5

Designing and Manufacturing a Virtual Instrument Vibroacoustic Method Diagnostic Package

5.1 VIRTUAL INSTRUMENTATION: LabVIEW GRAPHICAL PROGRAMMING ENVIRONMENT

The virtual instrumentation for vibroacoustic diagnosis, which is elaborated and presented in this chapter, uses the LabVIEW (Laboratory Virtual Instrument Engineering Workbench) program, version 2.5, made by National Instruments. The software uses a graphical programming language, G, to create programs such as block diagrams, without sacrificing any of the power or performance of a traditional programming language. LabVIEW uses terminology, symbols, and ideas that are familiar to engineers and researchers, and it is purposely based on graphical symbols, rather than a textual language, for describing programming activities. LabVIEW combines the technology of the most recent operating systems with specialized programming techniques (OOPT, object-oriented programming techniques) to obtain a simple and flexible operating environment.

The LabVIEW software objective is structured on several main levels.

1. The acquisition module provides the possibility of programming and controlling the hardware connected to the measurement/control system. This possibility is realized using a device driver software specific to each connected apparatus. At the present time over 450 of such kinds of drivers exist, made by drivers for instruments from over 45 different producers. It is important to note that all these drivers have a common programming interface (API, application programming interface) that allows the applied programs to be independent of the operating or calculus system. LabVIEW is based on the NI-DAQ (National Instruments Data Acquisition) driver, ensuring the data management, buffer memories, and other resources specific to each plate. The most used acquisition boards provided with this driver are:

Multifunctional: AT-MIO-16D, AT-MIO-64F-5, PC-LPM-16, Lab-PC+
With rapid analogous input: EISA-A2000
For signal dynamical acquisition: AT-A2150
With numerical input/output: AT-DIO-32F, PC-DIO-42, PC-DIO-96
With timing input/output (counting/time basis): PC-TIO-10

2. The processing modulus converts the primary acquisition data into significant results. LabVIEW has libraries of functions and routines for a multitude of programming requests and also a series of specific applications. LabVIEW also includes the tools necessary for building and/or developing applications developed by the user, visualization of data flow, and fixing possible programming errors. LabVIEW software offers a complete and powerful analysis ensemble for numerical data treatment, an ensemble that contains:

Statistical process: histograms, calculus of mean and square mean, distribution calculus, error functions, rational and polynomial interpolations, and so on
Linear and polynomial interpolations in 1D or 2D
Linear, exponential, and polynomial regressions
Linear algebra: vector and matrix normalization, matrix multiplication and inversions, determinant calculus, solving linear equations
Signal generation: impulse, ramp, triangle, sinus, rectangular, aleatory, Gauss distribution, white noise
Processing in the time domain; integration and differentials, decimation, cut off, limit detection, impulse analysis

Processing in the frequency domain: rapid Fourier, Hartley, and Hilbert transforms, spectrogram, magnitude and power spectrum, inter- and autocorrelation, convolution and de-convolution, phase calculation

Windows: Hanning, Hamming, the triangular, Blackmann, Kaiser–Bessel, cosinus, exponential, and others

IIR filters (infinite impulse response): Butterworth, Cebisev, Bessel for pass-up, pass-down, and cross-band

FIR filters (finite impulse response): Parks–McClellan, window, pass-up, pass-down, cross-band, and user-defined filters

Nonlinear filters: environment

3. The presentation modulus is of an interactive type, the computer display having the function of a front panel, similar to traditional instruments. Using the mouse's help, all the buttons, switches, inverters, and potentiometer from the front panel can be operated. In addition a series of options exists for stocking data on the hard disk, for transferring data to a network, or obtaining hard copies on plotter or printer.

The LabVIEW programming environment can be used both by inexperienced users (because of its graphical simplicity) and by specialists (because of its flexibility and the possibility of developing sophisticated applications).

5.2 STRUCTURE OF LabVIEW VIRTUAL INSTRUMENT

The programs elaborated using the LabVIEW programming environment are called VIs—virtual instruments—because of their similarity to traditional measuring and control instruments, not only in appearance, but also in the operating mode. In reality, they are analogous to the functions from conventional programming languages.

Virtual instruments work with graphic blocks that are sequences of the program presented in a graphical shape adequate for their purpose. A graphical block accepts one or more types of input data. These data are processed and then the results are sent as output usable in other sets of graphical blocks. In this manner the continuity of signal transmission is ensured. It must be noted that the route of each type of data is presented in a certain color and line thickness. The virtual instrument can be in edit mode, when the instrument is modified with specific tools, or run mode, when the instrument is used for the purpose for which it was created.

Any virtual instrument has three components: front panel, block diagram, and the graphical symbol with connectors. The front panel represents the graphical user interface. This panel simulates the front view of a traditional instrument and can contain buttons, switches, indicators, and displays for graphical representations. In addition, it must specify the inputs and outputs of the virtual instrument using adequate indicators and control elements. The panel is built using the Controls menu, where diverse options of indicators and control elements are preconfigured. Using the operating tool (the hand with the straight forefinger), which is operated by mouse, we can intervene on each element from the front panel (on-off, adjustments, rescaling). Using the positioning tool (the arrow) we can select, reposition, and resize the elements.

The block diagram represents the graphical solution of programming problems. A block diagram, that is, the equivalent of the working algorithm (of the program) for the virtual instrument, accompanies each front panel, and therefore the block diagram can be considered as a code source in the graphical programming language G. The block diagram is made by symbols framed in buckles (e.g., FOR, WHILE) and/or case structure. The components are linked in between by wires or nodes in such a way that they follow the data flow in the diagram from input to output. The block diagram is built using the Functions menu, to place the components (arithmetical and logical functions, FOR cycles, WHILE buckles, TRUE/FALSE cases), and also using the link tool to make the tracts between components. It must be noted that the LabVIEW application automatically places on the block diagram the terminals associated with the indicators and control elements from the front panel.

The Icon/Connector is the simplified graphical representation of a virtual instrument; this representation indicates only the instrument destination and the type and placement of its inputs and outputs. Concentrating a virtual instrument in such an Icon/Connector, it can be used as a subinstrument in any other block diagram connected to the other components of the operating schema. When they are defined, the icons and/or connectors are displayed in an alternative manner in the upper-right corner of the virtual instrument from the working window, in order to find the link mode between inputs and outputs. These connections are analogues to the parameters of a subroutine or of a function, and correspond to the indicators and control elements from the front panel.

LabVIEW is a modular and hierarchic programming environment. Modular because any block diagram can be concentrated in an icon and thus used as a subvirtual instrument (subVI), and hierarchic because any subinstrument may be used in the block diagram of an instrument of superior level. The number of virtual subinstruments from a hierarchy is practically unlimited, both on horizontal and vertical. These two characteristics of LabVIEW software facilitate creation, understanding, and maintenance of virtual instruments. A complex application may be divided into a series of simple tasks and a virtual instrument can be built to solve each of these tasks. Finally these instruments are included in a virtual instrument of superior level, which solves the complex application. Each instrument can be run individually, separated from the rest of the application, so the eventual malfunctioning can be rapidly located. More than that, subinstruments of inferior level can accomplish tasks that are common to other applications, so they can be reused.

5.3 VIRTUAL INSTRUMENTATION FOR SURFACE DIAGNOSIS

As presented above, surface diagnosis methods are useful for supervising the operating state of machine tools; they signal the overpassing of some signal levels which are considered normal, without providing other information concerning the cause or the nature of the abnormality and without evaluating the time remaining until the final stop.

Three virtual instruments have been elaborated and tested for surface diagnosis:

FACVARF, based on evaluation of the peak factor (Fv)
INDDIAG, based on evaluation of the diagnostic index $[K(t)]$
INDKURT, based on evaluation of the captured vibrational signal

The theoretical bases of diagnosis methods utilized were presented in Chapter 3 of this work, and are not redescribed here.

Being designated for "offline" type surface diagnosis, these virtual instruments operate in a working space different from the space where captioning of signals is done. Thus grouping of the acquisition files has been in view, depending on measuring points; that is why temporary positioning of each signal acquisition has also been in view, so that the file format saves both the signal and the moment of acquisition.

The three instruments can be used separately or simultaneously for the analysis of the same signal; they do not exclude each other—rather they are complementary. Following the idea of complementarity, the vibration signal reading zone works as a function of time and as a function of finding out the characteristic values common to the three virtual instruments (Fig. 5.1). Thus, in a FOR cycle, on the basis of the path built by using the graphical block 2, the hard disk is read, and block 1 (List Directory) returns two matrices that specify the names of acquisition directories and folders met. Graphical block 3 (File/Directory Info) provides information concerning the directory or the folder (such as size and the date of creation or last modification); the date in absolute time is converted into a calendar date through block 4 (Get Date/Time String); this is used to order the function of time for different acquisitions.

The graphical block 10 (Citvib.vi) is a specially built virtual instrument, here as a sub-VI, necessary for acquisitions reading as functions of time; it also has the possibility of amplifying the signal by a

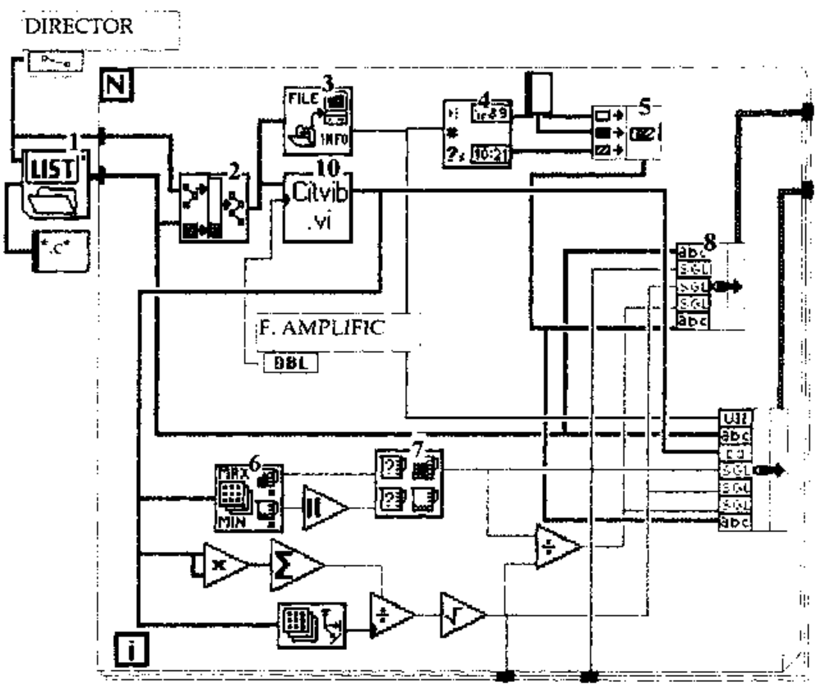


FIGURE 5.1 Vibration signal reading zone is common for FACVARF, INDDIAG, and INDKURT virtual instruments.

factor introduced by the operator. Figure 5.2a presents the block diagram of this virtual instrument; the icons and connectors are shown in Fig. 5.2b.

In the inferior zone of cycle FOR's windows the arrangement of the work matrices is accomplished with the help of graphical blocks 6 (Array Max & Min) and 7 (Max & Min). The matrices are then assembled in a single cluster, near the information referring to date in graphical block 8 (Bundle). The continuation of processing the acquisitioned signal is different for each of the three aforementioned virtual instruments, depending on the diagnostic method used.

The FACVARF.VI instrument (block diagram presented in Fig. 5.3) takes the data from the sorting block 11 (Sort 1D Arry), and displays on the front panel (Fig. 5.4) the graphic of two recordings of the processed signal, in the time domain, as follows: the recording considered as reference (having the machine in a perfect state of operation) and the current recording. For each of the two recordings the maximum value (RMS) is indicated; the value of the peak factor was calculated previously and thus, a first evaluation of the functioning state of the supervised element became possible. Data processing is possible by disassembling the information in graphical block 10 (Unbundled) and then connecting it to the blocks that make the link with the front panel (DBL). The ensemble of statistical processing of the signal is integrated in a WHILE buckle.

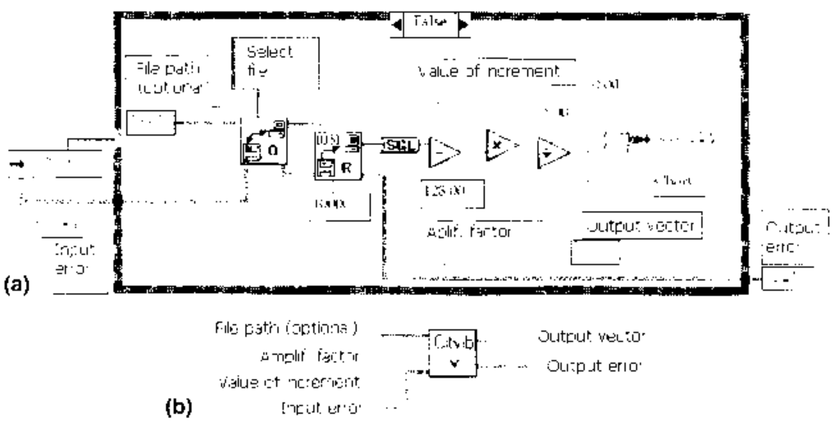


FIGURE 5.2 (a) Block diagram of the virtual instrument; (b) icons and connectors.

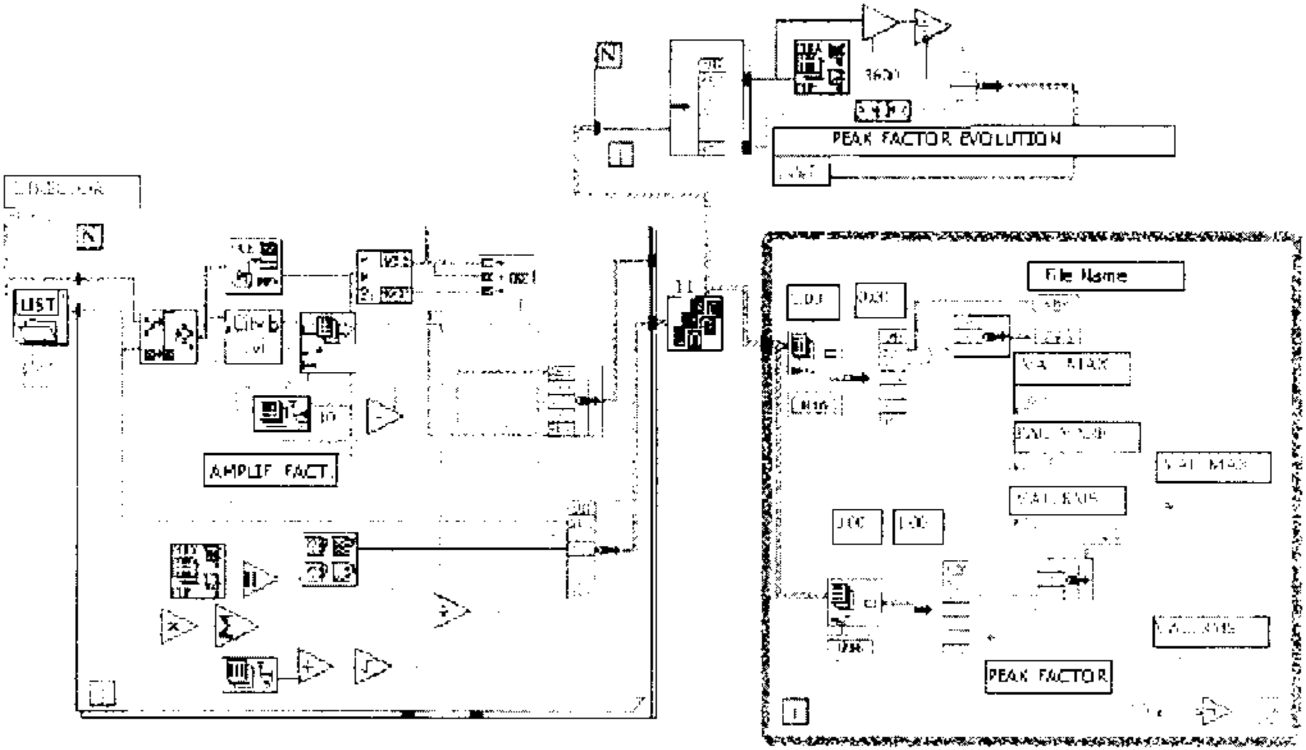


Figure 5.3 FACVARF.VI instrument—block diagram.

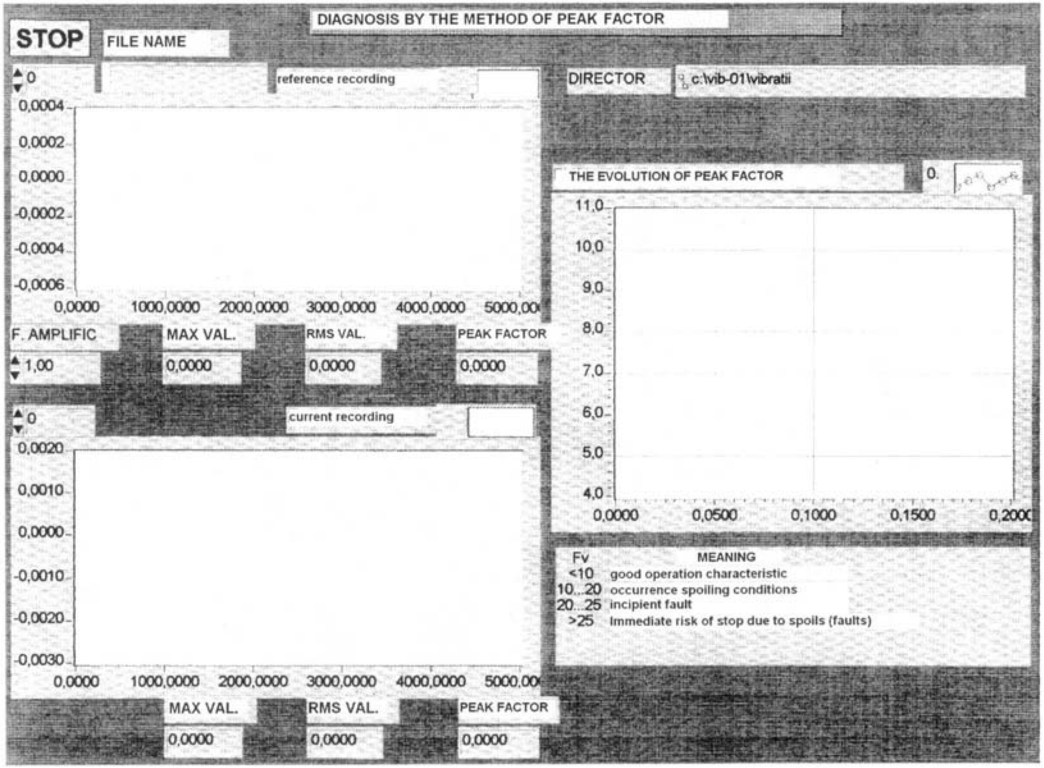


FIGURE 5.4 Front panel of FACVARF.VI instrument.

A third graphic from the front panel of the instrument follows the evolution in time of the peak factor. A point is marked on the tendency graph for each new acquisition, illustrating a short history of the operating state, as this state is captured in the respective measuring point. The graphic is scalable depending on the measuring unit.

The INDIAG.VI instrument (block diagram in Fig. 5.5) performs a processing series similar to that presented previously, but this time using the algorithm specific to the diagnosis index. The front panel (Fig. 5.6) also contains the reference recording and the current recording, near the graphic of the evolution of diagnosis index. Both instruments present a short legend on the front panel next to the graphic of evolution of diagnosis index to make the reference and the current recording easier.

The INDKURT.VI instrument is based on the diagnosis algorithm specific to the Kurtosis method. It is more complex compared to the other virtual instruments. In the block diagram (Fig. 5.7) the instrument contains a sub-VI (Kurt $\beta 2$.VI), integrated in a WHILE buckle, for the calculus of the fourth-order statistic moment ($\beta 2$) and the graphical representation of the probability distribution density of the captured signal.

The symbol and connectors of the graphical block Kurt $\beta 2$.VI are defined according to Fig. 5.8a. The calculus relation of the statistical moment is shown in Section 3.2.2.3, and for its instrumentation a few virtual instruments from the LabVIEW software library have been used (Fig. 5.8b). Those virtual instruments are the following: Standard Deviation.VI, to calculate the arithmetic mean of the signal and standard deviation; Gaussian White Noise.VI to test the instrument; Numeric Integration.VI, to integrate the entire domain; and Histogram.VI, to calculate the probability density of the same signal. Figure 5.9 presents the block diagram of the Kurt $\beta 2$.VI virtual instrument.

The INDIKURT.VI virtual instrument displays (Fig. 5.10) a table of files on the front panel; those files have the available acquisitions on the stocking directory, listed in terms of the acquisition data. When a file is selected from this table certain data processing is performed:

Representation of the captured signal, as a time function (left-up window)

Calculus of the maximum and effective values for the peak factor and Kurtosis index

Graphical representation of the probability density of the signal (left-down window)

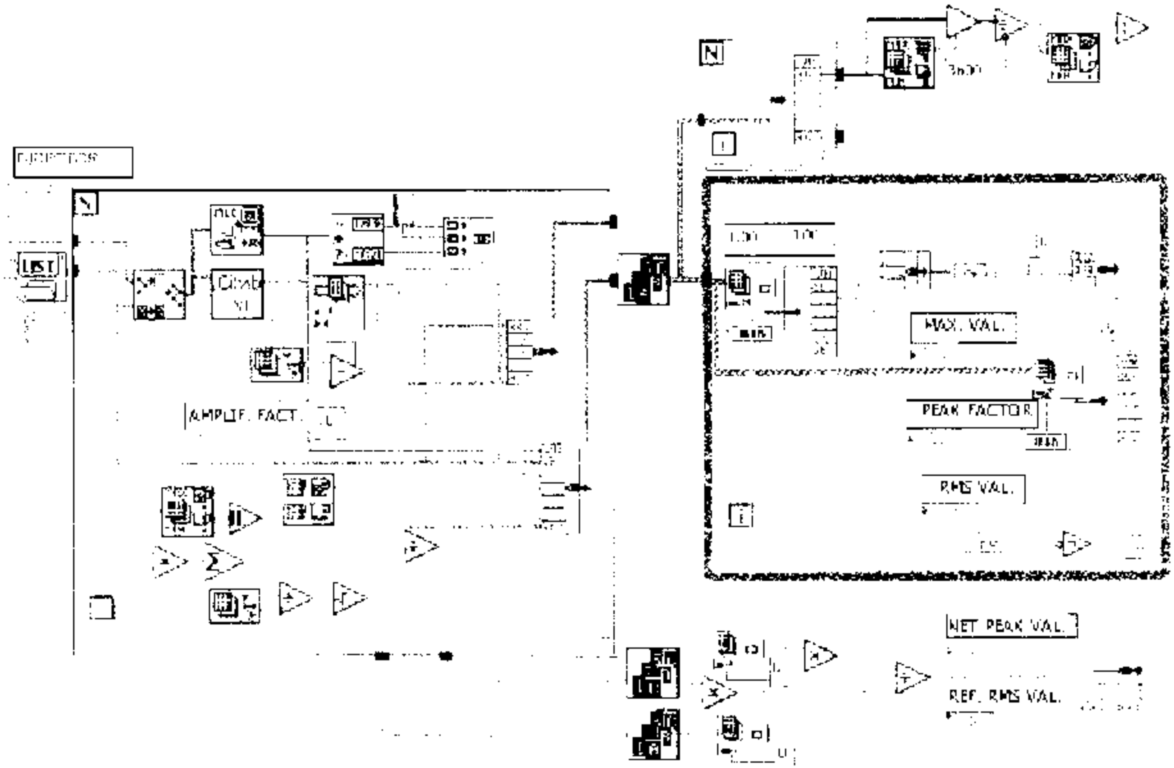


FIGURE 5.5 INDIAG.VI instrument—block diagram.

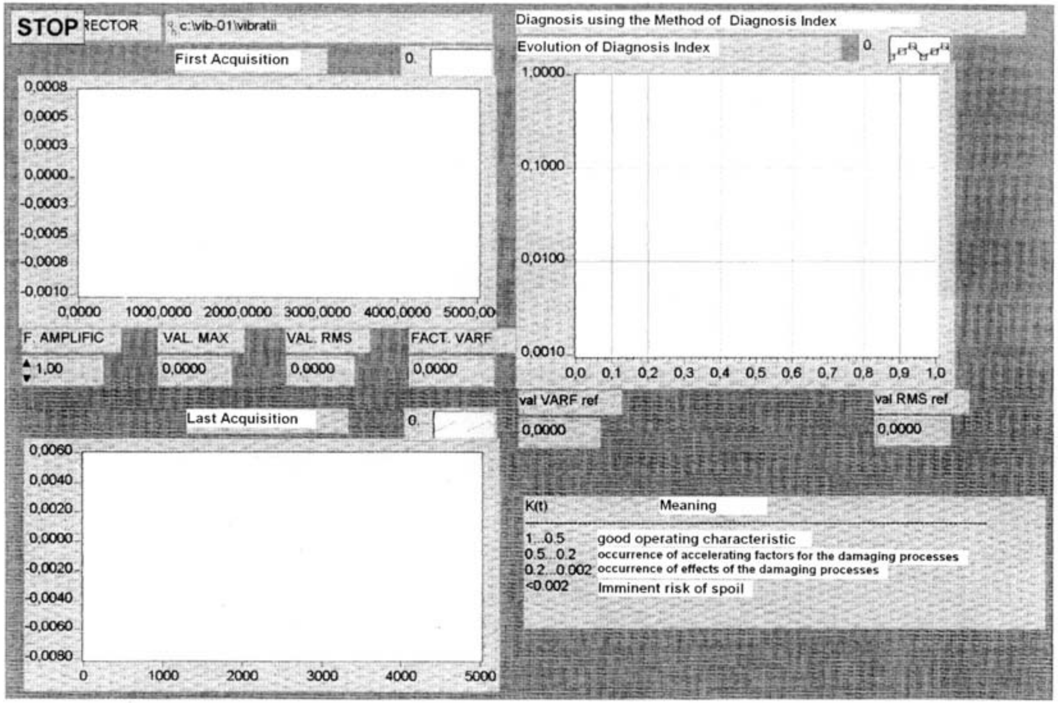


FIGURE 5.6 Front panel of INDIAG.VI instrument.

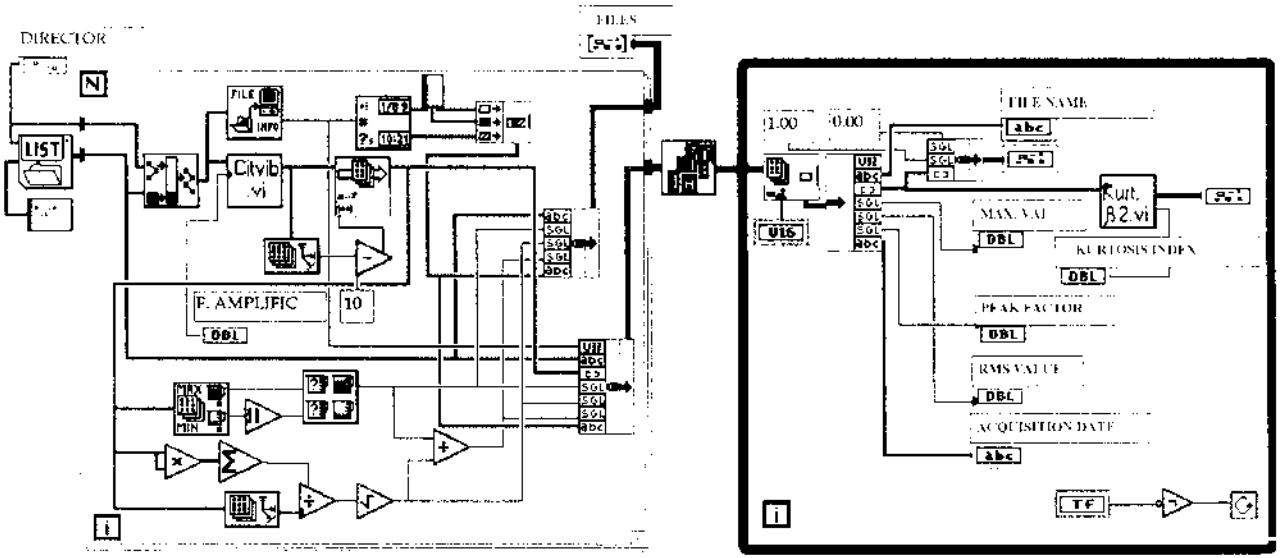


Figure 5.7 INDKURT.VI instrument—block diagram.

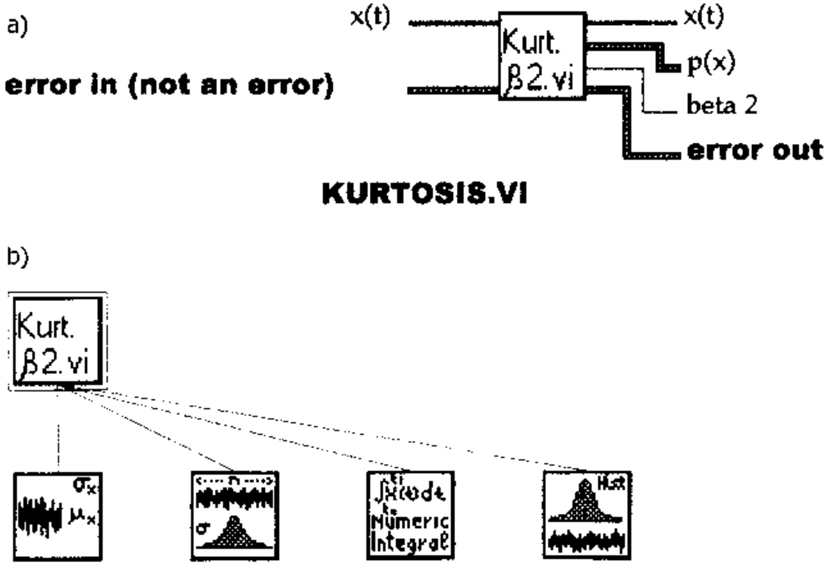


FIGURE 5.8 (a) Symbols and connectors of graphic block Kurt $\beta 2$; (b) virtual instruments from the LabVIEW library used to calculate the statistical moment.

Knowing the fact that a mechanism in good functioning state is the source of some stochastic vibrations that respect a normal (Gauss) distribution of amplitude (in this case the fourth-order statistic moment is placed in the range of value 3), an evident correlation can be made between the increase of the β_2 index value and the deviation of probability from the Gaussian shape, when a defect occurs and develops itself.

Taking into consideration the previous determinations, it has been noticed that the first instrument (which notes the abnormal state produced by the occurrence and development of a damage) is INDKURT; confirmation is done gradually by INDIAG and FACVARF.

5.4 VIRTUAL INSTRUMENTATION FOR PROFOUNDNESS DIAGNOSIS

A precision vibroacoustic diagnosis cannot be accomplished using only statistical parameters associated with signal processing in the time domain. The most rapid solution to avoid this deadlock is to pass the signal

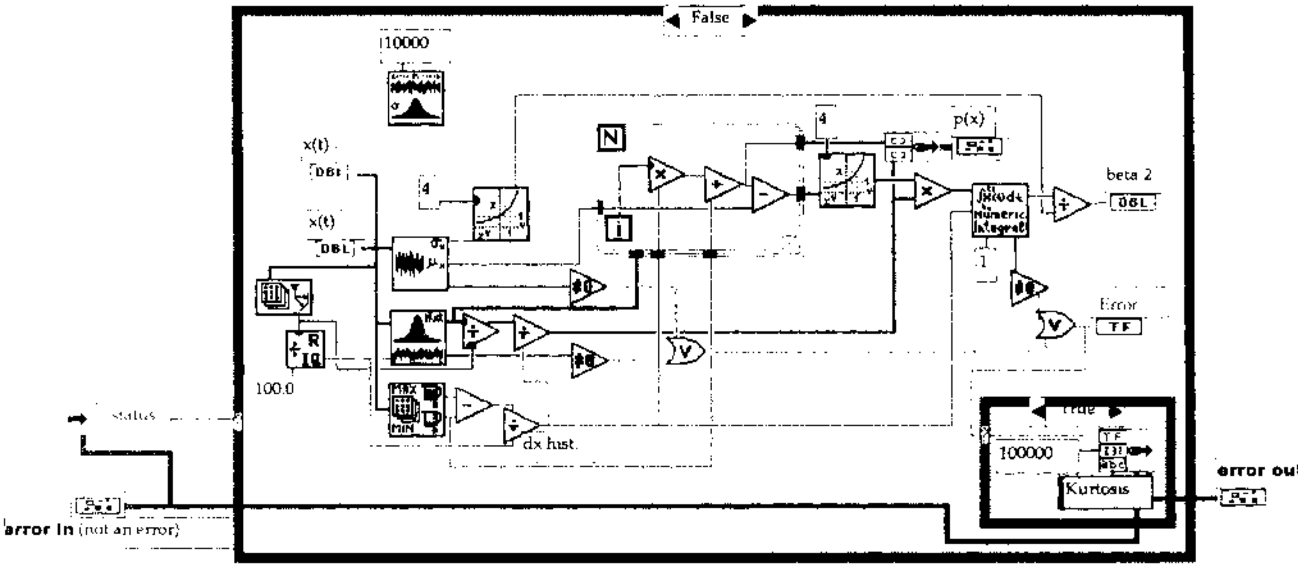


FIGURE 5.9 Block diagram of Kurt $\beta 2$ virtual instrument.

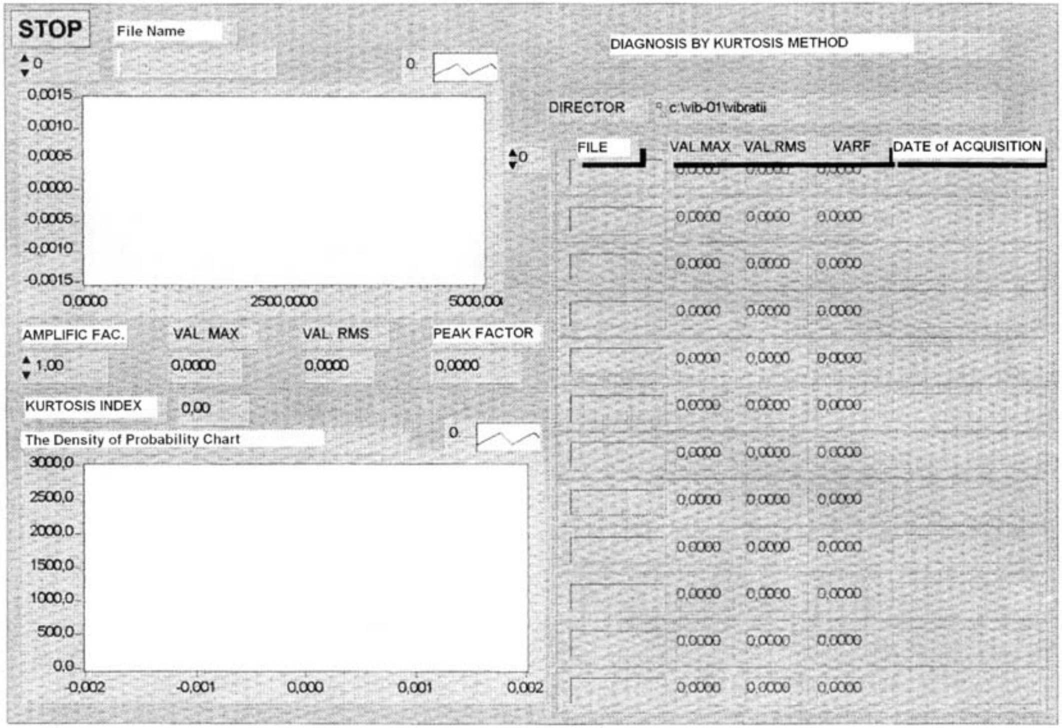


FIGURE 5.10 Front panel of INDIKURT.VI virtual instrument.

in a frequency range using a Fourier transform. Interpretation of the frequency spectrum produces, as seen in previous chapters, important data about the causes and the nature of the damage.

A first virtual instrument created for profoundness diagnosis, named MECOSPEC, has at its base the spectrum comparison method, and it has certain advantages:

The diagnostic method is included within the category of those which ensure from the beginning an increased precision of defect identification.

Identification of frequencies characteristic at defect is made automatically, excluding the subjective factor.

It is possible to estimate the reserve time interval until the machine comes to a stop because of a defect.

Acquisition intervals can be programmed with a fixed or variable step.

A diagnosis specific database can be created.

Although sophisticated, the method is simple to use.

Because of the complexity of virtual apparatus created to apply this method, the data processing has been organized on working blocks with the vibration signal.

The "acquisition and calculus of power" block, whose block diagram (partial) is presented in Figure 5.11, makes the link between the AT-MIO-16F acquisition plate and computer.

Captured signals using the Ach3p.VI virtual instrument are called and processed by another virtual instrument (Files.VI) especially created to manage the data files, whose front panel (Fig. 5.12) is made like a record of the measuring points. The virtual instrument associates a series of characteristics with each measuring point of the machine; those characteristics are useful for storing captured data such as point index, number of averages and averaging control, sensibility of acquisition transducer, and spectrum type (acceleration, speed, or displacement), as can be seen in the block diagram (Fig. 5.13). This supervising record must be completed by the user (operator). The signals are then passed through a Hanning window (Hann 2^17.VI) to avoid a cutting-up effect when the signal passes from the time domain to the frequency domain, and the power spectrum is obtained using the rapid Fourier transform (FFT).

The front panel of this first signal processing block (Fig. 5.14) contains a graphical representation in the time domain of the captured vi-

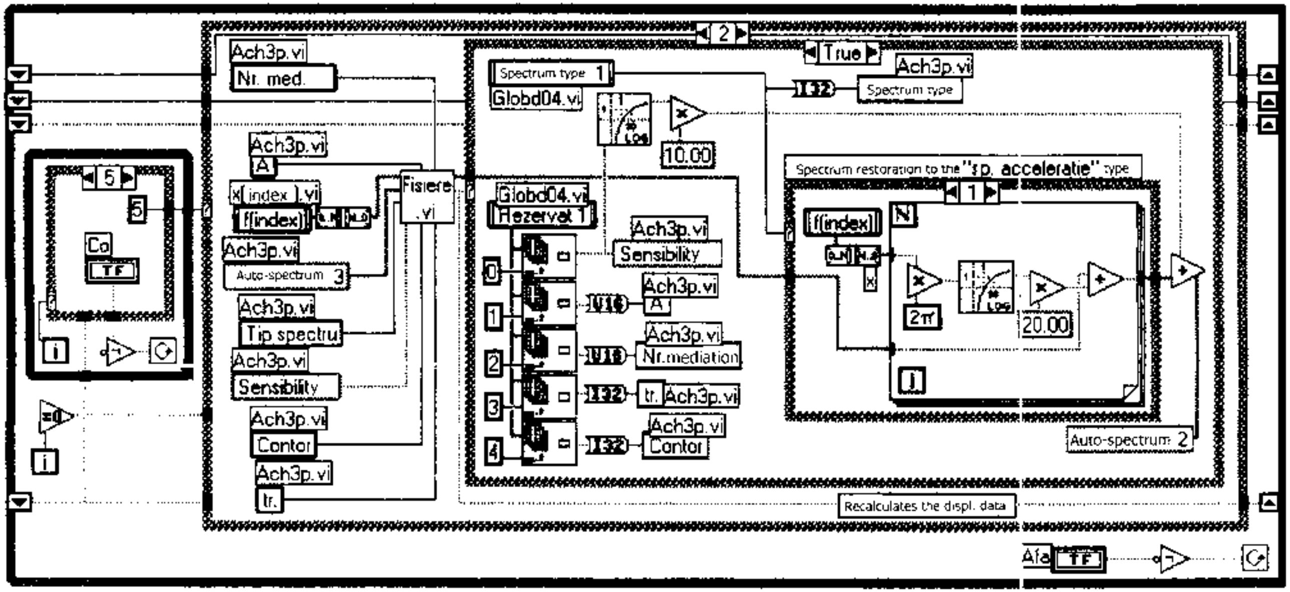


FIGURE 5.11 Partial block diagram of "Acquisition and calculus of power spectrum" block.

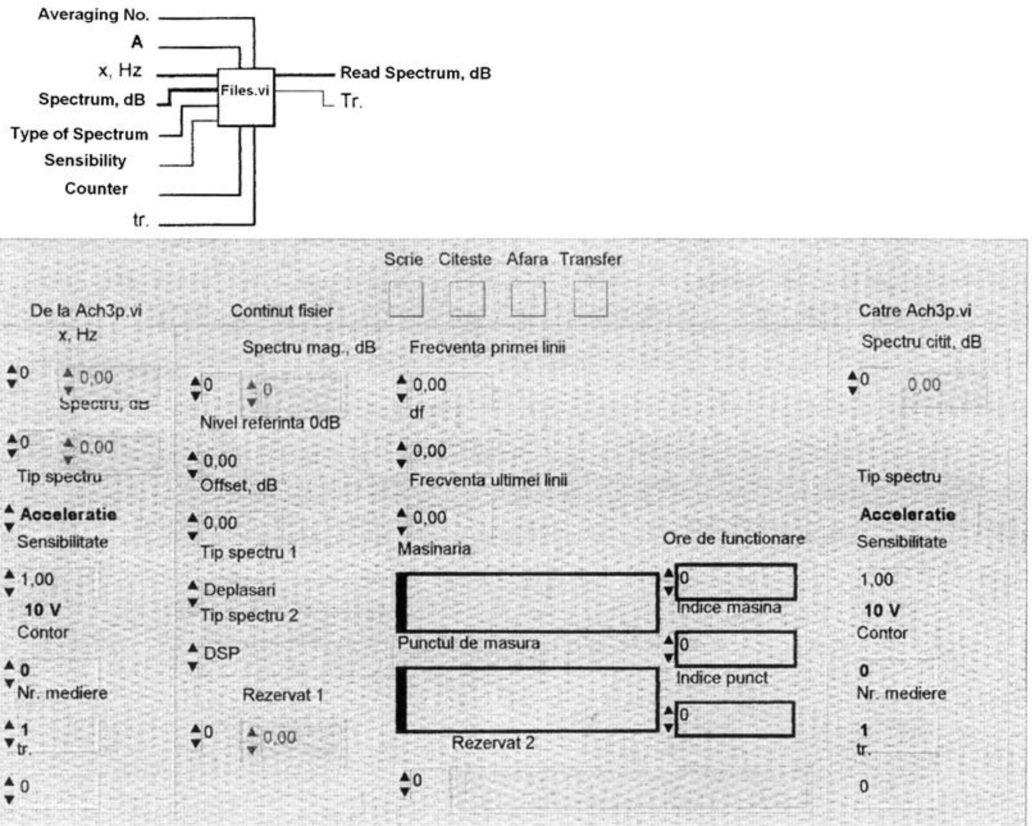
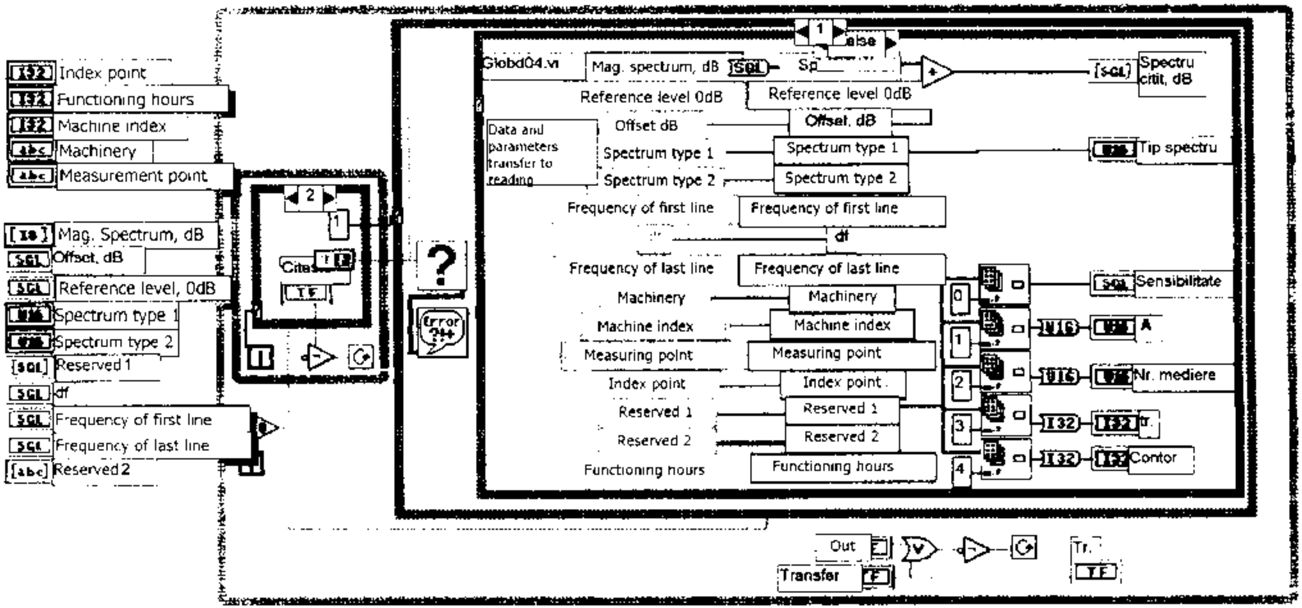


FIGURE 5.12 Front panel of Files.VI virtual instrument.


Index point
Functioning hours
Machine index
Machinery
Measurement point
Mag. Spectrum, dB
Offset, dB
Reference level, 0dB
Spectrum type 1
Spectrum type 2
Reserved 1
df
Frequency of first line
Frequency of last line
Reserved 2
Globd04.vi
Mag. spectrum, dB
Reference level 0dB
Offset dB
Spectrum type 1
Spectrum type 2
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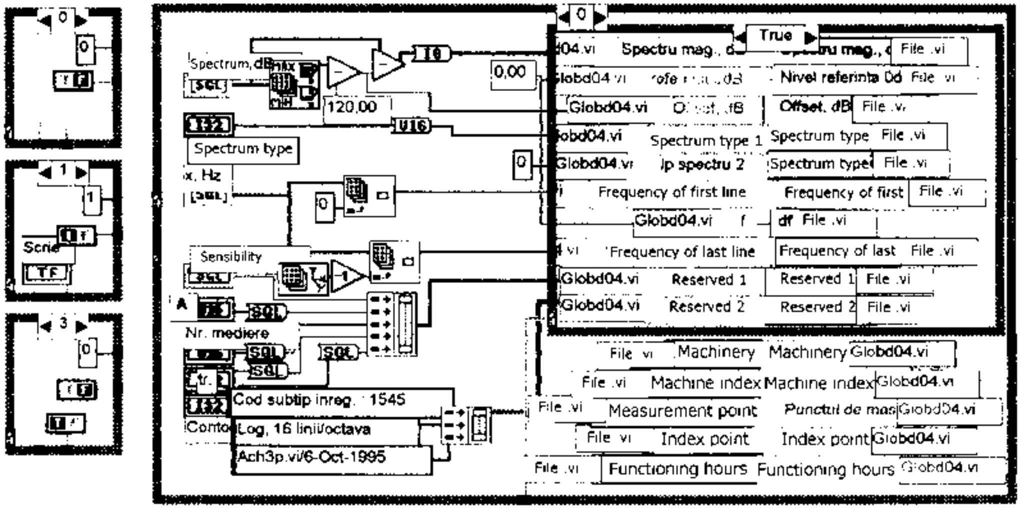

FIGURE 5.13 Block diagram of Files.VI virtual instrument.

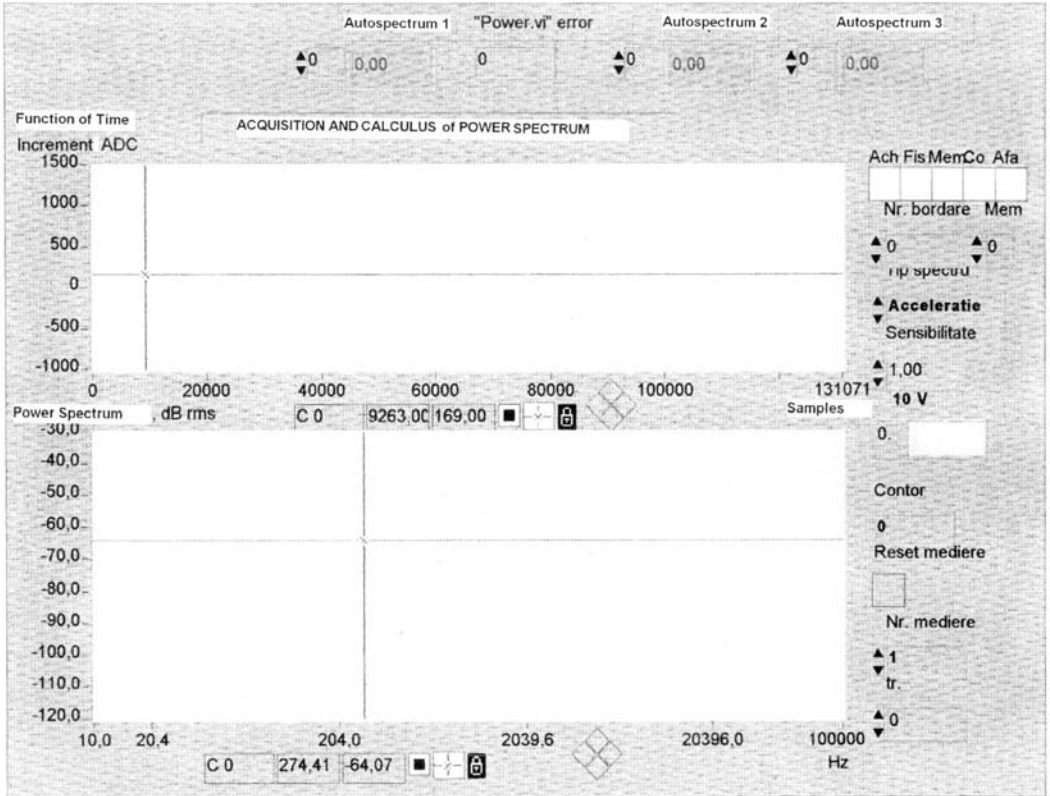

FIGURE 5.14 Front panel of first block for signal processing.

bration signal, and also contains the power spectrum graphic of the same signal, on an adjusting domain between 10 Hz and 100 kHz. In order to make possible the reading of values from the two graphics, CO pointers can be used to scavenge the graphics (using the four buttons disposed as a rhombus). The abscissa and the ordinate of the point indicated by the pointer are numerically displayed in the foot of graph. The right column groups the elements for adjusting the represented parameters influencing the block diagram.

The block "Comparison of power spectra" is presented as a block diagram in Figure 5.15. Comparison of spectra has as its starting point the assignment of the reference spectrum obtained with a machine in a perfect operating state; all of the spectra obtained from the signals captured previously are compared with this power spectrum. In order to avoid the false alarms caused by possible spectrum slipping (e.g., at small variations of working rpm), the reference spectrum is boarded in a virtual subinstrument (Bord 3p.VI), whose block diagram is presented in Figure 5.16. The boarding width can be manually adjusted from the block's front panel. Transformation of the reference spectrum, after boarding, in the warning and alarming patterns, respectively, is made by translating the reference spectrum to adjustable levels using the buttons of the front panel. The 2× levels are recommended for the warning pattern and the 10× for the alarm pattern.

The front panel (Fig. 5.17) "Comparison of power spectra" block contains two graphical representations as well: upwards, the currently captured spectrum superposed on the boarded reference spectrum; downwards, the difference derived as a result of comparison between the two spectra. Using the adjusting elements from the right column, the boarding width, warning level, and alarm level can be varied.

For the profoundness diagnosis, as presented in Chapter 3, a method with excellent results in identification of defects of mechanisms with rolling elements is the evolution method. A virtual apparatus that simulates the application of this method is presented in the following paragraphs.

Figure 5.18 presents a FOR buckle as a block diagram where two sinusoidal signals are composed and modulated. After the modulation an exponential damping is applied to the resulting signal. A pulse signal is obtained whose amplitude and frequency are adjustable from the front panel's buttons (Fig. 5.19) and which simulates the excitation signal introduced by the occurrence of a defect (running of ball or roller over irregularities/pinches occurring on one of the running tracks). The

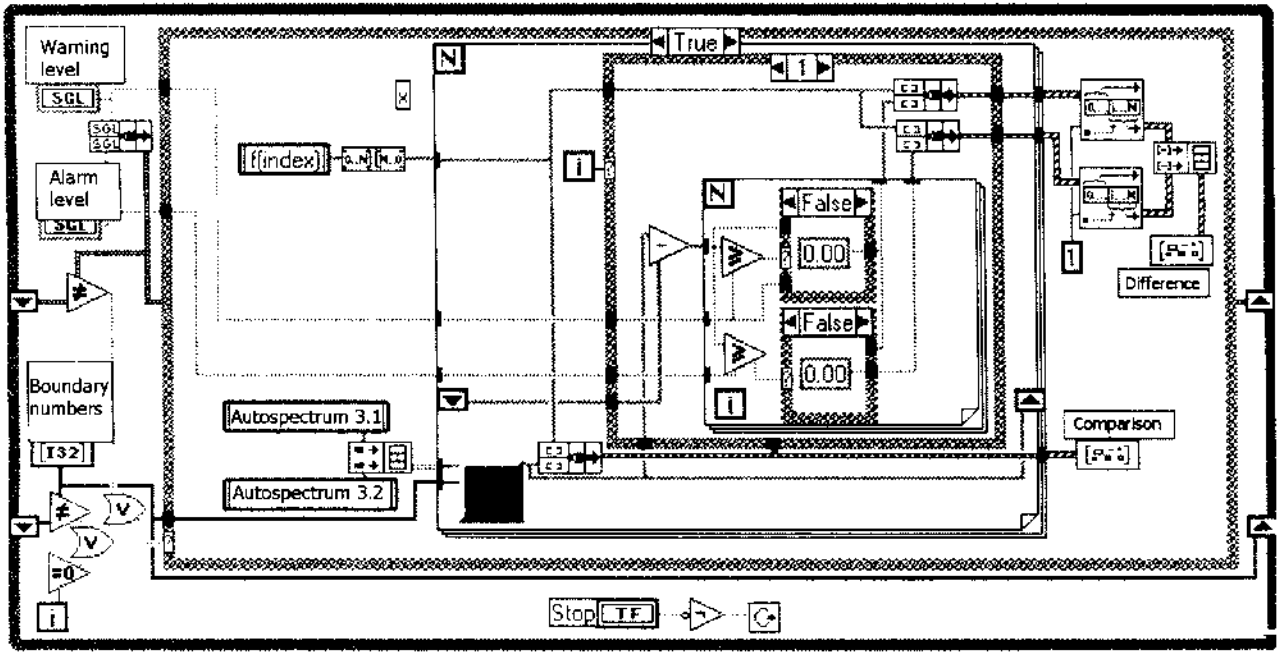

FIGURE 5.15 Block diagram of "Comparison power spectra" block.

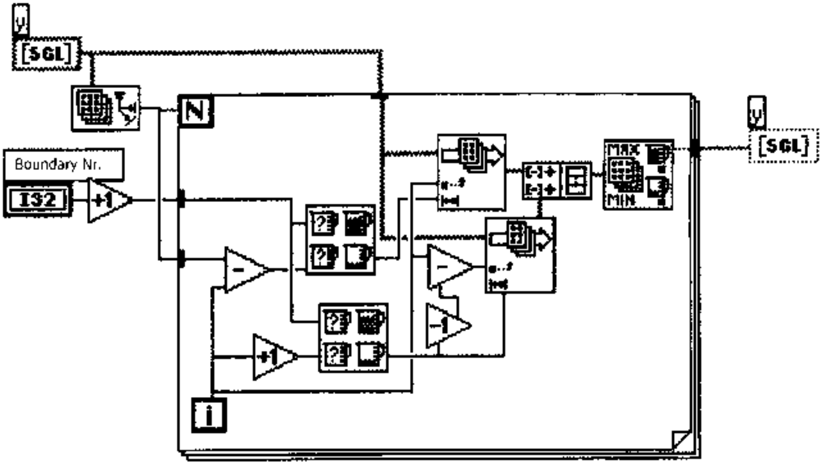

FIGURE 5.16 Block diagram of Bord.3p.VI virtual instrument.

impulses are identical and evenly distanced at period T. The spectrum of this series of impacts would be a spectral line that includes all of the harmonics of the repetition frequency $1/T$. These harmonics have the largest amplitudes in the vicinity of the resonance frequency and their diagnosing by simple evaluation of spectra is difficult.

In the next step, the critical zone, which contains the structural resonance that has been excited by the impact due to defect, is extracted from the frequency spectrum by zoom-in. Applying the Hilbert transform, evolution of the signal in the time domain is generated by the calculation of the time function amplitude. This evolution can be passed and analyzed in the frequency domain to establish the frequency or frequencies of impact. On this basis the type of defect and the place of occurrence can be identified, as well as its dimensions.

The instrument's front panel offers the representation of the simulated pulse signal (upward graphic) and the corresponding evolution from the time domain (downward graphic). The processing of this last signal in the frequency domain is similar to what was done in the "Acquisition and calculus of power spectrum" of the MECOSPEC apparatus, and it has not been included in the simulation.

Results from the work presented so far show that the evolution method has large perspectives in identification and separation of the existent modular sources in a machine tool; it allows a precise diagnosis of

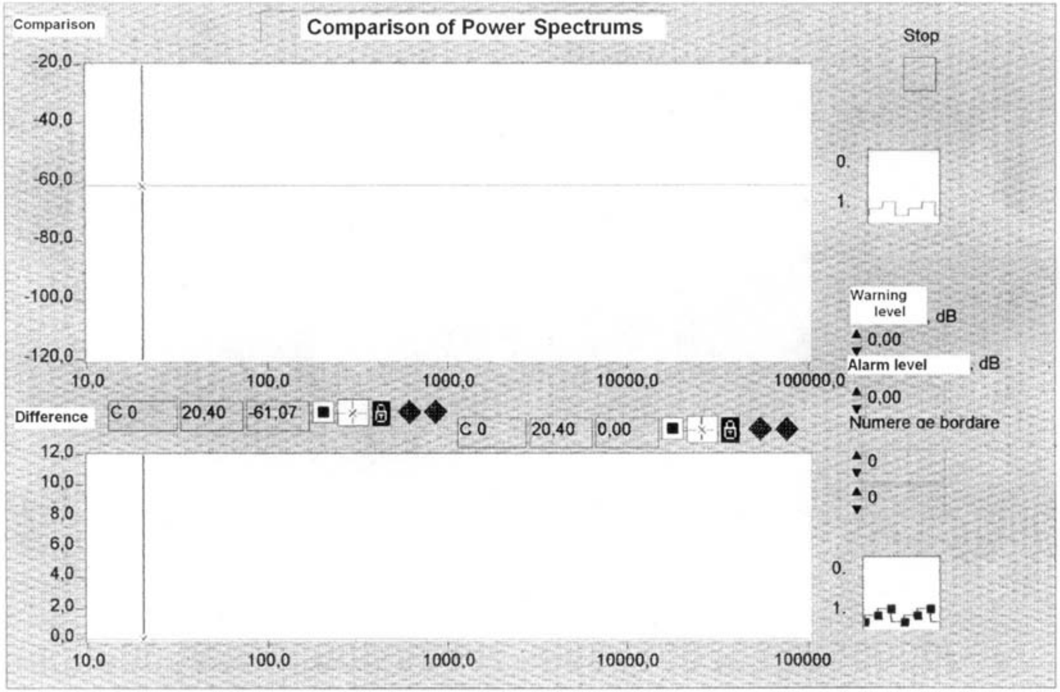

FIGURE 5.17 Front panel of "Comparison power spectra" block.

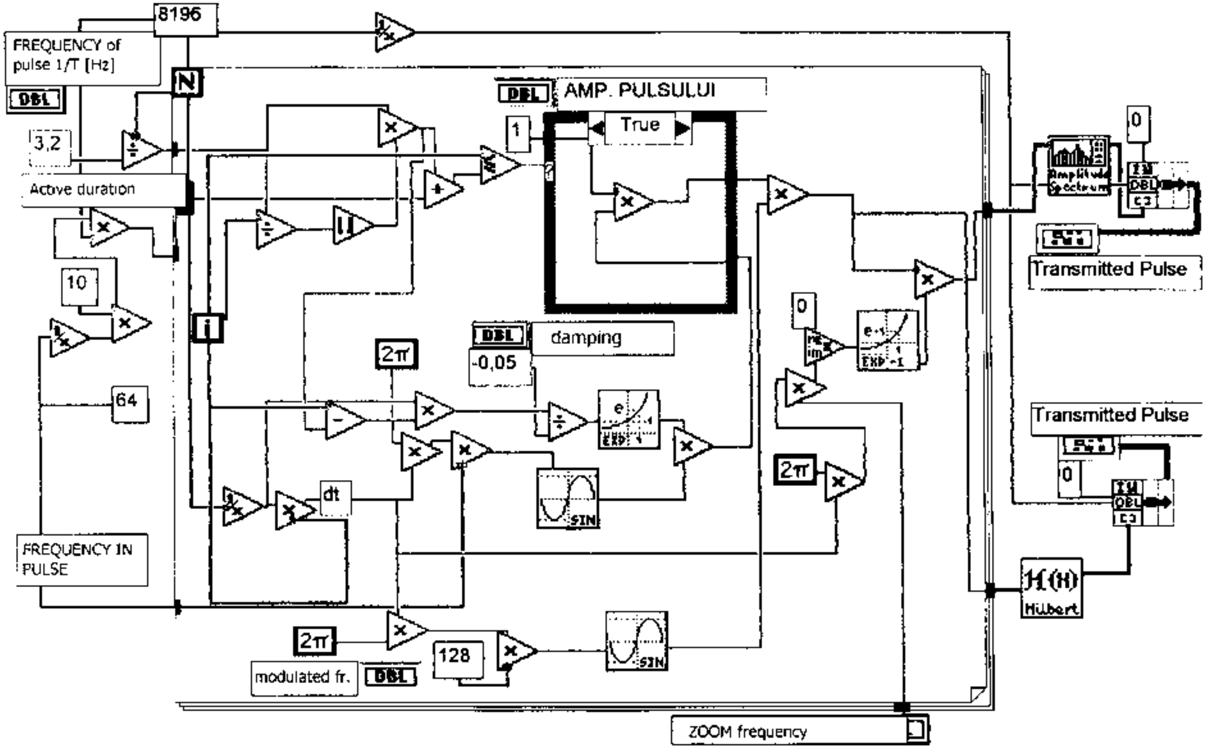

Figure 5.18 Block diagram of METINFA virtual apparatus.

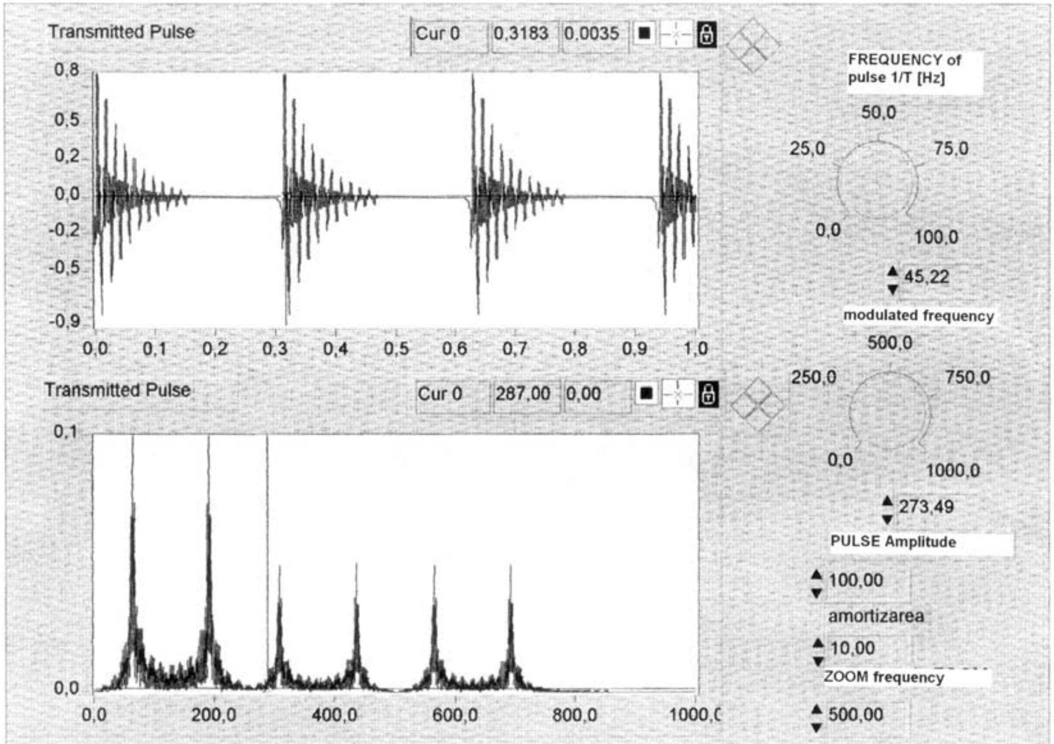

FIGURE 5.19 Front panel of METINFA virtual apparatus.

defects in bearings, rolling guides, and gears, even though many defects are simultaneously present.

These virtual instruments have been tested in the laboratory and then compared with traditional measurement schemes, built with traditional instrumentation. For example, the virtual instrument for the acquisition and calculus of the power spectrum has been mounted in parallel with the real-time frequency analyzer Brüel & Kjær 2034, belonging to the Eurotest laboratory, in order to process the same vibration signal. A perfect similitude has been noticed between the displayed power spectra, with a better resolution of the virtual instrument for lower frequencies. All of the virtual instruments described have been found to be adequate from the functional and operating accuracy point of view.