3

Systemization and Application of a Vibroacoustic Methods Package to Establish Machine Tool Technical Diagnostics

3.1 THEORETICAL METHODS TO ESTABLISH TECHNICAL DIAGNOSTICS

By clearly establishing the relations between the level of the supervised parameter or parameters and the functioning state of the technical system, pertinent methods of study have been obtained.

Theoretical research uses statistical and/or probabilistic evaluation methods, mono- or multiparametric. The purpose of these methods is either to establish a series of decision algorithms on the basis of analysis of the possible state of the technical system, or to evaluate the influence of not mentioning the state of the technical system on the global cost of operation.

3.1.1 Statistical Methods

Statistical methods start from the evaluation of the minimum risk of spoilage. A limit level x_0 is adopted for the supervised parameter x and the repartitions of this parameter in both its states are supposed to be known: $f_1(x)$ for the normal state D_1, and $f_2(x)$ for the wrong state D_2, as presented in Figure 3.1. It can be observed that adopting the limit

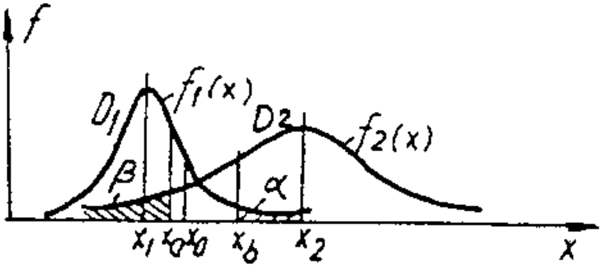

FIGURE 3.1 Repartitions of x parameter.

level implies a certain level of risk in decision making, illustrated by the hatched zones from the D_1 and D_2 domains, under the repartition functions. Two types of risk occurred: α, the risk of false alarm or the producer's risk, and β, the risk of not accomplishing the goal or the beneficiary's risk.

The Neyman–Pherson method is a statistical method that can be applied to technical systems with a single characteristic parameter. The method consists of establishing an a level, the maximum level allowed for the false alarm probability:

$$\int_{x_0}^{\infty} f_1(x)dx = a \tag{3.1}$$

From this a level, the risk value of the x_0 parameter is deduced. The same value may also result from the maximum b allowed level ($b < 0.05$) in the case of an unaccomplished purpose:

$$\int_{-\infty}^{x_0} f_2(x)dx = b \tag{3.2}$$

When establishing the two levels (a and b), the number of technical systems drawn out from operation must be higher than the number of those technical systems for which a spoilage is to be expected as a result of the inevitable errors when specifying the functioning state.

If the probabilities that the system is in its normal state $P(D_1)$ or in its incorrect state $P(D_2)$ are established and C_{21} equals the cost implied by a false alarm, C_{12} equals the cost implied by nonaccomplishment of purpose, and C_0 equals the cost of nondetermination of the functioning state, the cost of the global risk is given by the relation:

$$C = C_{21}P(D_1)\int_{x_b}^{\infty} f_1(x)dx + C_{12}P(D_2)\int_{-\infty}^{x_a} f_2(x)dx$$
$$+ c_0\left[P(D_1)\int_{x_a}^{x_b} f_1(x)dx + P(D_2)\int_{x_a}^{x_b} f_2(x)dx\right] \quad (3.3)$$

Deriving the expression function of x_a and x_b values of the x parameter, the minimizing conditions of the global cost are determined as

$$\frac{f_1(x_a)}{f_2(x_a)} = \frac{(C_{12} - C_0)P(D_2)}{C_0 P(D_1)}$$
$$\frac{f_1(x_b)}{f_2(x_b)} = \frac{C_0 P(D_2)}{(C_{21} - C_0)P(D_1)} \quad (3.4)$$

This method is used in cases where the costs of nonrealization of the goal or a false alarm are high. In this case, the existence of the nondetermined zone situated between the x_a and x_b values of the supervised parameter x is admitted.

3.1.2 Probabilistic Methods

Probabilistic methods allow the establishment of each state characterized by a number of parameters with discrete or continuum repartitions, using a diagram of a number of states of the technical system. On the basis of this correlation of state parameters, decision rules or parameters can be established.

The Bayes method is a multiparametric probabilistic method that allows determination of the most significant diagnostic, by evaluating the state combinations of the significant parameters. If in order to determine the diagnostic, the functioning state is noted D_i, x_j is a simple parameter, and if $P(D_i/x_j)$ is the probability of the D_i diagnostic in the known conditions of the influence of the x_j parameter on the system, and $P(x_j/D_i)$ is the probability that the x_j parameter manifests in the D_i state, then the probability that both events manifest (D_i, x_j) is given by the following equation.

$$P(D_i, x_j) = P(D_i)P\left(\frac{x_j}{D_i}\right) = P(x_j)P\left(\frac{D_i}{x_j}\right) \quad (3.5)$$

At a certain moment the diagnosed system can be in a unique state so the following relation is true.

$$\sum_{i=1}^{n} P(D_i) = 1 \tag{3.6}$$

If a concrete realization X is considered in the group of $x_1, x_2, \ldots, x_j$ parameters, then the Bayes relation becomes:

$$P\left(\frac{D_i}{X}\right) = \frac{P(D_i)P\left(\frac{X}{D_i}\right)}{\sum_{i\_1}^{n} P(D_i)P\left(\frac{X}{D_i}\right)} \tag{3.7}$$

It is considered that the x_j parameters are usually independent, which leads to the simplification:

$$P(X/D_i) = P(X_1/D_i)P(X_2/D_i)\ldots P(X_n/D_i) \tag{3.8}$$

This simplification is used many times in practice, despite some inevitable interdependencies.

In order to simplify Bayesian analysis, diagnostic matrices can be made. In these matrices are inscribed the following probabilities determined by statistical research: $P(D/x)$, the probability of the x parameter manifesting in D state and $P(D)$, the probability of finding D state. The most significant factor is recognized in matrix making $P(D/X) = \max$.

Considering the following equation,

$$\sum_{i\_1}^{n} P\left(\frac{D_i}{X}\right) = 1 \tag{3.9}$$

the basis of the estimation calculus of the technical diagnosis must be reevaluated if the probabilities $P(D/x)$ are under $(0.4 \ldots 0.5)$.

Observations:

1. The complex of X parameters, which were theoretically or experimentally determined, may define a D_i state if $P(D_i/X) > P_i$, where P_i is the limit probability for the D_i state ($P_i \approx 0.9$ is recommended).
2. The analysis' volume increases exponentially with the number of functioning states and parameters considered significant for these states.

3. The application of some rigorously controlled selection criteria leads to reduction of the number of significant values of X parameters.

3.2 EXPERIMENTAL METHODS TO ESTABLISH TECHNICAL DIAGNOSTICS

The functioning state of a machine tool may be correlated with divers parameters such as: (a) vibrations, (b) noise and acoustic emission, (c) temperature, and (d) cutting force and moment. Diagnostic methods based on the use of the first two parameters are presently the most widespread.

The acoustic or vibrator signal, captured by adequate transducers and used for diagnostic purposes, may be processed in many ways. The directly recorded vibration or acoustic signal is very rarely used in its primary form; usually the important elements used for analysis are the effective value or the power spectrum, thus the signal's energy. The advantage of methods based on the energy of the vibratory signal is that it allows the use of a common inexpensive instrumentation. The inexpensive quality recommends these methods for research laboratories and production technical systems. More elaborate procedures use the phase of the captured signal.

Use of the acoustic signal in diagnosis aims to create an ambient system that allows a correct acoustic measurement of the sound emitted by a machine tool, which is why measurements are done in an anechoic or reverberant room, well isolated from environmental sound. These conditions are hard to realize in a plant environment, but they may be produced in research laboratories.

Another major disadvantage of using the acoustic signal is its incapacity to identify the diverse noise sources of the machine, and because of this disadvantage, if the machine does not pass the noise test, other diagnostic procedures will be used in order to determine the source and the time until repairing. This disadvantage may be used to correlate the vibration tests with the noise tests. It is possible to locate an accelerometer in the immediate vicinity of a noise source in a variety of locations on a machine, to determine if this source is a problem for the machine. Precise information necessary to diminish the noise level is also obtained.

Use of the vibration signal for diagnostic purposes has proved to be very advantageous. The isolation of the machine from the vibrations of the plant environment is simpler and more efficient: a rubber or polyurethane foam carpet can serve as an excellent isolator as the environmental vibrations are of low frequency. From this point of view, it must be noted that machine tools need foundations that ensure antivibration isolation or at least use dampening pads for leaning. Environment-radiated noise in machine tools produces structural vibrations of incomparably smaller amplitude than those of the internal mechanisms; these vibrations can be ignored. The main advantages of the vibration measurements are twofold: the possibility of fault detection and the possibility of locating the source of these faults, that make vibration the main signal for diagnostic study.

There are major differences among diagnosis methods depending on their capacity to reach the imposed goal, identify the fault, and establish the technical diagnostic. In this respect there are methods that indicate the functioning state and/or the existence of a fault, called basic diagnosis methods, and methods that estimate the fault kind, location, and time until spoilage, called profoundness diagnosis methods. A comparative study of the two types of methods highlights the fact that the same physical effects and, many times, the same vibroacoustic signals, but treated with different mathematical algorithms, are differently valorized depending on the desired precision degree of the diagnosis.

3.2.1 Specific Parameters Common to Vibroacoustic Methods of Diagnosis

In order to process the vibration signal in the time domain (Fig. 3.2), some parameters specific to the analysis of the vibroacoustic signals are introduced:

The medium value (arithmetic) of the signal:

$$\overline{x} = \frac{1}{T}\int_0^T x(t)dt = \frac{1}{N}\sum_{i\_1}^{N} x_i \tag{3.10}$$

The effective value (effective of the root mean square, *RMS*):

$$x_{ef} = \sqrt{\frac{1}{T}\int_0^T x^2(t)dt} = \frac{1}{N}\sum_{i\_1}^{N} x_i^2 \tag{3.11}$$

The peak value of the signal:

positive peak: $x_{v+} = \max .x(t)$

negative peak: $x_{v-} = \min .x(t)$

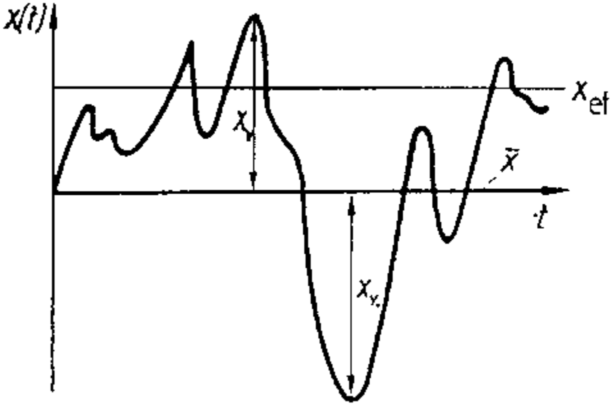

FIGURE 3.2 Vibration signal in time domain.

The signal's dispersion (σ-standard deviation of the same signal):

$$\sigma^2 = \lim_{T\to\infty} \frac{1}{T} \int_0^T (x(t) - \overline{x})^2 \, dt = \frac{1}{N-1} \sum_{i\_1}^{N} (x_i - \overline{x})^2 \tag{3.12}$$

The function of amplitude distribution [the probability that the vibration amplitude is inferior to a given value x; see also Fig. 3.3 (left)]:

$$P(x) = \lim_{T\to\infty} \frac{\sum_0^i \Delta t_i}{T} \tag{3.13}$$

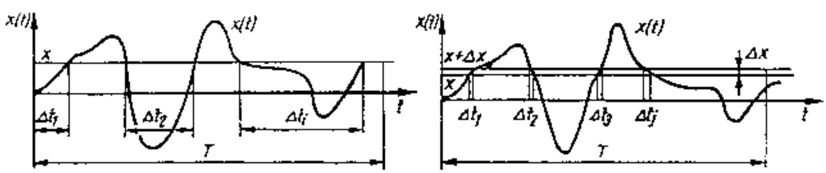

FIGURE 3.3 Amplitude of vibration: (left) inferior to a given value; (right) instant amplitude is in a given interval.

The function density of probability of the amplitude [the probability that the instant amplitude of the vibrator signal will be in a given interval; Fig. 3.3 (right)]:

$$p(x) = \lim_{\Delta x \to 0} \frac{P(x) - P(x + \Delta x)}{\Delta x} \tag{3.14}$$

It can be deduced from the last definition that between the function of amplitude distribution and the function density of probability of the amplitude exists the relation:

$$p(x) = \frac{P(x)}{dx} \quad \text{or} \quad P(x) = \int_{-\infty}^{\infty} p(x)dx \tag{3.15}$$

The autocorrelation function (estimation if the vibrator signal remains similar to itself):

$$C_x(\tau) = \frac{1}{T}\int_0^T x(t)x(t+\tau)dt = \frac{1}{N}\sum_{i\_1}^{N}(x_i + x_k) \tag{3.16}$$

Another parameter is added to those above in order to estimate the signal in the frequency domain:

The spectral density of power (the amplitude density in the power spectrum):

$$S_x(f) = \left| \frac{2}{T}\int_0^T x(t)e^{-2\pi jft}dt \right|^2 \tag{3.17}$$

This function is in fact the Fourier transform of the autocorrelation function from the time domain. With this function's help the total power of the signal is obtained by integrating the partial powers of the spectral components:

$$P = \int_0^{\infty} S_x(f)df \tag{3.18}$$

3.2.2 Diagnostic Surface Methods

3.2.2.1 Peak Factor Method

This method evaluates the vibroacoustic signal in the time basis by recording the peak value and the effective value, followed by the calculus of the peak factor:

$$F_v = \frac{\hat{x}}{x_{ef}} \tag{3.19}$$

On the occurrence and development of a fault in a bearing, the shocks generated while rolling over the fault make the peak value increase substantially, but the shocks have a very small influence on the effective value of the vibrator signal. In consequence the value of the peak factor increases and this tendency has to be supervised.

In the technical literature, on the basis of numerous tests, the following characteristic values are given for the peak factor.

$F_v < 10$: good bearing;
$F_v = 10, \ldots, 20$: fault conditions occur;
$F_v = 20, \ldots, 25$: incipient fault;
$F_v > 25$: fault bearing.

The effective value of the vibrator signal increases even as the shock's amplitude from individual faults remains constant, as the bearing is deteriorating and more and more faults occur. This phenomenon makes the peak factor "fall" to the initial value, toward the end of the bearing life cycle, making a deteriorated bearing appear in good condition. Such behavior will trick an uninformed user of this diagnostic technique.

The peak factor method is simple and easy to use. It is especially useful in the case of monitoring a large number of measuring points when an early warning is not required, and the consequences of spoilage are not too great. In particular situations, the method can be completed by another diagnosis method in profoundness, for example, Cepstrum analysis.

3.2.2.2 Diagnostic Index Method

This method has its basis in the use of normalized values of the effective and peak parameters of the vibrator signal.

Normalization aims to report the value of parameters characteristic of the analyzed signal, measured at a certain moment t, to a reference value for that parameter. For diagnosis, it is useful for the reference value of the normalized parameter to be the value measured in the perfect operating state of the supervised system.

Use of the normalization method allows the estimation of the functioning state of simple mechanical systems (e.g., bearings) and only by use of the normalized effective values or peak values of the vibration signal. For example, the fatigue of the radial ball or roller bearings can be correlated with the effective value of the signal acceleration as follows.

$x_{ef} = 20$ [mm/s^2]: normal function;
$x_{ef} = 20, \ldots, 45$ [mm/s^2]: slight traces of light settling;
$x_{ef} = 45, \ldots, 90$ [mm/s^2]: strong settling until visible faults;
$x_{ef} = 90, \ldots, 150$ [mm/s^2]: major faults;
$x_{ef} > 150$ [mm/s^2]: out of operation.

The diagnostic error by this method is approximately 50% (see Table 3.1), and decreases to under 30% by normalization of the effective value indicator.

The diagnostic index can be defined with the relation

$$K(t) = \frac{x_{ef}(0)\hat{x}(0)}{x_{ef}(t)\hat{x}(t)} \tag{3.20}$$

so it has a value between 0 and 1.

TABLE 3.1 Error Margin for the Diagnostic Index Method

Parameter	Without normalization	Error (%)	With normalization	Error (%)
Effective value, x_{ef}	$x_{ef}(t)$	<50	$\frac{x_{ef}(t)}{x_{ef}(0)}$	<30
Peak value, x_v	$x_v(t)$	<50	$\frac{x_v(t)}{x_v(0)}$	<35
Diagnostic index, $K(t)$	$x_{ef}(t)xx_v(t)$	<35	$\frac{x_{ef}(0)xx_v(0)}{x_{ef}(t)xx_v(t)}$	<25

The value of the diagnostic index correlates very well with the functioning state of the machine parts containing rolling elements:

$K(t) = 1, \ldots, 0,5$: good functioning characteristics;
$K(t) = 0,5, \ldots, 0,2$: appearance of accelerating factors of damaging phenomena;
$K(t) = 0,2, \ldots, 0,02$: effects of damaging phenomena occur;
$K(t) < 0,02$: risk of immediate work stoppage by spoilage.

In the technical literature this method is quoted with an error range of 25%, as presented in Table 3.1.

3.2.2.3 Kurtosis Method

The Kurtosis method is a probabilistic diagnostic method that uses the acceleration of the vibrator signal. The amplitude of this signal may be represented by the function density of probability [relation (3.14)].

A bearing in good functioning condition is the source of some stochastic vibration that respects a normal (Gauss) distribution of the amplitude. The injurious processes are the cause of the occurrence of some supplemental components that change the initial character of the signal and implicitly modify the probability density function of the signal. Thus, deviations from the normal (Gauss) distribution are born, and they can be quantified using the statistic moments of superior order.

The Kurtosis factor is a fourth-order moment expressed as

$$\beta_2 = \frac{1}{\sigma^4} \int_{-\infty}^{\infty} (x - \overline{x})^4 \, p(x) dx \qquad (3.21)$$

where $\overline{x}$ is the arithmetic mean of the signal, $p(x)$ is the density of probability of the same signal, and σ is the standard deviation. The value of the Kurtosis index for a Gaussian distribution of a signal is $\beta_2 = 3$, in a large band of frequency ($2.5 \div 80$ kHz) and with a maximum deviation of 8%. The increase of this index indicates the debut ($\beta_2 = 4 \ldots 6$) and the existence ($\beta_2 > 6$) of a mechanical fault, respectively. For higher values of the index ($\beta_2 = 9 \ldots 10$), the machine has to be stopped and the faulty spare part changed.

This method has been applied with good results in supervising the rolling bearings. Figure 3.4 presents the basic electronic circuit for the calculus of the Kurtosis index starting from the measured vibration signal on the box of a bearing. The role and type of each electronic block can be observed and also the successive transformations of the initial signal. The advantage of this method lies in renouncing the use of

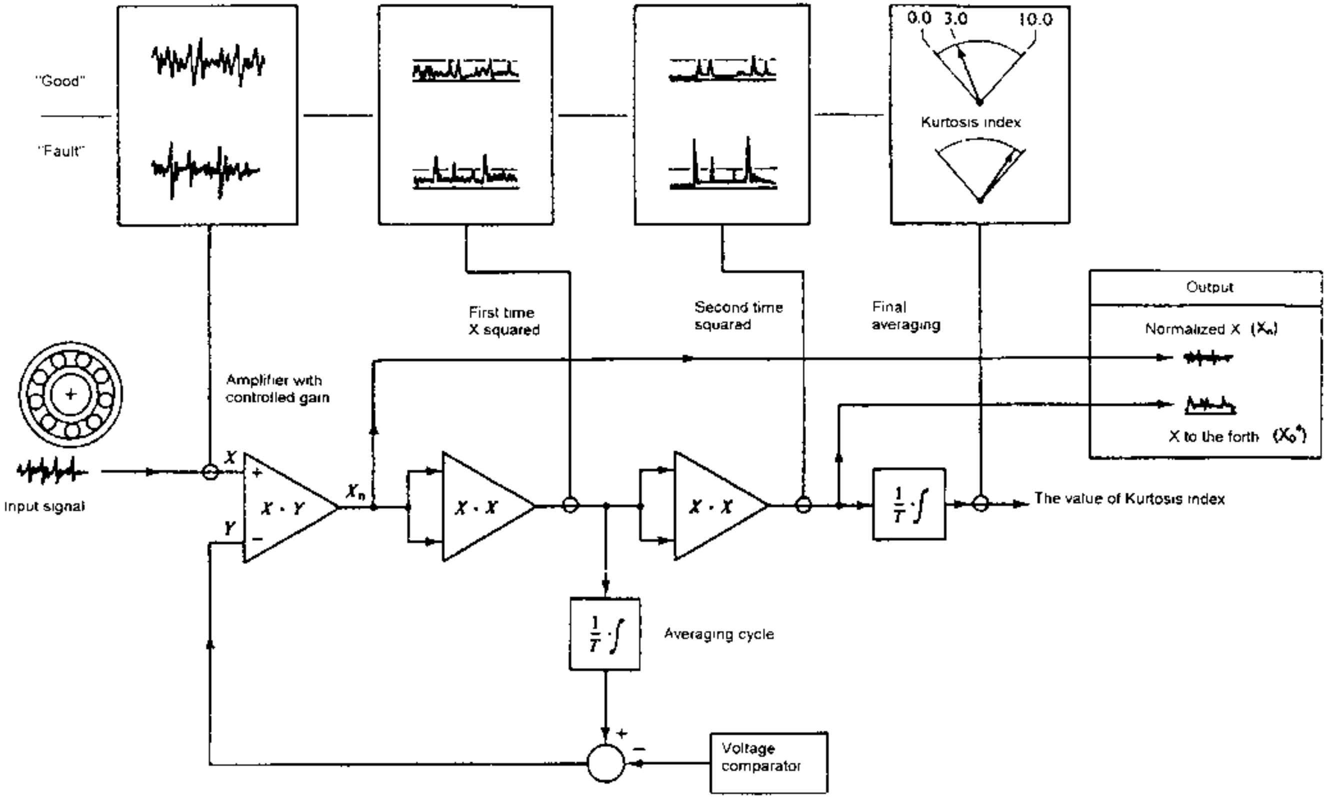

FIGURE 3.4 Basic electronic circuit for calculus of the Kurtosis index.

some comparative values that make the method useful without previous preparation. The Kurtosis method is quoted as one of the most precise surface diagnosis methods with an error range of 20 to 25%, according to the technical literature.

3.2.2.4 Shock Impulse Methods

Specific faults occur in the functioning of mechanisms that replace the slipping friction with the rolling friction such as some irregularities. The irregularities of rolling surfaces and bodies, which are due to mounting faults and/or wear damage, disturb the process of uniform rolling and lead to the occurrence of mechanical shocks. Thus, a wave of mechanical pressure occurs (shock impulse), which diffuses in the material as a spherical wave, with a speed specific to the bearing's material. The residual arrow dampens very slowly compared to the process of acceleration by shock (Fig. 3.5). The maximum value of the amplitude of these large band sonic waves is dependent on the kinetic energy transferred and by the square of the shock speed. At constant rpm, the shock speed modifies proportionally with the body mass and the depth to which the rolling body penetrates.

The magnitude of the damages can be established by measuring the shock impulses and by counting the sizes of the bearing (internal diameter D) and the rpm n. The level of maximal values dB_M and the white noise level dB_C determine the logarithmic value dB_{sv} (decibel shock value). The reference value is the initial value dB_I, representing

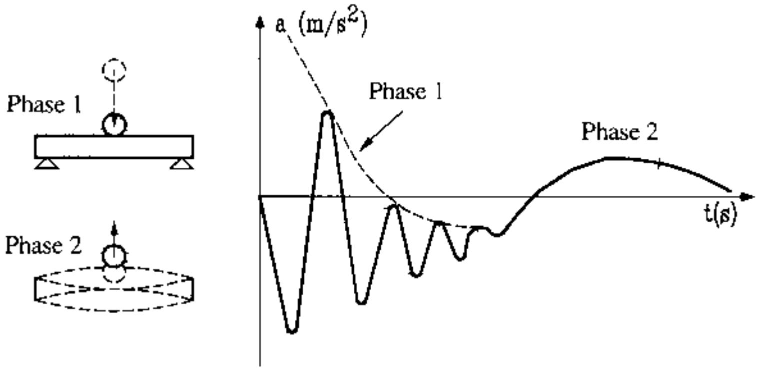

FIGURE 3.5 Wave of mechanical pressure.

the level of shock impulses of the new bearing perfectly mounted and greased. The reference value can be also established empirically using the relation:

$$dB_I = 20(\log n + 0.6 \log D - \log 2150) \tag{3.22}$$

The normal value of shock impulses dB_N is taken as the basis in order to evaluate the functioning state of the bearing:

$$dB_N = dB_{SV} - dB_I \tag{3.23}$$

and the correlation is as follows.

$dB_N = 0 \ldots 20$: good functioning state;
$dB_N = 20 \ldots 35$: functioning state to the limit, because of the lack of grease, some mounting errors, or the appearance of the pitting phenomenon;
$dB_N = 35 \ldots 60$: critical state, risk of "out of operation."

The working principle of the method is illustrated in Fig. 3.6. The shock wave, which is captured by an acoustic emission transducer, is introduced in a narrow band-pass filter. The filtered signal is transformed by an impulse generator in an amplitude impulse proportional to the shock speed.

The SPM diagnosis method has a statistic character and the diagnostic error is under 10%. This method especially highlights faults due to pitting, material fatigue, and mounting errors. The use of this method has the following advantages.

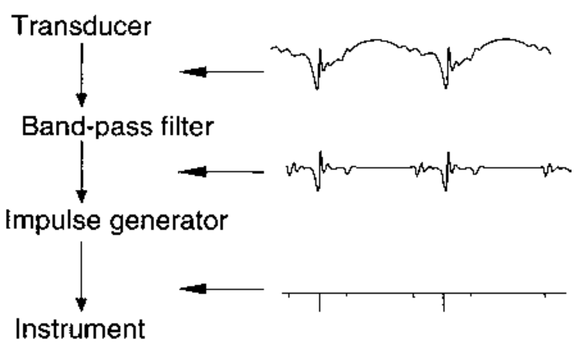

FIGURE 3.6 Working principle of shock impulse method.

The results of measurements are not influenced by machine tool or other equipment vibrations.
The level of the shock impulses of a damaged bearing, compared to a new bearing, may increase by a factor of 1000 (60dB).
The results of measurements of neighboring bearings can be separated as a result of dampening the high frequency vibrations.

Figure 3.7 presents typical shock impulse diagrams drawn by the SPM method: (a) a bearing in good functioning shape, (b) impure vis-

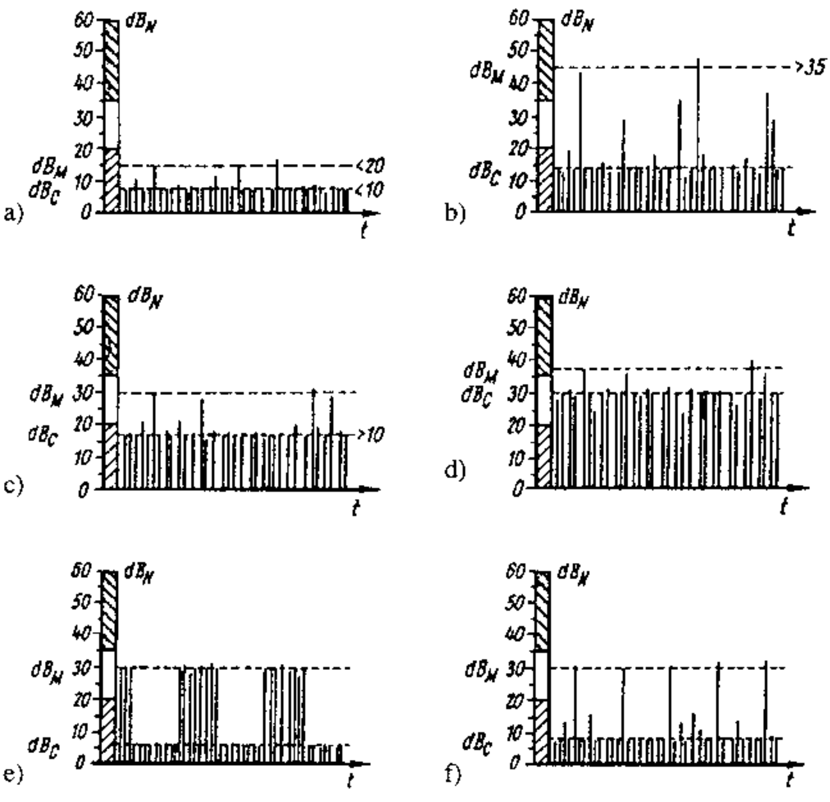

FIGURE 3.7 Typical shock impulse diagrams, drawn by the SPM method: (a) bearing in good functioning shape; (b) impure viscous grease; (c) fault or insufficient grease; (d) bearing not greased; (e) phenomenon of friction synchronized with rpm; (f) rhythmic functioning perturbations.

cous grease, (c) a mounting fault or insufficient grease, (d) bearing not greased, (e) phenomenon of friction synchronized with rpm, and (f) rhythmic functioning perturbations, for example, by load shocks or pressure shocks.

3.2.3 Profoundness Diagnosis Methods

3.2.3.1 Spectrum Comparison Method

Analysis in the frequency domain is based on obtaining the frequencies spectrum using the Fourier transform:

$$
\begin{aligned}
G(f) &= \int_{-\infty}^{\infty} g(t)e^{-j2\pi ft}\,dt \\
g(t) &= \int_{-\infty}^{\infty} G(f)e^{j2\pi ft}\,dt
\end{aligned}
\tag{3.24}
$$

Spectrum comparison is a frequency method that, on the basis of automatic comparison of the spectra coming from the same measuring point, but at different times, recognition of some faults and also, through tendency analysis, permits estimation of the time until final damage (out of use).

The method is applied in the following steps.

1. Obtaining the reference pattern. With the machine in perfect functioning state, more frequency spectra are recorded in the domain 2 Hz…20 kHz, depending on the memory of the analyzer. The reference spectrum is obtained from the mean of the recorded spectra (represented as darker shading in Fig. 3.8a), and is kept as it is. The reference pattern results as an evolute of the reference spectrum, by widening the frequency peaks (represented by the thick line in Fig. 3.8a). This widening of peaks is made to avoid the false signals that can occur on the translation of whole spectrum at small rpm fluctuations of the monitored element.

2. Definition of the limiting profiles. Two other profiles are defined related to the reference pattern: the tolerance pattern (of the admissible levels) and the alarm pattern (of maximum levels where the intervention for readjustment is compulsory). These profiles are obtained either adding a tolerance of the amplitude, on short frequency domains to the reference pattern, or translating the whole reference pattern to a preestablished level. Usually, in order to obtain the tolerance pattern,

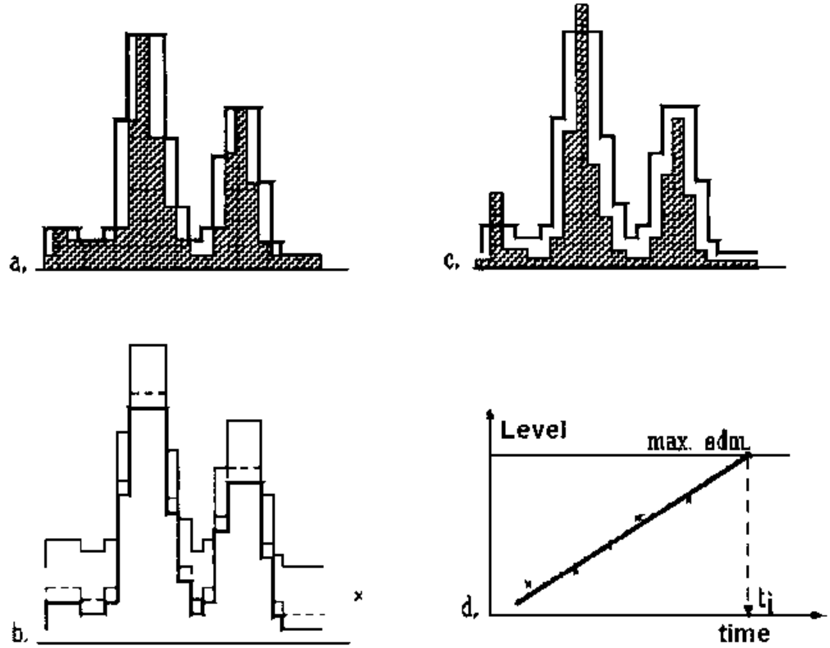

Figure 3.8 Steps of the spectrum comparison method: (a) reference spectrum and pattern spectrum, (b) tolerance pattern and alarm pattern, (c) current spectrum, (d) tendency chart.

the translation is made vertical to the "2 × reference pattern" (represented by the dash–dot line in Fig. 3.8b), and for alarm pattern to "10 × reference pattern" (represented by the thin line in Fig. 3.8b).

3. Comparison of spectra. The current spectrum (black in Fig. 3.8c), captured in the respective measuring point after a time interval or with a rhythm on the user latitude, is compared by superimposing on the tolerance pattern. After comparison, the frequencies that have surpassed this pattern and the value of the overages are highlighted in a chart. It is necessary to stop the machine when the alarm pattern has been surpassed, in order to find and fix the damage.

4. Drawing the tendency diagrams. Evolution of the frequencies that surpass the tolerance pattern can be analyzed on the basis of some successive comparisons for predetermined intervals. A diagram of the increase of the amplitude difference between the current spectrum and

the tolerance spectrum can thus be drawn by points, a diagram which is usually linear (Fig. 3.8d). The point whose abscissa indicates the moment of intervention (t_i) for reestablishment is at the intersection of this line with the horizontal line representing the maximum admissible value for the analyzed frequency (value taken from the alarm pattern). The difference between this moment and the time when the last current spectrum was drawn represents the interval for which the machine can still be used in limited operation conditions.

3.2.3.2 Evolute Method

The characteristics of part vibrations change while a fault begins to develop in a part that has rolling elements. Each time a rolling element meets a discontinuity on the rolling path, an impulse occurs. This impulse periodically repeats with a rate determined by the location of discontinuity, the geometry of the part, and the rpm of the driving element. These repetition frequencies are characteristic frequencies; they are not always easy to find in a standard frequency spectrum because they are mixed with vibratory components of a much higher level.

The impulses resulting from the concussion of the rolling elements with the discontinuities appear as an increase of the wide band in the domain of the superior frequencies of the vibratory signal. In consequence, separating this frequency domain using the Zoom function and the Fourier analyzers, or using a band-pass filter, a signal that contains these impulses is obtained. This signal is leveled in order to find the evolute of impulses in the time domain; then the signal is passed in the frequency domain and the evolute spectrum results. This spectrum has maximums at the impact frequency, thus the nature of the fault and also the element that has the fault can be recognized. This information is usually the key to the time approximation until stoppage due to damage. The absolute value of the peaks from the spectrum depends a great deal on filtration and on the excited resonance frequencies, and does not present interest for diagnosis.

The maximums indicated by the occurrence and the evolution of the mentioned faults are not usually perceptible in the raw spectrum of the vibrator signal because their modular frequency manifests as lateral bands around the natural frequencies.

If the periodic modulation function is also a harmonic oscillation then it can be written:

$$f_p(t) = A_T + A_M \cos \omega_M t, \tag{3.25}$$

where A_T is the amplitude of the carrier frequency, A_M is the amplitude of the frequency of modulation, and ω_M is the modulating pulsation.

The following relation is deducted from the previous relation.

$$x(t) = A_T \cos \omega_T t + \frac{A_M}{2}[\cos(\omega_T + \omega_M)t + \cos(\omega_T - \omega_M)t] \tag{3.26}$$

where ω_T is the pulsation of the carrying signal.

The lateral bands that appear are visible in the real signal spectra only in very rare cases. Most frequently, they are superposed with neighboring components of the frequency. The classical models for signal analysis can not draw sure conclusions from the analysis of such a spectrum, and that is why the extraction of the evolute curve is used. In order to extract this evolute curve, a modality to "positivate" the signal in the time domain must be found; this may be done using one of these methods:

Forming the mean value of short time
Forming the effective value of short time
Directing and filtering of the signal
Using the Hilbert transform
Passing directly to Cepstrum analysis (Fig. 3.9)

The mean value of short time can be calculated as

$$m(t) = \frac{1}{T}\int_t^{t\_T} x^*(t)dt$$

where

$$x^*(t) = 0 \quad \text{if } x(t) < 0$$
$$x^*(t) = x(t) \quad \text{if } x(t) \geq 0 \tag{3.27}$$

or

$$m(n) = \frac{1}{N}\sum_{i\_nN}^{nN\_N} x_i^*, \qquad n = 1, 2, 3, \ldots$$

where

$$x^* = 0 \quad \text{if } x_i < 0$$
$$x^* = x_i \quad \text{if } x_i \geq 0 \tag{3.28}$$

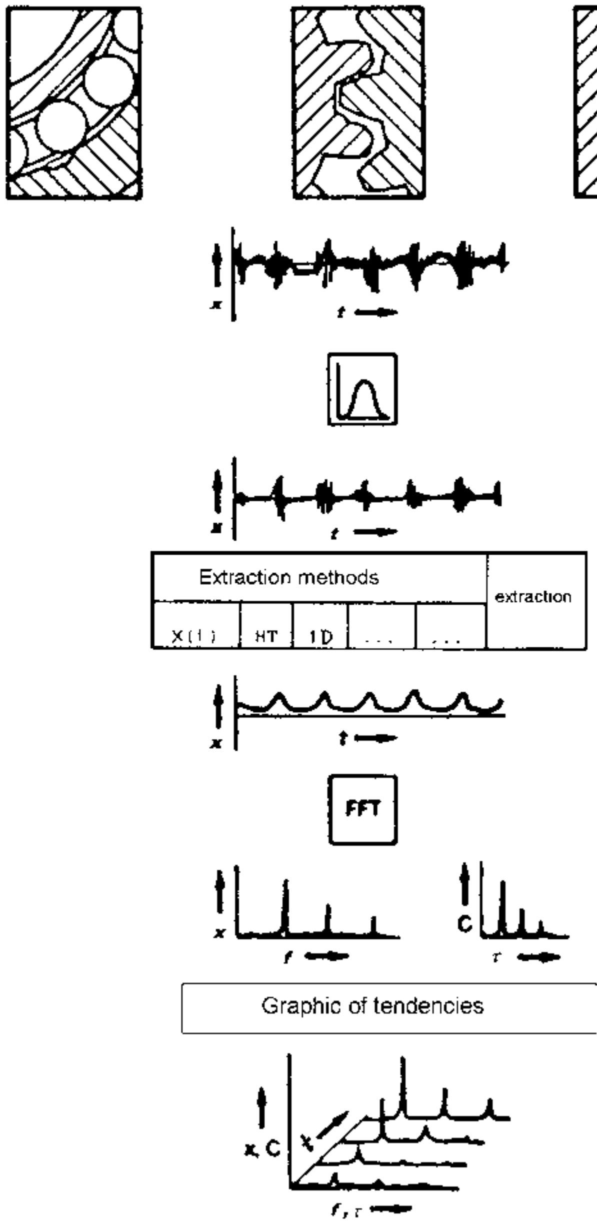

FIGURE 3.9 Diagram of amplitude difference increase between current spectrum and tolerance spectrum.

The effective value of short time can be calculated as

$$e(t) = \sqrt{\frac{1}{T}\int_{t}^{t\_T} x(t)^2\ dt} \tag{3.29}$$

or

$$e(n) = \sqrt{\frac{1}{N}\sum_{i\_nN}^{nN\_N} x_i^2}, \qquad n = 1, 2, 3, \ldots . \tag{3.30}$$

The length of the time interval has a special importance; usually the following relation must be respected,

$$f_t > \frac{1}{T} \geq f_M \tag{3.31}$$

where f_T is the carrying frequency and f_M is the modulation frequency. It can be mentioned in conclusion that the time interval T must be at least as large as the period of the carrying vibration having the smallest frequency.

The most exact method of extraction of the evolute is the application of the Hilbert transform of the time domain signal:

$$H\{x(t)\} = \frac{1}{\pi}x(t)\ ^*\ \left(\frac{1}{t}\right) \tag{3.32}$$

When passing in the frequency domain applying the Fourier transform, the following relation is obtained,

$$\mathcal{F}\{H\{x(t)\}\} = X(f)(-j\ \mathrm{sign}(f)) \tag{3.33}$$

Thus, using Fourier analyzers, changing the phase in the frequency domain is simple to realize; this change corresponds to a 90° rotation in the complex space.

If we consider the original signal and the Hilbert transform of this signal as real and imaginary parts of a complex function x_H; then this is the evolute of the time signal:

$$x_H(t) = x(t) + jH\{x(t)\} \tag{3.34}$$

If the frequency analyzer does not possess the algorithm needed to obtain the Hilbert transform, the method of signal directioning and filtering can provide very good results. The signal captured by the accelerometer contains, as specified above, lateral bands of the fault frequency and of the rotation frequency around each characteristic frequency. In other words, the carrying signal containing the whole characteristic frequency is modulated by a signal containing the fault frequency f_d, the rotation frequency f_r, and their subharmonics.

The reduction of the frequency content of the signal is realized when passing through a band-pass filter centered on one of the characteristic frequencies. The bandwidth of this filter is taken in such a way that the lateral frequencies induced by the fault can also pass. To make this possible, the largest value of the fault frequency f_{md}, and the bandwidth $l_b > \pm f_{md}$ (usually $\pm 2f_{md}$) must be approximated. Consequently, when leaving the filter, the signal will contain the characteristic frequency and its lateral frequencies $f_d(2f_d)$ si $f_r(2f_r)$. The signal is then demodulated and passed through a low-pass filter to eliminate the eventual lateral frequencies that are around the first superior harmonic of the central characteristic frequency.

Processed in the manner outlined above, the signal is then passed in the frequency domain by a Fourier analyzer, and the evolute spectrum is obtained, a spectrum that contains all the mentioned frequencies, including the frequency specific to the damage.

Separation of fault damage is realized using a "normalization method" similar to that presented in the diagnostic index method. This separation will be possible if previously a spectrum of evolute in a perfect functioning state of the machine was obtained. Normalization consists of the distribution of amplitude values of the corresponding frequencies, frequency with frequency, between the spectrum with fault and the spectrum without fault, using a relation such as

$$R(f) = \frac{\max\{A_d(i)\}}{\max\{A_b(i)\}} \tag{3.35}$$

where $A(i)$ is the amplitude of the frequency i, and the indices d and b have the meaning "fault" and "good."

3.2.3.3 Cepstrum Analysis Method

Cepstrum was first proposed in 1963, and it was defined then as the "power spectrum of the power spectrum logarithm." The reason for this definition is not entirely clear because even in the original work it is compared with the autocorrelation function that can not be obtained as an inverse of the Fourier transform of the power spectrum. Later, Cepstrum was defined as the "inverse of the Fourier transform of the logarithmic power spectrum," clarifying the link with the autocorrelation function. At the same time, a function similar to Cepstrum has been defined as the "inverse of the Fourier transform of the complex logarithm of the complex spectrum," and, in order to distinguish the Cepstrum defined above, it was named complex Cepstrum, and the first was renamed power Cepstrum.

The cepstru denomination is paraphrased from the word spectrum; in the same mode a series of other terms is introduced: quefrency from frequency, ramonic from harmonic, gamnitude from magnitude (amplitude), lifter from filter, and others.

The Theoretical Basis of Cepstrum Analysis. Using the $\mathcal{F}\{\ \}$ symbol to indicate the Fourier transform of the quantity in parentheses, the definition used for the power Cepstrum is

$$c_p(\tau) = \mathcal{F}^{-1}\{\log F_{xx}(f)\} \tag{3.36}$$

and for the complex Cepstrum is

$$c_c(\tau) = \mathcal{F}^{-1}\{\log F_x(f)\} \tag{3.37}$$

where $F_{xx}(f)$ is the power spectrum of the time signal $f(t)$,

$$F_{xx}(f) = |\mathcal{F}\{f_x(t)\}|^2 \tag{3.38}$$

and $F_x(f)$ is the complex Cepstrum of $f_x(t)$

$$F_x(f) = \mathcal{F}\{f_x(t)\} = a_x(f) + ib_x(f) = A_x(f)e^{i\phi_x(f)} \tag{3.39}$$

expressed in real and imaginary components, respectively, in amplitude and phases, with $f_x(t)$ real. From the previous relation, the complex logarithm of $F_x(f)$ results in

$$\log F_x(f) = \log A_x(f) + i\phi_x(f) \tag{3.40}$$

The Cepstrum analysis applications imply the detection of periodic structures from the spectrum (harmonics, lateral bands, echoes, reflections), followed by the separation of source from effects of the transmission path of the signal. The fundamental characteristic of this procedure is the representation, for any physical system, of output signal $y(t)$ as a convolute of input signal $x(t)$ with the system response in frequency function $h(t)$:

$$y(t) = x(t) * h(t) \tag{3.41}$$

Applying the convolution theorem, this relation transforms itself in a multiplication in the frequency domain, and applying the logarithm the relation becomes additive:

$$
\begin{aligned}
Y(f) &= X(f)\ xH(f) \\
\log Y(f) &= \log X(f) + \log H(f) \qquad (3.42)
\end{aligned}
$$

This additive relation maintains itself also in cepstru because of the linearity of the Fourier transform; so here, the effects of the source and transmission are additive:

$$\mathcal{F}^{-1}\{\log Y\} = \mathcal{F}^{-1}\{\log X\} + \mathcal{F}^{-1}\{\log H\} \qquad (3.43)$$

The power Cepstrum and the complex Cepstrum offer the possibility of separating the components because of the excitation from the components due to the dynamic characteristics of the structure (the way covered by the signal), because of the logarithm properties. In addition, the power Cepstrum and the complex Cepstrum offer the advantages of the possibility of eliminating the last-mentioned components and reconstituting on this basis the excitation. At the same time, Cepstrum is less sensible to these dynamic characteristics of structure: for the same excitation, the spectrum of frequencies depends more on the point where the transducer is mounted on a structure, as Cepstrum is less influenced by the choice of the measuring point.

Another important advantage of Cepstrum analysis is the fact that all the lateral bands of a certain frequency are mainly grouped in a single line (ramonica), this line containing significant information concerning the medium height of the lateral band. The use of Cepstrum analysis for machine tool diagnosis is based on the analysis ability to detect the periodicities from spectra (families of harmonics and lateral bands), and also on the insensibility of the analysis related to the path from the internal source to external measuring point. These advantages have imposed the use of Cepstrum analysis for diagnosis of mechanical systems, especially for gearing transmissions (reduction gears, gearboxes, etc.) and for bearings.

3.2.3.4 Acoustic Emission Method

Acoustic emission is defined as the succession of elastic waves generated by the liberation of the internal energy stored in a structure. The acoustic emission manifests in the high frequency domain ($f > 100$ kHz) by elastic waves detectable as vibrations on the supervised structure. As a working method, acoustic emission represents a nondestructive technique, capable of detecting when and where a fissure or crack occurs. The nature and the causes of these faults are then investigated by complementary methods. Four main sources of acoustical emission exist: structural dislocation movements, phase transformation, friction mechanisms (microfrictions, microconcussions), and fissure forming and extension.

In the case of dislocations (i.e., displacement of an imperfection of line in a crystalline network), that occur as an avalanche, the detected signal is of the continuum type, as for the phase transformations (i.e., forming of martensite in carbon steel), the signal is of the impulse type and can be detected for each transformed grit.

The fissures occur in the material nodes and points where the local effort surpasses the fracture stress. Thus, new surfaces are formed and energy is released, energy that is partially converted in acoustic emission. The signal is of impulse type and high frequency. At the same time, the friction mechanisms entered in action also emit impulse type acoustic signals.

In acoustic emission the signal amplitudes cover a wide domain; in relative units, these amplitudes are: 1 to 10 for structural movements, 5 to 1000 for phase transformations, and 20 to 1000 for fissures.

The propagation of acoustical emission is similar to that of radio waves. The source emits packages of spherical waves that are immediately affected by the numerous intersected surfaces that create reflections and surface waves (Fig. 3.10). The nonhomogeneity of the propagation environment also distorts the wavefronts. In consequence, the mathematical relations that describe the real propagation phenomenon are very complicated, and they introduce serious difficulties in sources and effect localization and measurement. This fact limits the usable domain of methods based on acoustical emission for large structures made of steel, where a specific incertitude coefficient can be tolerated.

Many types of treatment of the detected signal are available for the acoustic emission study; that is why at all times a general evaluation must be done first.

Counting of impulses is necessary in impulse type signal treatment. This method supposes an evaluation of the number of impulses that pass over a previously established limit value. In order to do this evaluation, the measuring chain contains a discrimination device for the impulse amplitude level, followed by an impulse counter (per total or per time unit). The simple count of impulses (Fig. 3.11c) can be improved by an evaluation of the impulse area (Fig. 3.11a), which also takes into

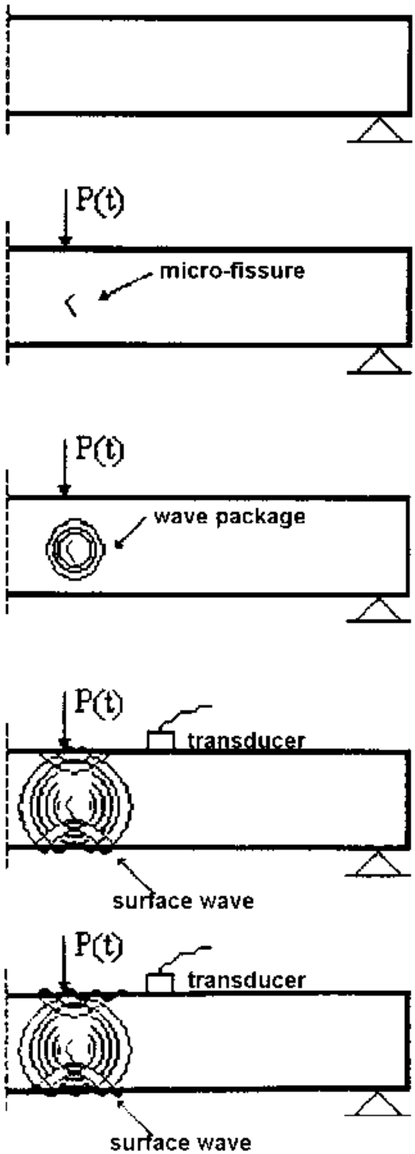

FIGURE 3.10 Propagation of acoustical emission.

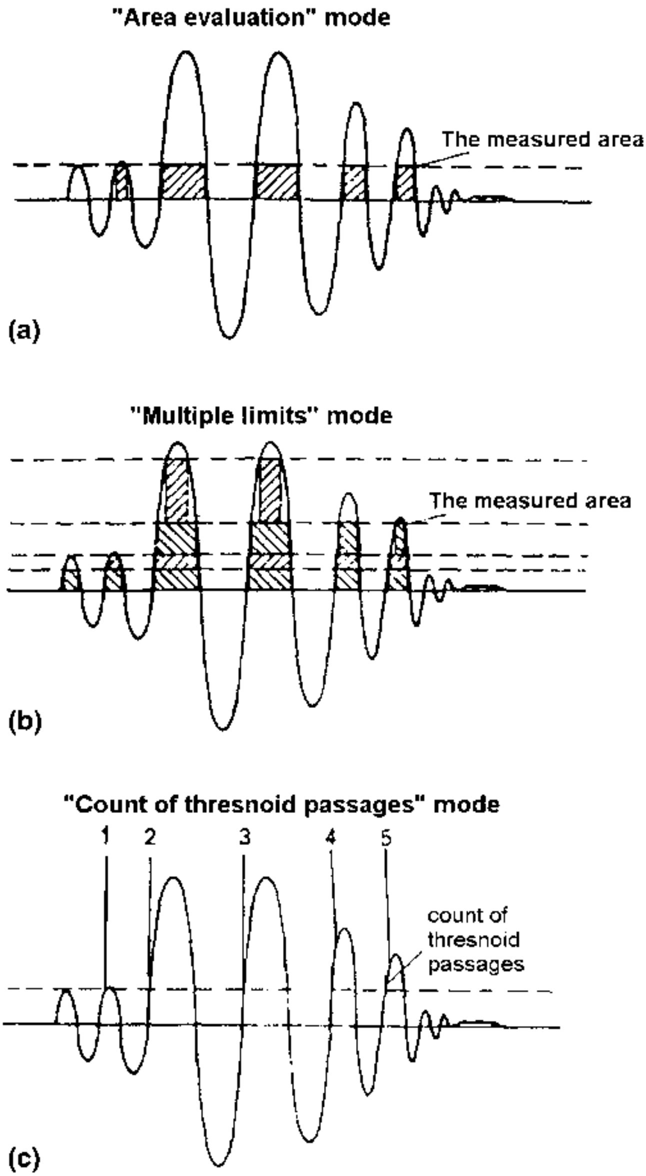

FIGURE 3.11 Impulse count: (a) evaluation of impulse area, (b) combination of limits, (c) simple count of impulses.

consideration the duration of the impulse, eventually by introducing a combination of limits (Fig. 3.11b).

The meaning in amplitude of the impulses is realized in cases when the acoustical emission manifests itself by signals of the continuum type. Calculation of the effective value (RMS) is significant because it is proportional to the power/energy of the signal. This method is encountered sometimes under the name of energetic analysis of the impulse.

It is useful to locate the source of the information provided concerning the source's and the wave trajectory's characteristics and modifications, localization of the primary faults, and the reduction of the times of re-putting into function. In order to locate the source, some controlled elastic waves are created from ultrasonic sources. The ultrasonic wavetrain is characterized by a factor of the simultaneous wave that depends on the frequency of the impulse succession, duration, and number of peaks that surpass a certain limit. In this way, breaking zones can be located with an anticipation in materials.

In order to locate a source, three transducers are used. The time difference between the moments when the signal arrives at two transducers determines a plain hyperbola, if the propagation speed in environment is known. The intersection of obtained hyperbolas from the pair of transducers (1;2), (1;3), (2;3) defines the correct position of the source.

3.3 RECOMMENDATIONS CONCERNING THE USE OF DIAGNOSIS METHODS FOR MACHINE TOOLS

The multitude of noise and vibration sources produced by the complex dynamic structure of machine tools provides serious problems for diagnosticians. However, it is expected that noise and vibrations, coming from functioning machines, are generated by the characteristics of the component mechanisms and subassemblies of the machine tool. At the same time, the working regime parameters and the characteristics of the processed materials have a great influence on these phenomena.

In order to apply vibroacoustic diagnosis to machine tools, the natural sources of noise and vibrations must be identified, and also the parameters that best correlate with the functioning state of the machine tool or its subassemblies and elements. It is indicated that the monitoring of the machine tool functioning state or its component elements may be realized using working techniques in the time domain, and the establishment of the technical diagnostic, using the method of analysis in the frequency domain.

Very good results have been obtained using the Kurtosis method, which has the advantage of immediate application, without knowing the machine history. In the appendices to this book the use of this method of diagnosis of the functioning state for the majority of the components of feed kinematic chain physical models is illustrated.

Concerning the profoundness diagnosis, the best results are obtained by the method of spectrum comparison that, besides indication of nature and place of fault, can also estimate the remaining time until a machine fails because of damage.