Vibration measurements in predictive maintenance
Vibration measurements in predictive maintenance

by Christian Claessens,
Mobil Plastics Europe Inc.

Introduction

In July 1980, the first production unit at the Mobil plant of Latour was started up.

Starting a new plant entails the establishment of a maintenance department with its workshops, laboratories and stores. But above all, it entails decisions about strategy, organization and maintenance methods. We shall try to give a brief account of our experiences over the last two and a half years, the alternatives chosen, the techniques employed and the results obtained.

Periodic or predictive preventive maintenance?

Nowadays the concept of preventive maintenance is widely recognised. In the process industry where the equipment is generally expensive and big, preventive maintenance proved economically sounder than run-to-break maintenance. An added benefit is a much safer operation.

Historically, periodic preventive maintenance was the first preventive type of maintenance to arise. It is based upon statistical background, that has been questioned quite a lot in recent years. It is based on the concept that the failure rate increases after a given number of running hours and that the period with low failure rate is constant for a type of equipment.

However, it is obvious that this troublefree operation period before maintenance if really needed varies greatly according to load conditions, production tolerancies, assembling conditions...

If a good reliability is requested between overhauls, this period must be shorter than the shortest time between failure. Thus, a large number of unnecessary overhauls will be carried out on machines that could have been kept in operation for a much longer time.

Furthermore, these overhauls are expensive in terms of spare parts, labour and downtime production losses. Even more serious is the fact that increasing overhaul frequency
also increases the number of human
errors during dismantling, reassem-
bling and starting-up.

Obviously the ideal method would
be to perform preventive main-
tenance at irregular intervals, depend-
ing of the actual condition of the ma-
chine. This is the aim of predictive
maintenance.

The main difficulties of this meth-
od are clear:

a) the actual condition of the ma-
    chine must be known at any time
b) any change of condition, or fault
development, must flash a warn-
ing with enough lead time.

   Lead time is necessary to:
   1. enable a scheduled shut-down
      which must not significantly dis-
      turb production
   2. inform and prepare the mainte-
nance crew
   3. prepare or store the necessary
      spare parts and tools.

   The condition monitoring of the
   machine is therefore the key in such
   a maintenance system. The monitor-
ing must be technically well suited to
   the equipment and organized with
   the greatest possible care. It should
   be performed with enough personnel
   and good quality equipment.

   Predictive maintenance is the
   method we are using on the five pro-
duction lines of our plant. Only some
machines, with a large amount of
fast wearing parts are maintained on
a periodic base.

Getting the monitoring program started

Machine condition monitoring is
based on the periodic, and some-
times continuous, measurement of
one or several parameters. The evolu-
tion of these is considered to be
representative of the actual condi-
tion of the machine.

This implies the analysis of the
trends, starting from a reference
measurement, taken when the ma-
chine was considered to be in per-
fect working condition.

   The choice of the parameter to be
   monitored and the measurement
   technique have therefore a tremen-
dous impact on the efficiency of the
   predictive maintenance.

   The sensitivity must be good
   enough to allow measurements with-
in a reasonable time interval, particu-
larly if periodic monitoring is used.

   Taking into account the variety of
   machines and the number of param-
eters that can be chosen, it is gener-
ally not possible to limit oneself to a
   single type of measurement on all
   the equipments.

<table>
<thead>
<tr>
<th>Monitor parameter</th>
<th>Machines monitored</th>
<th>Number of measurement points</th>
<th>Measuring equipment</th>
<th>Periodicity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vibration measurements</td>
<td>All rotating machinery</td>
<td>800</td>
<td>1 portable meter, 1 analogue analyzer, 1 FFT analyzer, 1 tape recorder, 1 computer + peripherals</td>
<td>6 weeks (4 weeks during the 2nd phase)</td>
</tr>
<tr>
<td>Shockwave measurements</td>
<td>All antifriction bearings (rolls and nips)</td>
<td>800</td>
<td>1 SPM* analyzer, 50 permanent transducers with grouped wiring</td>
<td>6 weeks (4 weeks during the 2nd phase)</td>
</tr>
<tr>
<td>Oil analysis</td>
<td>- Oil heating circuits</td>
<td>200</td>
<td>Partially contracted to Mobil Oil, Equipment for filtration membrane, Microscope, Kit for water determination</td>
<td>3 months</td>
</tr>
<tr>
<td></td>
<td>- Gearboxes</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>- Hydraulic circuits</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Water analysis</td>
<td>- Cooling circuits [closed]</td>
<td>15</td>
<td>Titration equipment, Portable pH-meter</td>
<td>1 week</td>
</tr>
<tr>
<td></td>
<td>- Cooling circuits [open]</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>- Hot water heating circuits</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thermography</td>
<td>- Accessible high-voltage installations</td>
<td>About 150 installations</td>
<td>Contracted to a consultant</td>
<td>6 months</td>
</tr>
<tr>
<td></td>
<td>- Low-voltage distribution</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>- DC drive circuits</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>- Relay panels</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* SPM: Shock Pulse Meter

Table 1. Monitoring programme
Table 2. Personal resources required

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Phase 1</th>
<th>Projected, &quot;Classical&quot; method</th>
<th>Phase 2 (with desk-computer)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Perio-</td>
<td>Number</td>
<td>Perio-</td>
</tr>
<tr>
<td></td>
<td>dicity</td>
<td>of measurement points</td>
<td>dicity</td>
</tr>
<tr>
<td>Perio- dicity</td>
<td></td>
<td>Number</td>
<td>dicity</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Average time per month</td>
<td>Average time per month</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(in minutes)</td>
<td>(in minutes)</td>
</tr>
<tr>
<td>Vibrations (spectral analysis)</td>
<td>6 weeks</td>
<td>400</td>
<td>6 weeks</td>
</tr>
<tr>
<td>Shockwave measurements</td>
<td>6 weeks</td>
<td>750</td>
<td>6 weeks</td>
</tr>
<tr>
<td>Analysis of oil</td>
<td>3 months</td>
<td>120</td>
<td>6 weeks</td>
</tr>
<tr>
<td>Analysis of water</td>
<td>1 week</td>
<td>13</td>
<td>3 months</td>
</tr>
<tr>
<td>Analyse and classification of data</td>
<td></td>
<td>3600</td>
<td>1 week</td>
</tr>
<tr>
<td>Diagnostic and decision-making</td>
<td></td>
<td>1000</td>
<td></td>
</tr>
<tr>
<td>Total time</td>
<td></td>
<td>11080</td>
<td></td>
</tr>
</tbody>
</table>

| Number of hours per month                | 185    | 313                          | 175    |
| Number of operators                      | one    | two                          | one    |
| Time required from engineer              | 10%    | 20%                          | 10%    |

These times do not include:
- Training of personnel
- Physical placement of the measurement points (bolts, tappets, measurement points tagging, sampling points, etc.)

For the case of our plant, we have briefly described the monitoring program in table 1.

On reading this table, it will be realised that the task requires quite a lot of investment in instruments, but also a lot of manpower. Not only is it necessary to perform the measurements but to file all data and follow up their evolution. Any discrepancy must trigger a sequence of events:

1. Decreasing the time interval of the measurements on the measuring point where the discrepancy was detected.
2. Additional measurements are taken in an attempt to produce a diagnose.
3. Planning of an overhaul during a scheduled shut-down.

When the number of measuring point exceeds about one hundred, the question arises whether or not to use a computer to handle the results. In the early beginning, our program was completely "manual". The results of this first phase, together with the increase in data volume due to plant extensions, led us to consider the use of a desk-computer.

To explain the problem more clearly, table 2 shows the work load related to the monitoring program.

The columns entitled "Phase 1" show the work load at the beginning of 1982; the columns under "Projected" show the workload for an increase in the number of measurement points without the aid of a desk-computer; the columns under "Phase 2" show the "desk-computer" solution which has actually been installed.

It is immediately evident that the use of a desk-computer enables a spectacular reduction in the time dedicated to vibration measurements and in particular to the spectral analysis.

Thus we were able to double the number of measurement points, reduce the interval between measurements (from 6 to 4 weeks) without an increase in personnel.

Furthermore the effectiveness of the system was found to be vastly improved. In fact:

1. The operators were relieved of a particularly boring job; the monthly analysis and the visual comparison of the spectra developed into a routine and led to a loss of attention. A machine may run for years without problems; this represents a considerable quantity of data which have no interest, and only serve to make the task more boring.

Thus if a modification appeared in the form of the spectrum, the probability that it would go unnoticed was increased. This also led the operator to no longer perform the spectral analysis and to be content with an overall level measurement (r.m.s. velocity for example). The automatic comparison of a spectral analysis with a memorised reference measurement enables the operator to dedicate his time to more inter-
esting and more useful tasks (diagnostics for example). The over-
all result is a greater motivation and a greater interest in the work
being done.

2. Data gathering using a tape re-
corder can be conferred to non-
specialised operators.

This implies pre-set equipment,
an easy procedure, as well as
well-prepared measurement
points with clear identification.
The method of operation must be
simple and clearly defined.

The great advantage of such a
procedure is that it permits data
to be gathered by the mainte-
nance team on watch for example
at night or at week-ends, with a
minimum of supervision.

3. The automatic analysis of the
data greatly reduces the errors of
estimation, reading, scale and
subjective impression.

Instrumentation and methods for measuring vibrations

In the first phase, the monitoring
program included an analogue ana-
lyzer with filters and automatic
sweep system. This system allows a
spectral analysis to be obtained on a
graphic level recorder.

Furthermore, a certain number of
simple machines (fans, small pumps)
were only monitored by overall level
measurement (r.m.s. velocity, and on
some the crest factor) by means of a
small vibration meter.

The majority of the SPM measure-
ments were performed using a hand-
held probe, without a measurement
stud.

We have progressively: —

1. Increased the number of ma-
chines on which a complete spec-
tral analysis is performed.

2. Mounted fixed measurement
studs on all the bearings moni-
tored by the SPM analyzer.

3. Mounted transducers permanent-
ly and have regrouped the wiring
together for SPM measurements
at points where access to the
bearings is difficult or dangerous
for the operator.
Finally, during recent months, we have started a second phase where the measurements are assisted by a desk-computer.

Measurement system in the second phase

Our measurement system is built essentially around the Bruel & Kjaer FFT analyzer Type 2033 and a Hewlett-Packard Calculator Type 9826 (see Fig. 1).

The software employed is Bruel & Kjaer module WH 1226 which we have slightly modified to meet our specific needs. It should be noted that programs to deal with the other measurements (SPM, analysis of oil and of water) are being prepared.

It is most important that these programs can be operated by non-specialised personnel. The programs are therefore built up with a "menu" (interactive language.)

We have two programs dedicated to monitoring and a series of programs which enable the diagnostic possibilities of the FFT analyzer to be fully exploited.

The calculator completely controls the analyzer via the IEEE interface.

The dedicated monitoring programs enable:

a) The definition of a reference spectrum which can then be stored on disc. To avoid having to store several constant bandwidth spectra (in order to cover all the spectrum with a sufficient resolution), the calculator converts spectra to constant percentage bandwidth. Three spectra, linearly averaged, having respectively bandwidths of 100, 1000 and 10 000 Hz, are converted to a spectrum with a logarithmic frequency scale. The resolution of this spectrum can be varied, with a maximum of 60 bands/decade. If machines with variable operating speeds are monitored, it may be of interest to reduce the resolution slightly (e.g. 15 bands/decade). This spectrum serves as a reference base for all further measurements. It should be noted that for machines with variable speeds and/or variable loads, it may be necessary to establish several references depending on the operating conditions.

b) The performance of the routine monitoring. The measurements are recorded on magnetic tape (one minute's recording at each measurement point) and accompanied by a commentary made by the operator into a microphone. It should be noted that separate...
charge amplifiers are employed although in the near future a tape recorder with built-in amplifiers will be used. This will practically reduce the control manipulations to a simple start/stop operation.

When a certain number of measurements have been performed, the tape recorder is connected to the analyzer and the reference of the first measurement is recalled from the mass storage.

The calculator then generates a "mask" by taking a band on both sides of each spectral line with a value of 2 to 6 dB greater than the amplitude of the line.

Fig. 4. New spectrum. Compared to Fig. 2, there is an increase in amplitudes between 170 Hz and 2000 Hz

If the new measurement "fits" into the mask, that is, if no spectral line is greater than the mask, then no alarm message is produced. If on the contrary, a spectral line exceeds the mask level, then an error message is produced, (Figs. 2 to 5).

Methods of analysis and diagnosis
When an anomaly is registered, either from the frequency analysis or from the SPM measurements, the next problem is to produce a diagnosis and to estimate the probable operation time before breakdown.

Other measures of monitoring can also supply complementary information or verification. For example an anomaly in a gear, detected by frequency analysis can be confirmed by the increase in the amount of debris in the oil or by a change in the debris' grain size.

Moreover, we use true diagnostic methods:

— Stroboscopic analysis: particularly useful in the analysis of belt drive transmissions and particularly timing belt drives.

Fig. 5. Generated messages
1. File 1: no evolution
2. File 3: alarm message with increases at 171 Hz and 185 Hz (corresponding to Fig. 4)
counting of SPM impulses: in the case of bearings rotating at very low speed, the amplitude of the pulses is not always indicative of the bearing condition. We prefer to use a counter over a one minute interval, or a graphical recording of the impulses as a function of time. The "blackening" of the paper is the criterion by which the state of the bearing is assessed (Fig.6).

examination of the relative phase of the unbalance, by means of a balancing phasemeter and a photoelectric cell. This enables information to be gathered concerning the state of the internal components of a roll (corrosion, deposits, looseness) for instance.

sideband analysis at the meshing frequencies of the gears. The meshing frequencies act as amplitude and/or frequency modulated carriers at the rotational frequencies of the various pinions or their harmonics. This is possible:

- either directly by using the zoom function of the analyzer and small programs to find the side bands (Fig.7).

- or via a "cepstrum" calculation. This is defined as the power spectrum of the logarithm of a power spectrum. It thus emphasizes those spectral lines reoccurring periodically in the spectrum that is, the harmonics and the sidebands.

This analytical tool is useful when confronted with a spectrum in which the sidebands of several meshing frequencies overlap and direct analysis is difficult (Fig.8 to 10). The calculation of "cepstrum" is part of the library of diagnostic programs.

Fig. 7. Zoom of 100 Hz about the meshing frequency of 850 Hz showing the sidebands.

Fig. 6. SPM measurements on bearings at low frequencies.

Fig. 8. Severe damage bearing.
Results obtained

The results of a predictive maintenance program are not easy to evaluate.

The success or failure of the program can be measured by the equipment up-time and the maintenance costs.

We have tried to evaluate the benefits obtained in an 18 month period from January 1981 to July 1982 concerning 28 documented cases (Table 3).

We have calculated:

1. The saving achieved in direct maintenance costs; that is, the difference between the cost of repairs made as a result of a scheduled shut-down (following the detection of a fault) and the costs which would have arisen had the fault been allowed to develop until a breakdown occurred.

![Fig. 8. Spectrum of a gear containing numerous harmonics and sidebands about the meshing frequency](image)

<table>
<thead>
<tr>
<th>Number</th>
<th>Machine</th>
<th>Component</th>
<th>Fault</th>
<th>Estimated savings (Belgian Francs)</th>
<th>Avoided stoppages (hours)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>201</td>
<td>Slitting roll</td>
<td>Bearing and shaft end damaged</td>
<td>220,000</td>
<td>16</td>
</tr>
<tr>
<td>2</td>
<td>201</td>
<td>MDO 1</td>
<td>4 bearings damaged (faulty mounting)</td>
<td>400,000</td>
<td>30</td>
</tr>
<tr>
<td>3</td>
<td>202</td>
<td>Cooling pump</td>
<td>Motor's pillow block and coupling</td>
<td>35,000</td>
<td>8</td>
</tr>
<tr>
<td>4</td>
<td>201</td>
<td>DC motor extruder</td>
<td>Brushes and brush holders faulty</td>
<td>500,000</td>
<td>120</td>
</tr>
<tr>
<td>5</td>
<td>211</td>
<td>Coating roll</td>
<td>Mounting fault in pillow block</td>
<td>215,000</td>
<td>12</td>
</tr>
<tr>
<td>6</td>
<td>202</td>
<td>MDO 2</td>
<td>Shaft's universal joint defective</td>
<td>50,000</td>
<td>8</td>
</tr>
<tr>
<td>7</td>
<td>auxil.</td>
<td>Circulation pump nr. 1</td>
<td>Mounting not bolted properly to foundation</td>
<td>40,000</td>
<td>4</td>
</tr>
<tr>
<td>8</td>
<td>201</td>
<td>TDO-fan nr. 9</td>
<td>Cracks on mover</td>
<td>75,000</td>
<td>6</td>
</tr>
<tr>
<td>9</td>
<td>211</td>
<td>Cooling roll nr. 2</td>
<td>Defect pillow block</td>
<td>175,000</td>
<td>30</td>
</tr>
<tr>
<td>10</td>
<td>201</td>
<td>Pump, transfer line</td>
<td>Defect pillow block</td>
<td>55,000</td>
<td>8</td>
</tr>
<tr>
<td>11</td>
<td>201</td>
<td>Blower of air-knife</td>
<td>Unbalance in rotor</td>
<td>86,000</td>
<td>12</td>
</tr>
<tr>
<td>12</td>
<td>202</td>
<td>Gauge helper</td>
<td>Defect in motor's coupling</td>
<td>20,000</td>
<td>6</td>
</tr>
<tr>
<td>13</td>
<td>211</td>
<td>Transmission of treater E</td>
<td>Gear (bad pre-tension of the bearings)</td>
<td>60,000</td>
<td>8</td>
</tr>
<tr>
<td>14</td>
<td>202</td>
<td>MDO 3 — Angle piece gearbox</td>
<td>Bearing ruined on the primary shaft</td>
<td>39,000</td>
<td>3</td>
</tr>
<tr>
<td>15</td>
<td>201</td>
<td>Main gear — treater W</td>
<td>Worn attack pinion due to bad mounting</td>
<td>43,000</td>
<td>5</td>
</tr>
<tr>
<td>16</td>
<td>211</td>
<td>Cooling roll nr. 1</td>
<td>Defect bearing</td>
<td>175,000</td>
<td>12</td>
</tr>
<tr>
<td>17</td>
<td>211</td>
<td>Roll at exit of oven nr. 2</td>
<td>Defect bearing</td>
<td>32,000</td>
<td>4</td>
</tr>
<tr>
<td>18</td>
<td>211</td>
<td>Cooling roll nr. 3</td>
<td>Pillow block support crack</td>
<td>85,000</td>
<td>12</td>
</tr>
<tr>
<td>19</td>
<td>202</td>
<td>Winder W</td>
<td>Damaged shaft end</td>
<td>131,000</td>
<td>3</td>
</tr>
<tr>
<td>20</td>
<td>201</td>
<td>Aerial transfer 3 &amp; 5</td>
<td>Worn bearings</td>
<td>34,000</td>
<td>3</td>
</tr>
<tr>
<td>21</td>
<td>202</td>
<td>Treater E</td>
<td>Poor alignment of pulleys</td>
<td>25,000</td>
<td>2</td>
</tr>
<tr>
<td>22</td>
<td>202</td>
<td>Folder transmission at oven exit</td>
<td>Dry gear, defective seal</td>
<td>60,000</td>
<td>13</td>
</tr>
<tr>
<td>23</td>
<td>211</td>
<td>Schmitt coupling TCl</td>
<td>Needle bearing defective</td>
<td>60,000</td>
<td>6</td>
</tr>
<tr>
<td>24</td>
<td>201</td>
<td>Thermal fluid pump nr. 9</td>
<td>Bearing worn</td>
<td>25,000</td>
<td>3</td>
</tr>
<tr>
<td>25</td>
<td>201</td>
<td>Oven's circulation ventilator</td>
<td>Unbalance due to deposits on the rotor</td>
<td>35,000</td>
<td>4</td>
</tr>
<tr>
<td>26</td>
<td>203</td>
<td>Presser transmission</td>
<td>Misalignment of pulleys</td>
<td>32,000</td>
<td>2</td>
</tr>
<tr>
<td>27</td>
<td>202</td>
<td>Gauge gear</td>
<td>Dry gear, packing leak</td>
<td>60,000</td>
<td>3</td>
</tr>
<tr>
<td>28</td>
<td>203</td>
<td>Main extruder</td>
<td>Motor misalignment</td>
<td>133,000</td>
<td>10</td>
</tr>
</tbody>
</table>

**TOTAL** 3,035,000 253

Table 3. Documented cases from January 1981 to July 1982
2. The saving achieved in production time due to the fact that the repair was made at scheduled shut-down (e.g. a change in production) and its effect was reduced relative to the repair time required after a breakdown.

Overall then, considerable savings were made compared to run-to-break maintenance.

The saving obtained by comparison with a periodic preventive maintenance is more difficult to estimate as it is difficult to set a figure on the efficiency of this approach.

Conclusions

Predictive preventive maintenance has proved to be a viable alternative to periodic preventive maintenance. It has produced considerable gains in machine up-time as well as substantial savings in spare parts and in labour costs.

Although vibration measurements are the basic tools for machine monitoring, they should be used simultaneously with other techniques (analysis of oil, thermography, efficiency tests).

Furthermore, if a high degree of efficiency is required from these measurements, then it is not enough to perform non-filtered measurements of vibration level, but as much as possible, to perform a spectral analysis.

When the number of measurement points reaches a hundred (and this number is rapidly reached if predictive maintenance is employed), the only viable solution is to employ a computer to help in the measurements and data reduction.