simple maintenance procedure documented by flowchart and based on simple replacement can handle most problems. In fact, the major maintenance problem is simply servicing pre-amplifiers and sensors, which is a very straightforward process.

Implementation Follow-up

In summary, the implementation of the second generation IFD project involved five major areas: project development, installation, training, application, and maintenance. The latter two areas are part of a continuing program to utilize the systems to their fullest extent. One of the keys to doing this is to make sure that users, operations personnel, and management are kept aware of progress and experience. For this reason a newsletter is published twice a month to highlight activity on the systems. To reiterate a point already made, the benefits of an IFD system ultimately depend on the amount of such effort spent in making sure the program is properly implemented.

CASE HISTORIES

The proper application of second generation IFD systems is best illustrated by examples from field experience. As can be seen, these examples do not always involve bearing failure, which IFD technology was initially developed to detect. There are several instances of gear failures, misalignment, cavitation and process changes which are clearly detected in the IFD data. This simply emphasizes that IFD technology has a wide range of applications in the machinery surveillance field and can be used effectively for general purpose plant monitoring.

Cavitation of Centrifugal Pump

Figure 25 shows the historic record (function HR) of a pump cavitation event. Operating normally, this pump had displayed RMS signal levels ranging between 8 and 25. Accordingly, the alarm threshold was set at 40.

The first alarm occurred on 02/19/78 around 2AM (Note that Figure 25 shows *average* values retroactively retrieved from the computer disc memory. This explains the average signal value of 64.75 calculated at 02:35:43). Alarms were automatically incremented in steps of 10; i.e., signal values of 50, 60, 70, etc., had to be exceeded to trigger subsequent alarms. This historic record was retrieved from the computer on 22-Feb-78, at 08:36:37. About an hour later, at 08:46:35 the RMS historic data trend (function DT) was requested and displayed on the CRT screen as seen in Figure 26 in logarithmic form. It shows that the pump had been shut down from February 2 until February 9 (log signal = 0.4). After startup on February 9 it ran without excessive signal deviation until February 14 (averaged log signal = 1.2). Step increases were experienced on February 14 and 16 to approximate log values of 1.6 and 2.1, respectively. Frequent cavitation took place on and after February 18 with peak events clustered around February 19 be-

```
DATE 22-FEB-78   TIME 08:36:37      IFD SYSTEM  2          FUNCTION (HR)
        CPA075 - P321B PUMP INBD         RMS TABULAR DATA DISPLAY

  33 02/20/78 14:37:03   75.31          49 02/19/78 22:35:43  27.44
  34 02/20/78 13:36:17   62.24          50 02/19/78 21:35:43  46.33
  35 02/20/78 12:30:54   47.10          51 02/19/78 20:35:43  53.02
  36 02/20/78 11:30:19   48.44          52 02/19/78 19:35:43  51.71
  37 02/20/78 10:30:11   73.25          53 02/19/78 18:35:43  36.46
  38 02/20/78 09:29:50   72.06          54 02/19/78 17:35:43  48.68
  39 02/20/78 08:29:52   58.57          55 02/19/78 16:35:43  73.29
  40 02/20/78 07:29:43   42.74          56 02/19/78 15:35:45  60.32
  41 02/20/78 06:29:43   75.46          57 02/19/78 14:35:43  72.79
  42 02/20/78 05:29:43   99.43          58 02/19/78 13:35:43 125.28
  43 02/20/78 04:29:43   79.81          59 02/19/78 12:35:43 153.76
  44 02/20/78 03:29:43   79.25          60 02/19/78 11:35:43 167.46
  45 02/20/78 02:29:43   56.46          61 02/19/78 10:35:49 218.03
  46 02/20/78 01:35:43   94.31          62 02/19/78 09:35:43 193.91
  47 02/20/78 00:35:43   43.31          63 02/19/78 08:35:43 216.86
  48 02/19/78 23:35:43   45.29          64 02/19/78 07:35:43 243.47

ENTER N FOR NEXT PAGE,ITEM NUMBER TO SCALE DATA,<CR> TO EXIT
 HR>

DATE 22-FEB-78   TIME 08:36:37      IFD SYSTEM  2          FUNCTION (HR)
        CPA075 - P321B PUMP INBD         RMS TABULAR DATA DISPLAY

  65 02/19/78 06:35:58 199.30           81 02/18/78 14:41:55  18.50
  66 02/19/78 05:35:43 170.40           82 02/18/78 13:41:43  19.79
  67 02/19/78 04:35:43  71.49           83 02/18/78 12:41:43  27.88
  68 02/19/78 03:35:43  41.79           84 02/18/78 11:41:43  17.35
  69 02/19/78 02:35:43  64.75           85 02/18/78 10:41:43  20.49
  70 02/19/78 01:41:43  20.96           86 02/18/78 09:41:43  23.43
  71 02/19/78 00:41:43  14.43           87 02/18/78 08:41:43  22.74
  72 02/18/78 23:41:43  17.69           88 02/18/78 07:41:43  17.31
  73 02/18/78 22:41:43  19.62           89 02/18/78 06:41:43  20.22
  74 02/18/78 21:41:43  23.14           90 02/18/78 05:41:43  17.13
  75 02/18/78 20:41:43  19.78           91 02/18/78 04:41:43  23.34
  76 02/18/78 19:41:43  15.54           92 02/18/78 03:41:43  19.61
  77 02/18/78 18:41:43  17.53           93 02/18/78 [illegible]  23.06
  78 02/18/78 17:41:43  26.47           94 02/18/78 01:47:43  13.14
  79 02/18/78 16:41:48  29.17           95 02/18/78 00:47:43   8.56
  80 02/18/78 15:41:43  22.85           96 02/17/78 23:47:43   8.62

ENTER N FOR NEXT PAGE,ITEM NUMBER TO SCALE DATA,<CR> TO EXIT
 HR>
```

Figure 25. HR Display of Cavitation.

tween 05:35 and 13:35 hours on tabular and graphic display records.

The cavitation events on this pump were fully corroborated by strip chart recordings retrieved from the control center which placed severe flow fluctuations into identical time frames over a period of one week.

Serious Coupling Defect
Leading to Sleeve Bearing Failure

P-312A is a large multi-stage process pump with impellers located between pump inboard ball bearing (Channel CPA 003), and pump outboard ball bearing, (Channel CPA 001). The pump is driven by a 250 HP, sleeve bearing-equipped electric motor. Channel CPA 007 represents the IFD transducer located on the inboard bearing of the motor.

Figure 27 shows how the two pump AFB channels accounted for 14 acknowledged alarm events in the time period from January 25, 1978, until February 1, 1978. This history of acknowledged alarms (function AH) shows that Channel CPA 003 was initially set to alarm at a threshold RMS level of 10.00. It was programmed to increment upward in steps of 5. Consequently, it alarmed again when signal levels of 15, 20, 25, etc. were exceeded. This channel reached a maximum RMS signal level of 30 about 13 hours after the first alarm was logged in. Channel CPA 001 started out with an initial alarm limit of 5, was programmed to increment in steps of 1 and consequently alarmed sometime later when threshold levels of 6 and 7 were exceeded. On February 1, Channel CPA 001 was reprogrammed for an RMS alarm threshold of 10.00 and increments of 2. In only 4 hours, the alarm limit had incremented itself to 20.00, causing 5 alarm events in the process.

Channels CPA 003 and CPA 001 remained at their new, and somewhat high signal levels until February 19, 1978, when the motor sleeve bearing channel (CPA 007, Figure 28) suddenly caught up and in the span of only 20 minutes went from an average RMS reading of 0.98 (at 14:35:43) to 12.09 (at 14:53:43). At 14:56, the operator's log shows that an emergency shutdown had become necessary because the motor inboard bearing had been destroyed.

A thorough analysis showed that the grease lubricated gear-type limited end-float coupling had experienced lubrication failure which caused "tooth hangup" around January 24/26, January 31/February 1, and again later. These events are observable on the trend plots (function DT) and historical record displays (function HR) of Figures 29 and 30 for channels CPA 003 and CPA 001, respectively. While the pump antifriction bearings were not involved in the failure incident, their IFD sensors nevertheless picked up the signal disturbances created by the coupling defect. The IFD sensor mounted on the massive motor sleeve bearing (Channel CPA 007) proved sensitive only after the oil film was destroyed and the motor journal made contact with the bearing babbitt.

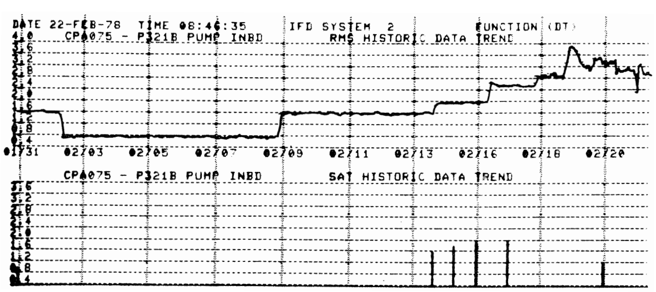


Figure 26. DT Display of Cavitation.

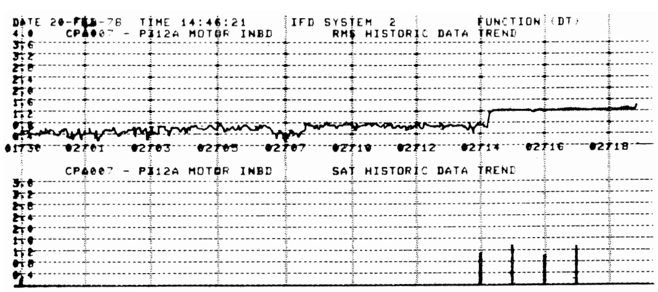
```
DATE 03-FEB-78  TIME 13:01:00      IFD SYSTEM  2            FUNCTION (AH)

     ACKNOWLEDGED  ALARMS FOR CRT NUMBER: 1
                                                              ALARM     ALARM
     DATE      TIME      NAME      DESCRIPTION         TYPE   LIMIT     VALUE

   02/01/78  18:20:52  CPA141 - P322A VIBRATION        VIB    40.00     40.64
   02/01/78  14:05:36  CPA001 - P312A PUMP OUTBD       RMS    20.00     20.03
   02/01/78  12:17:36  CPA001 - P312A PUMP OUTBD       RMS    18.00     19.64
   02/01/78  10:59:10  CPA001 - P312A PUMP OUTBD       RMS    16.00     19.59
   02/01/78  10:54:40  CPA001 - P312A PUMP OUTBD       RMS    14.00     16.12
   02/01/78  10:51:38  CPA001 - P312A PUMP OUTBD       RMS    12.00     15.10
   02/01/78  10:50:08  CPA001 - P312A PUMP OUTBD       RMS    10.00     17.73
   01/31/78  17:55:10  CPA001 - P312A PUMP OUTBD       RMS     7.00      7.75
   01/31/78  11:42:26  682027 - P3 PUMP OUTBD          RMS    12.00     13.63
   01/31/78  09:44:10  CPA139 - P322A MOTOR INBD       RMS    10.00     28.38
   01/31/78  02:13:52  682027 - P3 PUMP OUTBD          RMS    11.00     17.15
   01/30/78  12:40:22  CPA141 - P322A VIBRATION        VIB    30.00     30.78
   01/30/78  10:11:55  CPA141 - P322A VIBRATION        VIB    20.00     22.37
   01/28/78  01:19:49  682041 - P6 PUMP INBD           RMS    10.00     10.16
   01/27/78  12:02:45  100HZ1 - 100HZ TEST SIGNAL      VIB    90.00     92.46
   01/27/78  12:01:20  100HZ1 - 100HZ TEST SIGNAL      VIB    85.00     92.53
ENTER N FOR NEXT PAGE OR <CR> TO EXIT
   AH>
```

```
DATE 03-FEB-78  TIME 13:01:00      IFD SYSTEM  2            FUNCTION (AH)

     ACKNOWLEDGED  ALARMS FOR CRT NUMBER: 1
                                                              ALARM     ALARM
     DATE      TIME      NAME      DESCRIPTION         TYPE   LIMIT     VALUE

   01/27/78  11:59:53  100HZ1 - 100HZ TEST SIGNAL      VIB    80.00     92.48
   01/27/78  11:56:51  100HZ1 - 100HZ TEST SIGNAL      VIB    80.00     92.53
   01/26/78  04:11:24  682021 - P4 PUMP OUTBD          RMS     6.00      7.77
   01/26/78  02:30:52  682021 - P4 PUMP OUTBD          RMS     5.00      5.86
   01/25/78  16:57:45  682027 - P3 PUMP OUTBD          RMS    10.00     10.11
   01/25/78  13:51:32  CPA003 - P312A PUMP INBD        RMS    30.00     35.64
   01/25/78  13:39:29  CPA001 - P312A PUMP OUTBD       RMS     6.00      6.08
   01/25/78  12:42:30  CPA003 - P312A PUMP INBD        RMS    25.00     25.95
   01/25/78  12:39:30  CPA003 - P312A PUMP INBD        RMS    20.00     20.01
   01/25/78  12:38:00  CPA003 - P312A PUMP INBD        RMS    15.00     19.54
   01/25/78  10:32:52  682027 - P3 PUMP OUTBD          RMS     9.00     14.51
   01/25/78  08:32:59  682027 - P3 PUMP OUTBD          RMS     8.00     10.55
   01/25/78  08:24:07  CPA065 - P322A PUMP OUTBD       RMS    10.00     10.38
   01/25/78  04:44:59  CPA001 - P312A PUMP OUTBD       RMS     5.00      5.46
   01/25/78  02:11:56  682027 - P3 PUMP OUTBD          RMS     7.00      8.35
   01/25/78  00:00:10  CPA003 - P312A PUMP INBD        RMS    10.00     11.72
ENTER N FOR NEXT PAGE OR <CR> TO EXIT
   AH>
```

Figure 27. AH (Alarm History) Display for Coupling Defect.

Process Reaction Monitoring Via Acoustic IFD

Figure 31 shows the high frequency signal trend of a process reactor over a period of approximately 18 hours. When the reaction was inhibited, the signal returned to a low value. This example illustrates how acoustic IFD methods can be used to




```
DATE 20-FEB-78  TIME 14:46:56      IFD SYSTEM  2           FUNCTION (AL)

LIST ALARM LIMITS
ENTER CHNAME<CR> (CHANNEL NAME)
   AL>CPA007
      RMS    8.00   SAT   10.00

ENTER CHNAME<CR> (CHANNEL NAME)
   AL>
```

```
DATE 20-FEB-78  TIME 14:31:57      IFD SYSTEM  2           FUNCTION (HR)

      CPA007 - P312A MOTOR INBD        RMS TABULAR DATA DISPLAY

   225 02/19/78 16:05:43    0.12
   226 02/19/78 15:59:43    0.00
   227 02/19/78 15:53:43    0.00
   228 02/19/78 15:47:43    0.00
   229 02/19/78 15:41:43    0.00
   230 02/19/78 15:35:45    0.00
   231 02/19/78 15:29:49    0.24
   232 02/19/78 15:23:54    0.00
   233 02/19/78 15:17:58   -0.12
   234 02/19/78 15:11:55    0.00
   235 02/19/78 15:05:43    0.00
   236 02/19/78 14:59:43   -0.12
   237 02/19/78 14:53:43   12.09
   238 02/19/78 14:47:43    3.79
   239 02/19/78 14:41:43    1.71
   240 02/19/78 14:35:43    0.98

ENTER N FOR NEXT PAGE,ITEM NUMBER TO SCALE DATA,<CR> TO EXIT
  HR>
```

Figure 28. Displays Associated With Sleeve Bearing Failure.

DATE 03-FEB-78 TIME 13:04:40 IFD SYSTEM 2 FUNCTION (HR)

CPA003 - P312A PUMP INBD RMS TABULAR DATA DISPLAY

161	01/27/78	11:59:48	1.11	177	01/26/78	20:05:46	1.41
162	01/27/78	10:59:47	1.08	178	01/26/78	19:05:46	1.14
163	01/27/78	09:59:47	1.20	179	01/26/78	18:05:46	1.37
164	01/27/78	08:59:46	1.03	180	01/26/78	17:05:46	1.09
165	01/27/78	07:59:46	1.02	181	01/26/78	16:05:46	8.90
166	01/27/78	06:59:47	1.07	182	01/26/78	15:05:52	5.59
167	01/27/78	05:59:47	1.12	183	01/26/78	14:05:46	1.89
168	01/27/78	04:59:46	1.14	184	01/26/78	13:05:46	1.13
169	01/27/78	03:59:46	1.15	185	01/26/78	12:05:46	1.71
170	01/27/78	02:59:46	1.10	186	01/26/78	11:05:46	1.02
171	01/27/78	01:59:47	1.27	187	01/26/78	10:05:51	1.78
172	01/27/78	00:59:46	1.03	188	01/26/78	09:05:51	1.32
173	01/26/78	23:59:47	1.00	189	01/26/78	08:05:46	1.04
174	01/26/78	23:05:46	1.06	190	01/26/78	07:05:46	1.00
175	01/26/78	22:05:46	1.08	191	01/26/78	06:05:47	0.96
176	01/26/78	21:05:47	1.66	192	01/26/78	05:05:46	0.99

ENTER N FOR NEXT PAGE, ITEM NUMBER TO SCALE DATA, (CR) TO EXIT
HR>

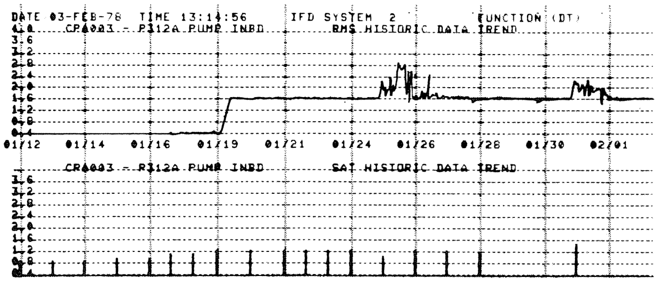
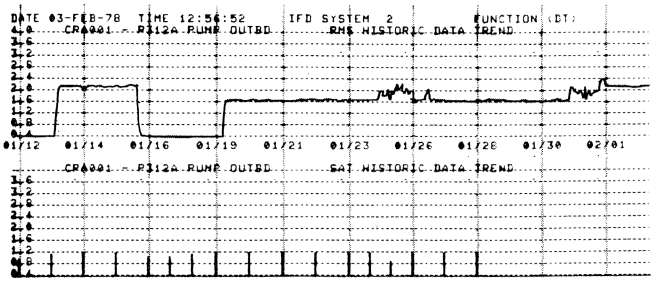


Figure 29. Displays Associated With Coupling Defect — Pump Inboard.



DATE 03-FEB-78 TIME 12:57:56 IFD SYSTEM 2 FUNCTION (HR)

CPA001 - P312A PUMP OUTBD RMS TABULAR DATA DISPLAY

33	02/01/78	20:20:45	3.67	49	02/01/78	04:19:15	1.46
34	02/01/78	19:20:45	3.46	50	02/01/78	03:19:16	2.52
35	02/01/78	18:20:45	4.12	51	02/01/78	02:19:22	1.67
36	02/01/78	17:20:46	4.14	52	02/01/78	01:19:23	0.99
37	02/01/78	16:20:45	3.70	53	02/01/78	00:25:15	3.35
38	02/01/78	15:20:45	5.27	54	01/31/78	23:25:15	1.92
39	02/01/78	14:20:45	6.50	55	01/31/78	22:25:15	1.19
40	02/01/78	13:20:55	4.61	56	01/31/78	21:25:15	2.33
41	02/01/78	12:20:45	5.04	57	01/31/78	20:25:15	2.77
42	02/01/78	11:20:32	5.57	58	01/31/78	19:25:16	1.89
43	02/01/78	10:20:21	2.31	59	01/31/78	18:25:15	2.11
44	02/01/78	09:20:33	2.54	60	01/31/78	17:25:15	1.81
45	02/01/78	08:20:09	2.26	61	01/31/78	16:25:15	3.02
46	02/01/78	07:19:46	1.92	62	01/31/78	15:25:17	2.55
47	02/01/78	06:19:54	2.13	63	01/31/78	14:25:15	2.66
48	02/01/78	05:19:15	1.67	64	01/31/78	13:25:02	3.31

ENTER N FOR NEXT PAGE, ITEM NUMBER TO SCALE DATA, (CR) TO EXIT
HR>

DATE 03-FEB-78 TIME 12:57:56 IFD SYSTEM 2 FUNCTION (HR)

CPA001 - P312A PUMP OUTBD RMS TABULAR DATA DISPLAY

65	01/31/78	12:24:47	2.08	81	01/30/78	20:28:46	1.11
66	01/31/78	11:24:57	1.06	82	01/30/78	19:28:46	1.07
67	01/31/78	10:24:52	1.03	83	01/30/78	18:28:46	1.06
68	01/31/78	09:24:32	1.08	84	01/30/78	17:28:46	1.06
69	01/31/78	08:23:46	1.10	85	01/30/78	16:28:46	1.08
70	01/31/78	07:23:46	1.04	86	01/30/78	15:28:46	1.09
71	01/31/78	06:23:46	1.03	87	01/30/78	14:28:34	1.05
72	01/31/78	05:23:46	1.06	88	01/30/78	13:28:15	1.05
73	01/31/78	04:23:50	1.07	89	01/30/78	12:28:15	1.06
74	01/31/78	03:23:17	1.10	90	01/30/78	11:28:15	1.06
75	01/31/78	02:23:17	1.10	91	01/30/78	10:28:17	1.06
76	01/31/78	01:23:06	0.99	92	01/30/78	09:28:15	1.05
77	01/31/78	00:28:46	1.10	93	01/30/78	08:28:15	1.09
78	01/30/78	23:28:46	1.10	94	01/30/78	07:28:15	1.06
79	01/30/78	22:28:46	1.10	95	01/30/78	06:28:15	1.04
80	01/30/78	21:28:46	1.11	96	01/30/78	05:28:15	1.03

ENTER N FOR NEXT PAGE, ITEM NUMBER TO SCALE DATA, (CR) TO EXIT
HR>

Figure 30. Displays Associated With Coupling Defect — Pump Outboard.

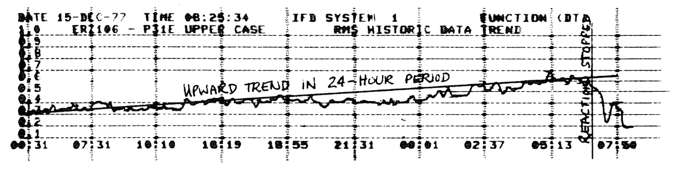


Figure 31. DT (Trend) Plot Showing Reaction Progress.

monitor chemical reaction processes through trend plotting of RMS signals reaching transducers mounted on the reactor shell.

Excessive Seal Leakage Triggers IFD Alarms

A leakage event on the outboard seal housing of a centrifugal pump (P-30A, Channel EFH 217) is captured on Figures 33 through 35. Figure 32 shows two alarms occurring on January 20, 1978. The first event took place at 01:19:22 when the RMS signal exceeded the initial alarm threshold of 10.00. The limit was automatically incremented to 15.00, and this new limit again exceeded at 07:00:09. The pump was then examined and found to have developed a serious seal leak. It was shut down around 8 AM. Trend display (Function DT, Figure 33) and historic tabular record (Function HR, Figure 34) were requested around IPM. Both plots showed how the increasing signal trend began around 10 PM on January 19, and progressed upward until shutdown was effected.

Motor Pump Misalignment

Figure 35 shows an example of the spectrum analysis capabilities of the system being used to analyze the misalignment problem. In this case the first time the FF function was requested (note that there is no baseline plot shown on the upper graph of Figure 35) two significant spectral lines were noted at 29HZ (1750 RPM) and 58Hz (3500 RPM). This pump is a 90 HP, 1750 RPM electric motor driven centrifugal water

DATE 20-JAN-78 TIME 13:13:14 IFD SYSTEM 1 FUNCTION (AH)

ACKNOWLEDGED ALARMS FOR CRT NUMBER: 2

DATE	TIME	NAME	DESCRIPTION		TYPE	ALARM LIMIT	ALARM VALUE
01/20/78	07:00:09	EFH217	- P30A OUTBRD HSNG		RMS	15.00	15.05
01/20/78	01:19:22	EFH217	- P30A OUTBRD HSNG		RMS	10.00	10.41
01/18/78	00:21:44	EFH176	- EXPELLER	A	RMS	30.00	37.13
01/10/78	17:58:53	EFH127	- P30B COUPLING		RMS	10.00	10.99
01/10/78	02:21:22	EFH176	- EXPELLER	A	RMS	25.00	27.85
01/09/78	00:36:08	EFH171	- EXPANDER DRYER	B	RMS	10.00	11.48
01/08/78	19:34:39	EFH176	- EXPELLER	A	RMS	20.00	20.76
01/08/78	09:00:25	EFH161	- EXPELLER L.S. DR.	A	RMS	10.00	10.26
01/08/78	05:45:38	EFH150	- EXPELLER HOUSING	A	RMS	10.00	11.24
01/08/78	05:27:39	EFH176	- EXPELLER	A	RMS	15.00	16.85
01/06/78	14:13:03	EFH176	- EXPELLER	A	RMS	10.00	10.99
12/07/77	10:52:37		POWER FAIL				
11/03/77	13:00:25	EFH236	- VCU THRUST BRGOUTE		RMS	MUX-COMM	ERROR
11/03/77	13:00:23	EFH235	- VCU THRUST BRG INE		RMS	MUX-COMM	ERROR
11/03/77	12:55:37	EFH236	- VCU THRUST BRGOUTE		RMS	MUX-COMM	ERROR
11/03/77	12:55:36	EFH235	- VCU THRUST BRG INE		RMS	MUX-COMM	ERROR

ENTER N FOR NEXT PAGE OR (CR) TO EXIT
AH>

Figure 32. AH Display Showing Effects of a Seal Leak.

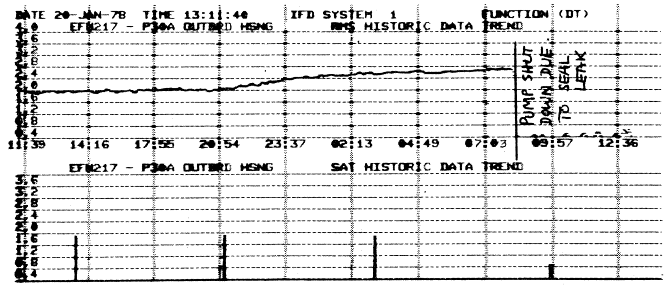
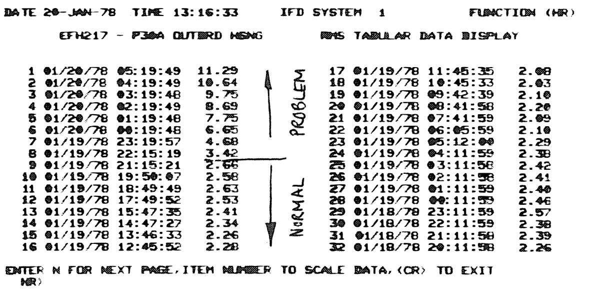


Figure 33. DT Display Trend Associated with Seal Leak.



DATE 20-JAN-78 TIME 13:16:33 IFD SYSTEM 1 FUNCTION (HR)

EFH217 - P30A OUTBRD HSNG RMS TABULAR DATA DISPLAY

1	01/20/78	05:19:49	11.29	17	01/19/78	11:45:35	2.08
2	01/20/78	04:19:49	10.64	18	01/19/78	10:45:33	2.03
3	01/20/78	03:19:48	9.75	19	01/19/78	09:42:39	2.10
4	01/20/78	02:19:49	8.69	20	01/19/78	08:41:58	2.20
5	01/20/78	01:19:48	7.75	21	01/19/78	07:41:59	2.09
6	01/20/78	00:19:48	6.65	22	01/19/78	06:05:59	2.10
7	01/19/78	23:19:57	4.68	23	01/19/78	05:12:00	2.29
8	01/19/78	22:15:19	3.42	24	01/19/78	04:11:59	2.38
9	01/19/78	21:15:21	2.66	25	01/19/78	03:11:58	2.42
10	01/19/78	19:50:07	2.58	26	01/19/78	02:11:58	2.41
11	01/19/78	18:49:49	2.63	27	01/19/78	01:11:59	2.40
12	01/19/78	17:49:52	2.53	28	01/19/78	00:11:59	2.46
13	01/19/78	15:47:35	2.41	29	01/18/78	23:11:59	2.57
14	01/19/78	14:47:27	2.34	30	01/18/78	22:11:59	2.38
15	01/19/78	13:46:33	2.26	31	01/18/78	21:11:58	2.39
16	01/19/78	12:45:52	2.28	32	01/18/78	20:11:58	2.26

ENTER N FOR NEXT PAGE, ITEM NUMBER TO SCALE DATA, (CR) TO EXIT
HR)

Figure 34. HR Display Showing Five-Fold Increase Due to Seal Leak.

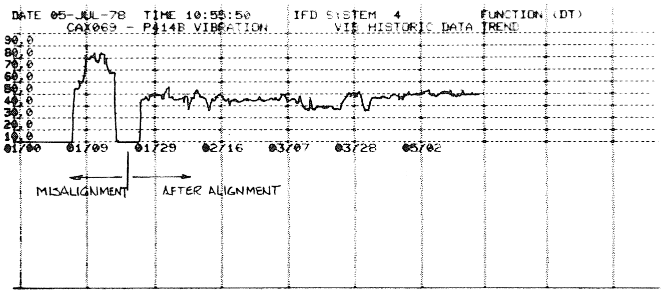


Figure 36. DT Plot Showing Vibration Levels Before and After Alignment.

pump, and it was immediately suspected of misalignment. Although conventional vibration readings confirmed a higher-than-normal level, the problem was not considered severe enough for immediate service. In fact, the RMS parameter showed that there was no upward trend to indicate wearout.

This example illustrates an unusual fact: unbalance and misalignment can be detected by high-frequency spectrum analysis even though IFD technology is generally not suited to this purpose [5]. As this instance shows, though, there are occasions where a low frequency phenomenon has a significant effect on IFD measurements. What appears to happen is that vibration causes a "rattle" in a loosely loaded bearing, and this metal impact is picked up with high frequency acoustics [12].

Pump Alignment Lowers Vibration

Second generation IFD systems also have the capability of making low-frequency vibration measurements (VIB). As shown in Figure 36, this type of measurement makes possible simple diagnosis of running condition — in particular, detection of misalignment. Although, the vibration levels shown were not calibrated, the relative difference between the values obtained at startup on 1/9 and after alignment on 1/29 reflects a definite improvement in running condition. In addition, the time period between 3/7 and 3/28 shows the effect of decreased load, indicating that vibration levels are sensitive to process changes.

Extruder Pelletizer Bearing Failure

Data illustrated in Figure 38 was plotted from tabular RMS data taken on three channels on the pelletizer assembly of a large extruder. Data on all three of these channels had previously run consistently at about 1% when the pelletizer was in operation, so the alarm level had been set at 2.5%. When RMS suddenly increased around 11:00 on 5/2/78, it caused an alarm which attracted the attention of the equipment engineer for

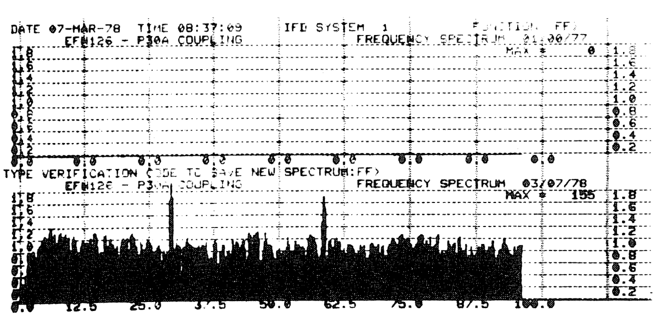


Figure 35. FF Display Showing Misalignment.

that unit. After a few more hours of operation, a definite trend and audible noise seemed to justify a shutdown.

Teardown of the pelletizer revealed a damaged inboard bearing, which was the location associated with channel PFV301. As can be seen, the acoustic signals generated from this source were also picked up on channel PFV303, the outboard bearing location. This illustrates the fact that IFD sensors are sensitive over fairly long ranges (several feet), although the absolute amplitude is different.

In essence, this is why it is very difficult to assign an absolute calibration to IFD measurements; distance from a defect determines the magnitude of the measurement, not just the severity of the defect. However, it should be obvious from Figure 37 that the relative magnitude of changes does not vary with distance, although the changes may be so small in absolute magnitude that they cannot be distinguished from noise beyond a certain point.

Defective Motor Bearing

Figure 38 shows a trend plot for a failing inboard motor antifriction bearing. The significance of this example is that the initial problem seemed to occur about 2/7 when data suddenly "jumped." Process records indicate problems with the pump after that time, and the trend graph shows frequent starts and stops. A decision was made to replace the motor bearings on 2/14, although the IFD readings were not examined until later. The data illustrates that the IFD system detected the initial problem a week ahead of time and indicates that this was a sudden mechanical failure and not a normal bearing wearout.

Extruder Screw Failure

Data characterizing failures that occur over a long period of time is often very difficult to analyze; however, the long-term graph provided by second generation IFD systems makes this much easier. An example of this was a corrosion-induced failure of a 24-foot shaft screw in a butyl rubber extruder, which occurred over a period of about a month. There were two factors that made it difficult to utilize the IFD system: (1) the channels on the extruder were frequently out of service until a month before the failure and (2) the nearest sensor was on the drive end gearbox, nearly 20 feet from the failure point.

However, as Figure 39 indicates, there was a definite upward trend of RMS data that was unrelated to process conditions in the period from 5/29 to 6/9, when the screw failed. This evidently reflected the condition of the shaft although the sensor was only intended to monitor the gearbox and was some distance from the shaft failure point. Consequently, when alarms were first detected by the system (6/6/78) the possibility of a shaft failure seemed unlikely and the alarms were disregarded since there was no confirming evidence.

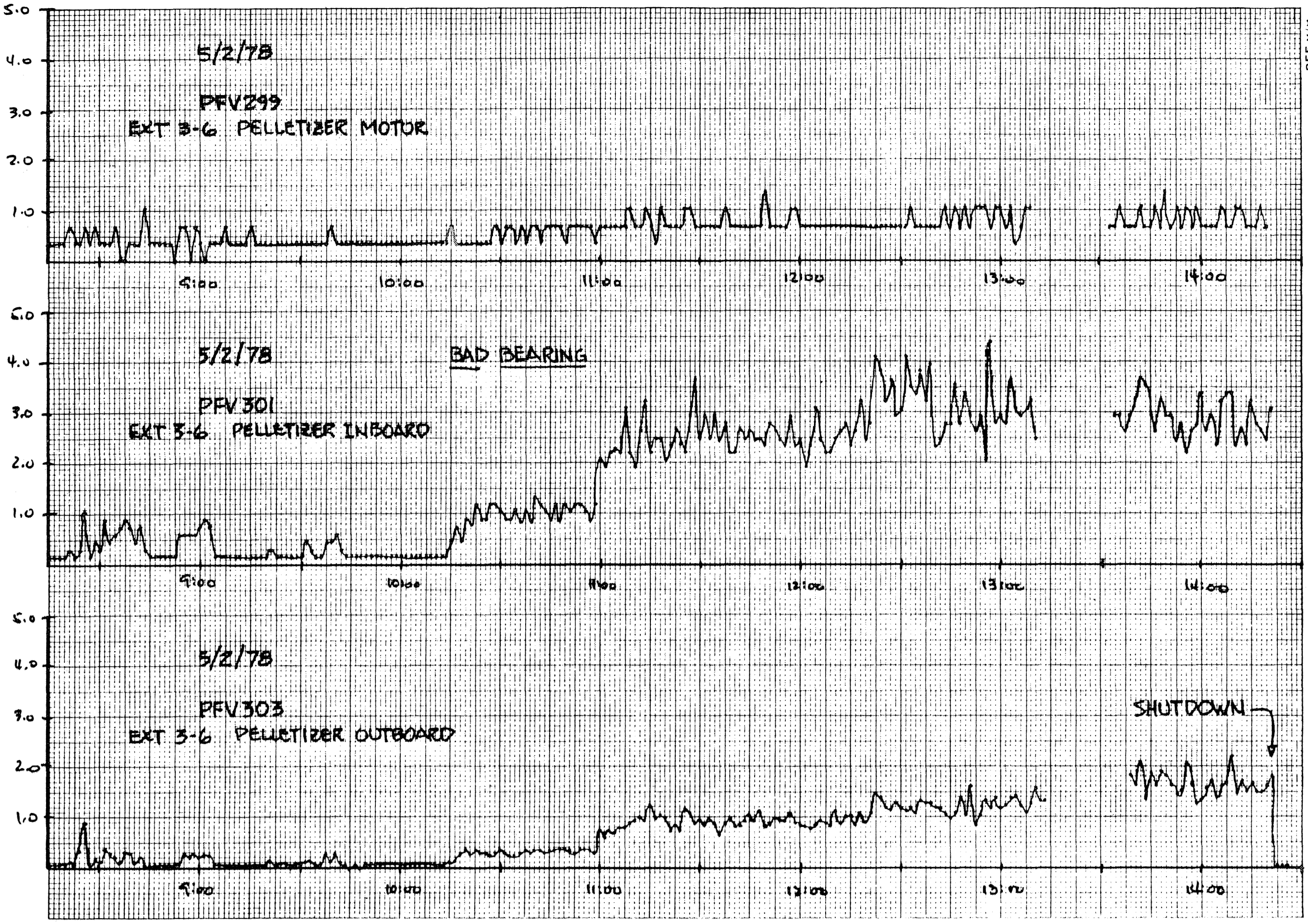


Figure 37. Plot of Three Channels Showing Bearing Defect.

This was in fact an illustrative example of how IFD technology can provide a warning far in advance of other techniques, even though it was not thought to be practical for monitoring shaft cracking. This instance has been documented since it does appear to be a valid application, although further cases are needed for corroborating data. Early tests of IFD techniques have indicated their suitability for such monitoring [3] but data from first generation systems was inconclusive. Second generation systems, though, will permit an in-depth study because of the greater data handling capability.

Piping Stress Causes Misalignment

Another example of the FF function is shown in Figure 40. In this case a relatively small overhung pump is attached to relatively stiff piping that induces misaligning stresses between the pump and motor. Several harmonics of the operating speed (60 Hz, or 3600 RPM) show up at various amplitudes depending on the amount of misalignment and the stresses involved. The RMS parameter on this machine is watched fairly closely since this condition cannot be corrected without major piping changes, even though the bearing may ultimately fail from vibration stresses.

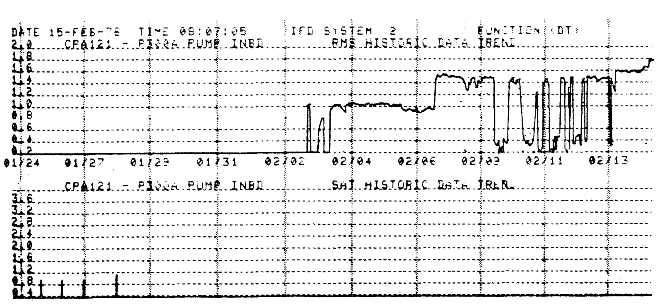


Figure 38. DT Plot Showing Motor Bearing Failure.

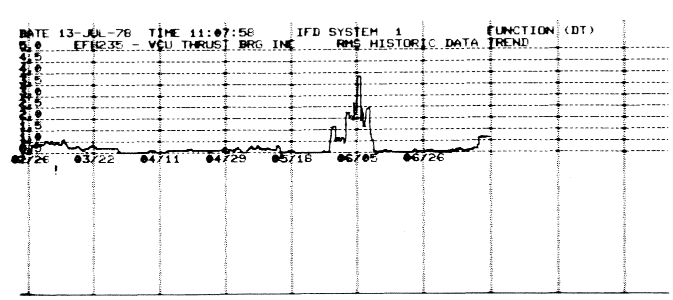


Figure 39. DT Plot Showing Failure of Extruder Screw Shaft.

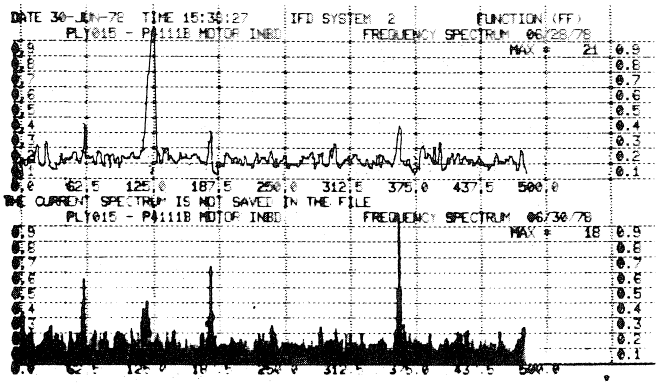


Figure 40. FF Display Showing Effects of Misalignment.

Extruder Pelletizer Spring Failure

Figure 41 shows the alarm history (AH) and trend (DT) plots for an extruder-pelletizer unit which was later found to have a broken spring in the knife assembly. The DT plot shows the magnitude of the increase (a factor of 8) while the AH listing shows the alarm incrementing feature and the progressively increasing measurements over about an hour. The pelletizer was allowed to run over a weekend before the equipment specialist ordered it shut down. There were no immediate problems although pelletizer performance was poor and the peller size was not uniform.

Extruder Drive Gear Failure

A large parallel shaft double reduction gear reducer is used in conjunction with an extruder to produce a one hundred (100) RPM screw drive from a 1050 RPM motor. On 6/3/78 a series of alarms were issued on this gearbox by the IFD system (Figure 42) and the equipment engineer went to check it. By looking through an inspection cover, he noticed a severly cracked (but not broken) tooth on the intermediate stage gear. Maintenance work was immediately begun.

DATE 30 JUN 78 TIME 15:21:43 IFD SYSTEM 2 FUNCTION (AH)

ACKNOWLEDGED ALARMS: FOR CRT NUMBER: 1

DATE	TIME	NAME	DESCRIPTION	TYPE	ALARM LIMIT	ALARM VALUE
06/23/78	20:28:06	PFV069 -	EX4A PELL I/B	RMS	13.30	13.53
06/23/78	20:03:57	PFV069 -	EX4A PELL I/B	RMS	12.60	12.75
06/23/78	19:45:55	PFV069 -	EX4A PELL I/B	RMS	11.90	11.97
06/23/78	19:30:45	PFV069 -	EX4A PELL I/B	RMS	11.20	11.82
06/23/78	19:21:48	PFV069 -	EX4A PELL I/B	RMS	10.50	10.55
06/23/78	19:15:35	PFV069 -	EX4A PELL I/B	RMS	9.80	10.99
06/23/78	19:14:05	PFV069 -	EX4A PELL I/B	RMS	9.10	10.21
06/23/78	19:12:35	PFV069 -	EX4A PELL I/B	RMS	8.40	9.62
06/23/78	19:09:33	PFV069 -	EX4A PELL I/B	RMS	7.70	8.01
06/23/78	00:54:30	PFV007 -	EX3B GEAR L/S O/B	RMS	0.30	0.34
06/21/78	09:03:25	PFV095 -	EX1A GEAR L/S I/B	RMS	9.10	16.12
06/21/78	09:01:55	PFV095 -	EX1A GEAR L/S I/B	RMS	8.10	13.58
06/17/78	05:58:16	PLY163 -	C4101B GEARBOX OUT	SAT	MUX-ADDR	ERROR
06/16/78	03:51:17	PLY037 -	P4207B PUMP INBD	RMS	2.50	5.28
06/15/78	23:24:34	PFV011 -	EX3B PELL O/B	RMS	2.25	4.35
06/15/78	23:23:03	PFV011 -	EX3B PELL O/B	RMS	2.00	3.71

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AH

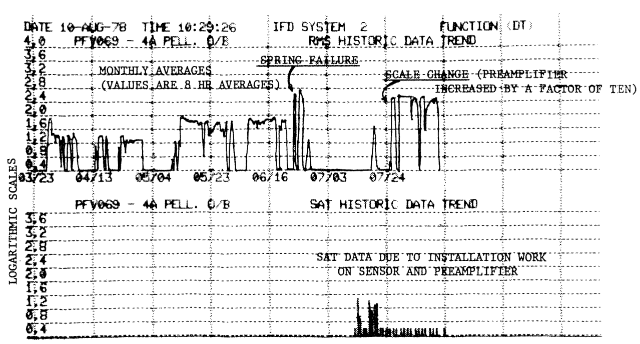

Figure 41. AH and DT Displays for Pelletizer Spring Failure.

DATE 12-JUN-78 TIME 15:07:43 IFD SYSTEM 2 FUNCTION (AH)

ACKNOWLEDGED ALARMS FOR CRT NUMBER: 1

DATE	TIME	NAME	DESCRIPTION	TYPE	ALARM LIMIT	ALARM VALUE
06/08/78	00:07:19	MUX 2			MUX-COMM	ERROR
06/08/78	00:07:18	100KZ2 -	100KHZ TEST SIGNAL	RMS	MUX-ADDR	ERROR
06/08/78	00:07:17	MUX 4			MUX-COMM	ERROR
06/08/78	00:06:46	PFV019 -	EX2A GEAR I/S I/B	SAT	MUX-ADDR	ERROR
06/07/78	12:38:49	PFV019 -	EX2A GEAR I/S I/B	RMS	32.00	33.41
06/07/78	06:15:07	MUX 1			MUX-COMM	ERROR
06/07/78	05:58:17	PFV069 -	EX4A PELL I/B	RMS	7.00	7.43
06/06/78	13:13:41	PFV019 -	EX2A GEAR I/S I/B	RMS	29.00	30.29
06/06/79	05:20:55	PLY043 -	P4207A PUMP INBD	RMS	10.00	11.14
06/05/78	06:10:22	MUX 1			MUX-COMM	ERROR
06/04/78	10:57:46	MUX 1			MUX-COMM	ERROR
06/03/78	15:30:44	PFV103 -	EX1A GEAR I/S O/B	RMS	10.50	11.04
06/03/78	15:27:44	PFV103 -	EX1A GEAR I/S O/B	RMS	10.00	10.94
06/03/78	13:21:45	PFV103 -	EX1A GEAR I/S O/B	RMS	9.50	9.62
06/03/78	11:09:45	PFV103 -	EX1A GEAR I/S O/B	RMS	9.00	9.23
06/03/78	10:57:44	PFV103 -	EX1A GEAR I/S O/B	RMS	8.50	8.79

ENTER N CR FOR NEXT PAGE OR CR TO EXIT
AH N

DATE 12-JUN-78 TIME 15:07:43 IFD SYSTEM 2 FUNCTION (AH)

ACKNOWLEDGED ALARMS FOR CRT NUMBER: 1

DATE	TIME	NAME	DESCRIPTION	TYPE	ALARM LIMIT	ALARM VALUE
06/03/78	10:50:15	PFV103 -	EX1A GEAR I/S O/B	RMS	8.00	8.06
06/03/78	10:45:48	PFV103 -	EX1A GEAR I/S O/B	RMS	7.50	8.16
06/03/78	10:32:25	PFV103 -	EX1A GEAR I/S O/B	RMS	7.00	7.23
06/03/78	10:30:56	PFV103 -	EX1A GEAR I/S O/B	RMS	6.50	7.18
06/03/78	10:29:26	PFV103 -	EX1A GEAR I/S O/B	RMS	6.00	6.64
06/03/78	10:27:57	PFV103 -	EX1A GEAR I/S O/B	RMS	5.50	8.26
06/03/78	10:25:03	PFV069 -	EX1A PELL I/B	RMS	6.30	6.35
06/03/78	10:22:04	PFV069 -	EX1A PELL I/B	RMS	5.60	7.38
06/03/78	10:18:57	PFV103 -	EX1A GEAR I/S O/B	RMS	5.00	5.47
06/03/78	10:11:29	PFV103 -	EX1A GEAR I/S O/B	RMS	4.50	4.64
06/03/78	10:08:30	PFV103 -	EX1A GEAR I/S O/B	RMS	4.00	7.13
06/03/78	10:07:01	PFV103 -	EX1A GEAR I/S O/B	RMS	3.50	6.40
06/03/78	10:05:34	PFV103 -	EX1A GEAR I/S O/B	RMS	3.00	5.96
06/03/78	10:00:51	PFV103 -	EX1A GEAR I/S O/B	RMS	2.50	2.54
06/03/78	09:42:43	PFV103 -	EX1A GEAR I/S O/B	RMS	2.00	2.83
06/03/78	05:47:16	PFV027 -	EX2A GEAR L/S O/B	RMS	5.00	5.37

Figure 42. AH Display Showing Alarms due to Gear Defect.

Two things should be apparent from the AH display in Figure 42. First, there are a number of other alarms during this time frame that did not reflect an equipment problem. When checked, they appeared to only be transient conditions due to known process variations, and the alarm level was allowed to stay at the slightly higher incremented level to ignore these transients in the future. Some of the other alarms were system error checks in the multiplexer communication link, which were being serviced.

The second important aspect of the AH display is that only the intermediate stage (I/S) channels on the gearbox went into alarm. Normally IFD sensors have a fairly long range of sensitivity, as described in the extruder shaft cracking example, so it might be expected that the other four gearbox sensors would have shown increases. However, the failure had not progressed to the point of actually breaking a tooth, so the defect signal was relatively weak. Obviously the maintenance savings were significant because the equipment was shut down before the tooth was broken.

One other important point should be made: even when the IFD systems have issued "false" alarms that do not relate to abnormal conditions, they do at least focus attention on a relatively small number of machines. Some alarms may represent unusual process conditions, some will be reporting true equipment problems, and some may indicate faults in the IFD instrumentation itself. However, focusing attention on a small percentage of cases needing attention has the effect of improving surveillance and therefore of averting major machinery failures. This improvement in monitoring effectiveness is a major justification for the necessary investment costs.

CONCLUSION

The examples presented demonstrate the key features of second generation acoustic incipient failure detection (IFD). The ease of use and data presentation capabilities make computerized IFD highly effective for detecting and analyzing failures. As the systems become more widely used and the base of experience grows, the number of valid applications of IFD technology increases and can be documented to further demonstrate the benefits. Above all, it should be apparent that the principles and operation of second generation systems are easy to understand and therefore easy to apply.

These concepts have been covered in six major areas: principles, benefits, instrumentation, operation, implementation, and experience. In each area an attempt was made to emphasize the advantages of acoustic IFD systems for machinery surveillance. In summary, these advantages have been shown to be the low cost, the applicability to general equipment monitoring, the simplicity of measurement, and the ease of use.

IFD systems are presently implemented are clearly practical for industrial equipment monitoring. Experience has shown that the principles of high-frequency acoustic emission technology can be used effectively to achieve better monitoring of equipment. Because they are based on this technology, second generation IFD systems are the simplest, most cost-effective general purpose systems currently available. Above all, they achieve the primary goal of machinery surveillance: early warning.

REFERENCES

1. Bloch, H. P., "Predict Problems with Acoustic Incipient Failure Detection Systems," *Hydrocarbon Processing*, October, 1977, pp. 199-198.
2. James, R., and Bloch, H. P., "Predictive Maintenance System Improved at Exxon Chemical Plant," *Oil and Gas Journal*, February 2, 1976, pp. 59-64.
3. James/Reber/Baird/Neale, "Application of High Frequency Acoustic Techniques for Predictive Maintenance in a Petrochemical Plant," presented at the 28th Annual ASME Petroleum Mechanical Engineering and Pressure Vessels and Piping Conference, Los Angeles, CA, September 1973.
4. Drago, R. J. and Board, D. B., "High Frequency Vibration Monitoring Techniques for Gear/Bearing-System Failure Detection," AGMA Paper No. 109.36, October 1975.
5. Baird, B. C., "Vibration Detection of Component Operability," ASME Paper No. 76-ENAs-18, presented at Intersociety Conference on Environmental Systems, San Diego, Calif., July 12-15, 1976.
6. Harting, D. R., "Incipient Failure Detection by Demodulated Resonance Analysis," *Instrumentation Technology*, September 1977, pp. 59-63.
7. Parry, D. L., "Industrial Applications of Acoustic Emission Analysis Technology," *Monitoring Structural Integrity by Acoustic Emission*, ASME STP 571, American Society for Testing and Materials, 1975, pp. 150-183.
8. Bell, R. L., "A Progress Report of the Use of Acoustic Emission to Detect Incipient Failure in Nuclear Pressure Vessels," DUNEGAN/ENDEVCO, San Juan Capistrano, Calif., January 1974.
9. "Development of Modular (Portable) Acoustic Monitors Based on Experience at Exxon Chemical's Baytown Plant," Internal Correspondence File Memo 10-16-3b(1), May 18, 1976.
10. James/Reber/Baird/Neale, "Acoustic Instrumentation Technique Predicts Mechanical Failures," *Oil and Gas Journal*, Dec. 17, 1973.
11. Hudachek, R. J., and Dodd, V. R., "Progress and Payout of a Machinery Surveillance and Diagnostic Program," ASTM Paper No. 76-Pet-69, September 1976.
12. Pekrul, P. J., "Vibration Monitoring Increases Equipment Availability," *Chemical Engineering*, August 18, 1975, pp. 72-75.
13. O'Dea, D. M., "Experience With Computerized Machinery Vibration Analysis," ASME Paper No. 75-Pet-21, September 1975.
14. Bloch, H. P., "Development and Experience with Computerized Acoustic Incipient Failure Detection (IFD) Systems," ASME Paper No. 77-Pet-2, September 1977.
15. Bloch, H. P., "Using High Frequency Acoustic Emission Measurement To Monitor Machinery Condition," *Hydrocarbon Processing*, May, 1977.
16. Baird, B. C., "IFD Feasibility Study," report to Exxon Chemical Co. USA (then Enjay Chemical Co.), June 1972.
17. Bloch, H. P., "Acoustic Incipient Failure Detection Systems Are Successful at Exxon." *Oil and Gas Journal*, February 6, 1978, pp. 62-72.
18. McIntire, J. R., "Reliability Monitoring Cuts Plant Downtime," *Oil and Gas Journal*, June 27, 1977, and July 4, 1977 pp. 59-61.
19. Borhaug, J. E., and Mitchell, J. S., "New Tool for Vibration Analysis," *Hydrocarbon Processing*, November, 1972.
20. Price, M. H., "Computer Assisted Vibration Monitoring Successful," *Hydrocarbon Processing*, December, 1977, pp. 85-90.