Product Information

Dynamic Sound Testing of Earth-moving Machinery to ISO 6393, 6394, 6395, 6396

by Patrick Glibert, Brüel & Kjær Sound & Vibration Measurement A/S, Denmark
and Mark B. Sutherland, Caterpillar Inc., USA

The Dynamic Sound Test System performs dynamic and static sound testing on earth-moving machinery according to ISO standards. The major components of the system are the AudiBel software and the PULSE™ Multi-Analyzer platform.

Due to an advanced system design, only one person, the machine operator, is required to perform a complete test.

Introduction

Late in 1980's the European Union (EU) laid down new regulations for noise emitted by construction equipment under stationary test conditions. These regulations required machines to meet EU specified exterior sound power levels, measured according to ISO 6393, and manufacturer-specified operator compartment sound pressure levels, measured according to ISO 6394. In addition, manufacturers were required to affix labels to each machine that specified these manufacturer-guaranteed sound levels.

In January 1997, two additional EU regulations became effective. The most significant aspect of the new regulations is the change in machine operation from stationary or static, to dynamic operation, in which exterior sound power and operator sound pressure are measured as documented in ISO 6395 and ISO 6396, respectively.

The test procedures specify one to four different machine cycles, dependent on the construction equipment type.

The basic machine categories and related cycles are:

- ❍ Excavators – simulated trenching
- ❍ Bulldozers – forward and reverse drive-by
- ❍ Loaders – hydraulic loader lift, forward and reverse drive-by
- ❍ Backhoe Loaders – as required for excavators and loaders

These new EU regulations impact manufacturers of earth-moving machinery in several ways.

In order to get approval to sell machines in EU countries, manufacturers must submit a representative machine of each model type for testing by an approved laboratory.

After successfully completing tests, the manufacturing facility receives a "Certificate of Conformance" and must affix labels specifying Exterior & Operator Levels on each machine sold. These labels are further defined to mean "manufacturer guaranteed levels" – in other words, every machine is guaranteed to meet its label value.

For example, a given machine has an dynamic exterior requirement of 112 dB(A). The EU approved lab measures 112 dB(A) exterior and 80 dB(A) operator. The manufacturer is approved for sale and can affix labels specifying 112 and 80, respectively. The lab is further chartered to conduct random field checks and/or review manufacturers' internal test data to ensure continued compliance with the regulation.

If the machine submitted to the testing laboratory is assumed to represent the "mean value" specimen, there is no guarantee, from a statistical point of view, that more than 50% of the production run machines will meet the "guaranteed label value". Thus, manufacturers can avoid shipping machines which do not meet the label value by implementing a measurement system per ISO at the end of the production line. At the same time, the noise data provided by this system may be used to provide statistical process feedback and keep a general eye on production quality.

As an example, it can be mentioned that Caterpillar has had a production test program for over 10 years and continues to identify and account for production variability when labelling products, such that every product sold will conform.

The EU has recognized that production variability is a key issue and will be implementing ISO 4871 to address this. Essentially, this document specifies factors of 4 – 6 dB that must be added to single machine measurements. Manufacturers that can produce data which documents actual variability factors could use those numbers. As can be seen, unless a manufacturer is conducting on-going tests, he would essentially have to develop his machine 4 – 6 dB lower or raise the label value by this amount – the latter may not even be an option if he is at or close to the EU Limit.

Why an Automated Dynamic Sound Testing System?

In order to identify production variability of each and every model, a statistically significant sample is required. Most statisticians will recommend samples of 20 – 30 to establish basic summary statistics. One may take, say, six samples per model as an initial guide with the aim of carrying out later additional tests. If there are 20 – 30 different models requiring certification, this becomes a large test program.

As an example, Caterpillar facilities typically average 300 – 400 sound tests per year with high volume plants testing more than 800 per year. It should also be noted that the test frequency is a function of margin or cushion from the limits. If the requirement is 112 and the mean of the population is 112, 100% testing is required to ensure compliance. If the mean is 109, a 20% sampling might be appropriate.

Based on current techniques, whether it be 3 – 6 sound level meters or a multichannel analyzer or recording device, a manufacturer would incur hundreds of thousands of dollars in costs trying to measure the number of machines necessary. Even if the money was invested, the amount of time required would be prohibitive to a production manufacturing environment.

Thus the need for an automated system, requiring small resources to run the system on a daily basis, is indicated. For this reason, the PULSE/AudiBel system was conceived.

The benefits and advantages which the system provide are numerous.

Cost

Fig. 1 Comparative costs of a manual, sound level meter based system and the automated system

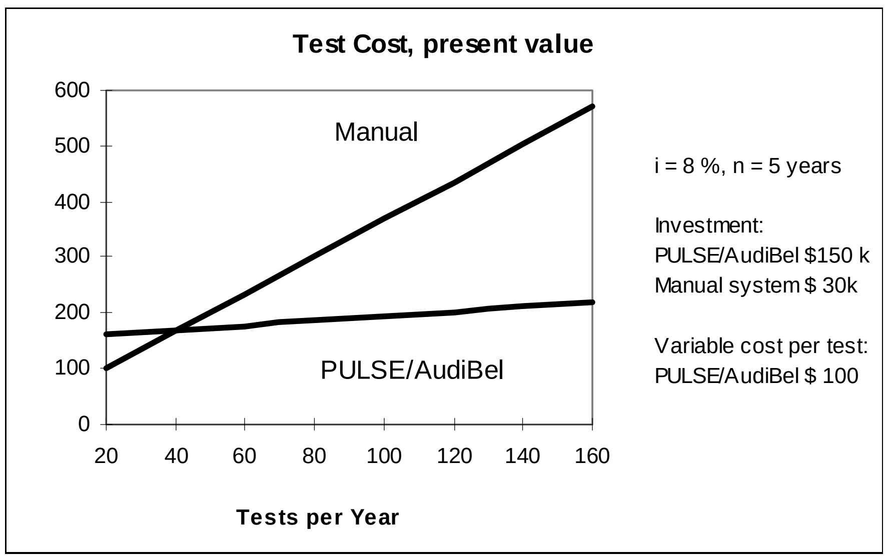


Fig. 1 illustrates the relative costs of a manual, sound level meter based system versus the automated system*. Due to its much shorter test cycle, compared to a manual test, and the need for only one person in total, the crossover point between the two system types is at 40 machines tested per year.

Design and process feedback

The key is not to incur costs just because of regulations, but to create true value. In addition to the customer getting quieter machines, the entire process benefits from the production test data. Design and process personnel are made keenly aware of a model's "process capability" and when inadequate, steps may be taken to rectify this. The manufacturer can avoid shipping machines with uncertain noise data.

In addition to design and process personnel, the entire corporate structure is made more aware of noise as a key parameter and how they compare competitors.

*) Data courtesy of Caterpillar

Technology

One of the most important features of PULSE/AudiBel is that it takes technology that has been limited to high-tech users and puts it into the hands of non-technical personnel.

Manufacturing

Another benefit is in the manufacturing areas. Although very adept at validation through end-of-line tests such as emissions, leaks, pressures, etc., noise is still a black art outside of a small group of acoustic engineers. Providing a robust tool that is easy to understand and operate, is important to these users. Because it is user-friendly, tests are painlessly conducted and, over a period of time, manufacturing personnel have raised their level of expertise dealing with noise parameters.

Customers

The system puts manufacturers in a much better position to provide meaningful data to customers. Data is often required just to bid on a construction job. In other cases (i.e., Germany), machines must meet levels which are more stringent than EU laws in order to bid on government jobs.

Research and development

Although technical engineering personnel are what we would refer to as high-end users, there is still a role for PULSE/AudiBel to play in these applications. Development areas must typically run all kinds of baseline tests and iteration after iteration, typically changing one or more machine components. With PULSE/AudiBel, these tests can be run by technicians or hourly employees, freeing up the engineers' time for higher tech. activities. Similar to the production application, test times and costs are reduced due to the level of automation present.

Based on measurement instrumentation from Brüel & Kjær, Caterpillar Inc., USA developed a measurement system for automation of measurements. The complete system, known as the Dynamic Sound Test System, is now in use at several of Caterpillar's Production and R & D Facilities worldwide.

Other manufacturers of earth-moving machinery are invited to benefit from experience already achieved, so measurements required for machine labelling can be carried out quickly and easily.

Features of the Dynamic Sound Test System will be described in the following sections.

System Overview

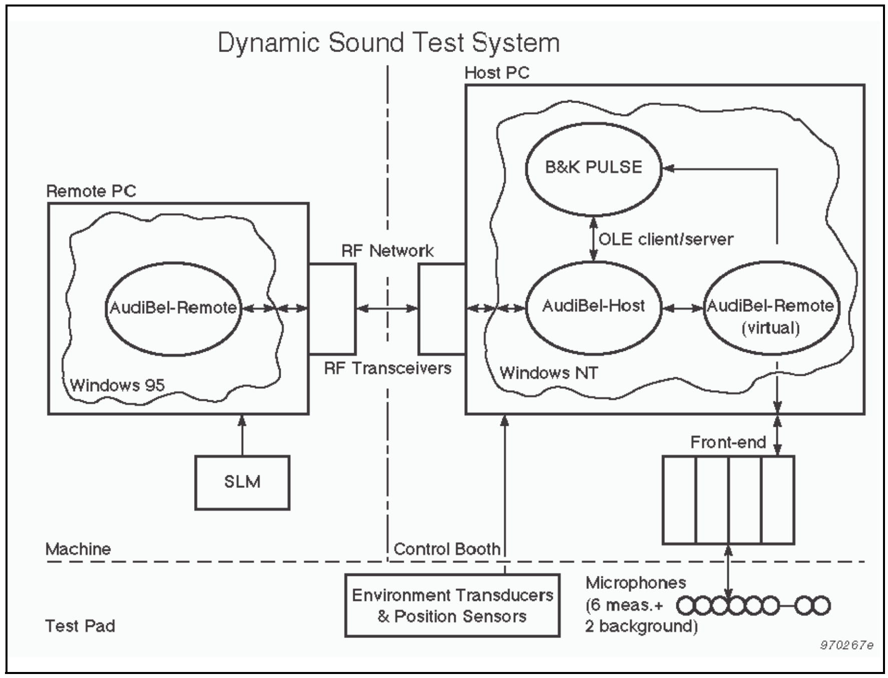
The Dynamic Sound Test System automates the testing of earth-moving machinery noise to four ISO test standards. The system simultaneously measures exterior noise levels and the interior (operator) noise level. Noise data is available in terms of sound pressure, third-octave levels (CPB[†]) and the overall sound power level for each test cycle.

†) Constant Percentage Bandwidth

The system supports six unique test cycles: four dynamic, one static and a user-defined cycle. The static cycle mode performs testing according to ISO 6393 and ISO 6394. A combination of the four dynamic cycles performs testing to ISO 6395 and ISO 6396.

Although AudiBel automates many tasks associated with sound testing, its key feature is the ability to conduct these tests with one, non-technical person. Even complex dynamic cycles, which have typically required 2 – 4 support personnel, can now be conducted by the test machine operator, who controls the machine as well as the entire measurement task.

Fig. 2 The Dynamic Sound Test System

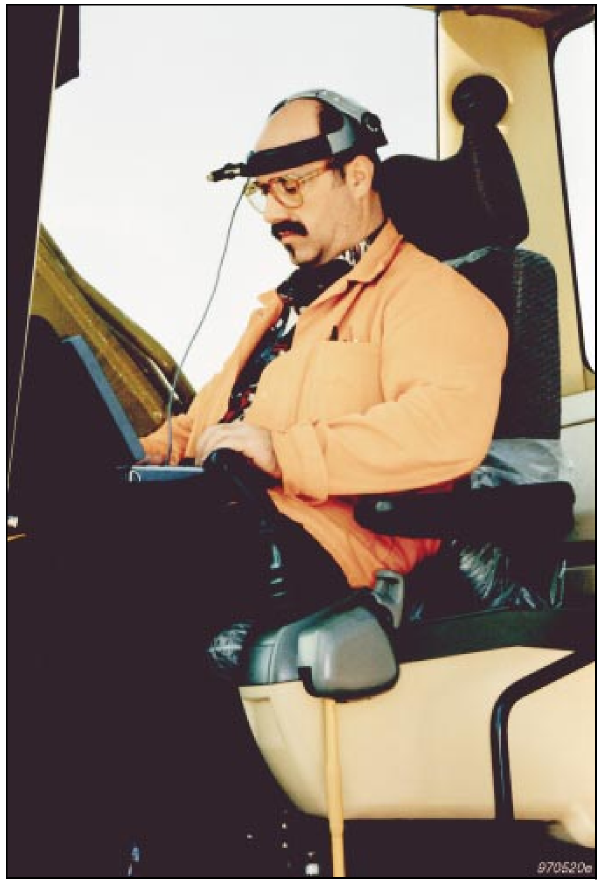


The Dynamic Sound Test System comprises several major components (see Fig. 2), some of which are typically located in a control booth adjacent to the test pad. These are: A host PC with Audibel-Host and AudiBel-Remote (virtual) software, a Brüel & Kjær PULSE™ Multi-analyzer System Type 3560 and environmental parameter sub-systems.

The earth-moving machine is located on the test pad as per ISO specifications. On board the machine, the operator has a remote Notepad PC with Audibel-Remote software. Additionally, a sound level meter connects to the remote PC via a serial port.

A radio frequency network links the remote PC and the host PC together in a wireless local area network (WLAN). The WLAN hardware works in the industrial, scientific and medical band (ISM band, 2.4 to 2.4835 GHz), which is made available worldwide for unlicensed use.

There are photocell sensors on the test pad for triggering Start/Stop of measurements, measuring microphones for machine noise data acquisition, as well as separate microphones for background noise assessment. A weather station placed close to the test pad captures and communicates wind speed, wind direction and ambient temperature to the host PC.



From the operator's point of view, primary control of the system is accomplished through the remote PC with its Audibel-Remote software, attached to the host PC via the WLAN network. The test system can also be controlled at the host PC through the AudiBel-Remote (virtual) software, a separate program that emulates the exact functions of the real remote. Certain functions, such as system administration and database management operation, are accomplished only on the host PC, and only by an authorized administrator.

A Typical Test Session

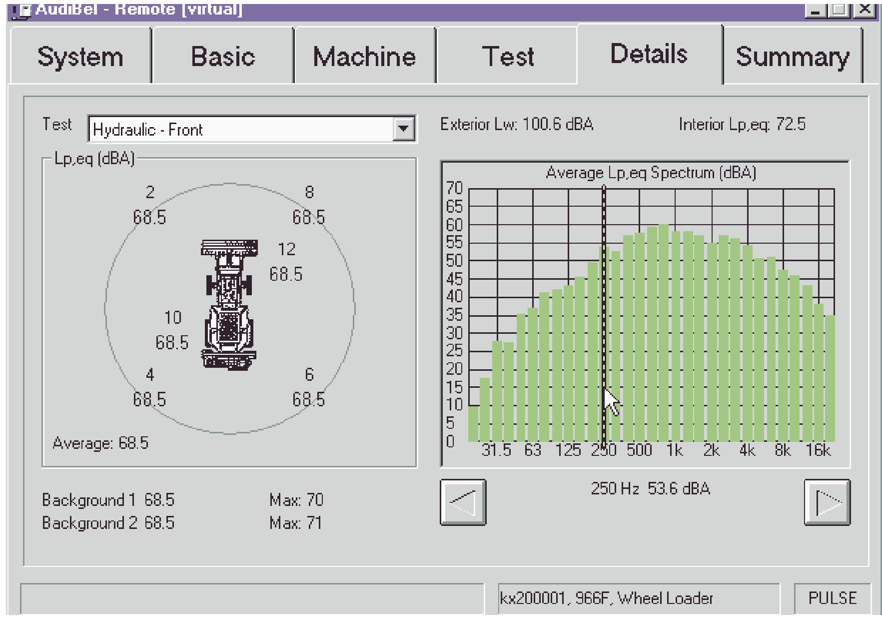
After logging onto the Dynamic Sound Test System (via Audibel-Remote software), the operator simply selects the machine model to be tested. Pre-defined, machine description data is subsequently retrieved and, after entering any machine specific information required, the system is ready to perform the desired test measurements.

Depending on the machine model, only relevant test cycles are enabled while other non-applicable parts are disabled. For example, a wheel loader would have Static, Dynamic Forward, Dynamic Reverse, and Dynamic Front Hydraulic enabled. Since the machine has no rear hydraulic, the sub test "Dynamic Rear Hydraulic" is disabled.

At the completion of each sub-test, the results can be reviewed by the operator, i.e., individual microphone levels, sound power level, operator ear level, and background levels (see Fig. 3). The average spectrum is also plotted. It is possible to inspect test details of all applicable sub-tests, pending or accepted. After all dynamic sub-tests are completed, the operator can review the overall dynamic sound power level, and is informed of whether measurements passed or failed requirements.

Measurement data is stored on the host PC, and a report is generated automatically.

Fig. 3 Details Tab of the Remote PC



The AudiBel Software

Host Operation

The host computer ultimately manages all operations. Through OLE automation, the AudiBel-Host program communicates with the PULSE multi-analyzer and the AudiBel-Remote program to perform all test functions. In addition, the AudiBel-Host program has several unique administrative functions like User Administration, Machine Database Management, Ambient Levels, CIC[#] verifications and Report Generation.

Fig. 4 shows a screen dump from the Host PC with the “Pad 1” Tab of the Settings window (selectable in the Options menu) opened on top of the Edit Machine Database form.

Adding or editing a User Profile is done in User Administration.

With Machine Database Management, machine models to be tested are pre-defined and stored. Each machine record contains relevant machine information, test conditions, suppression part numbers and associated test specifications.

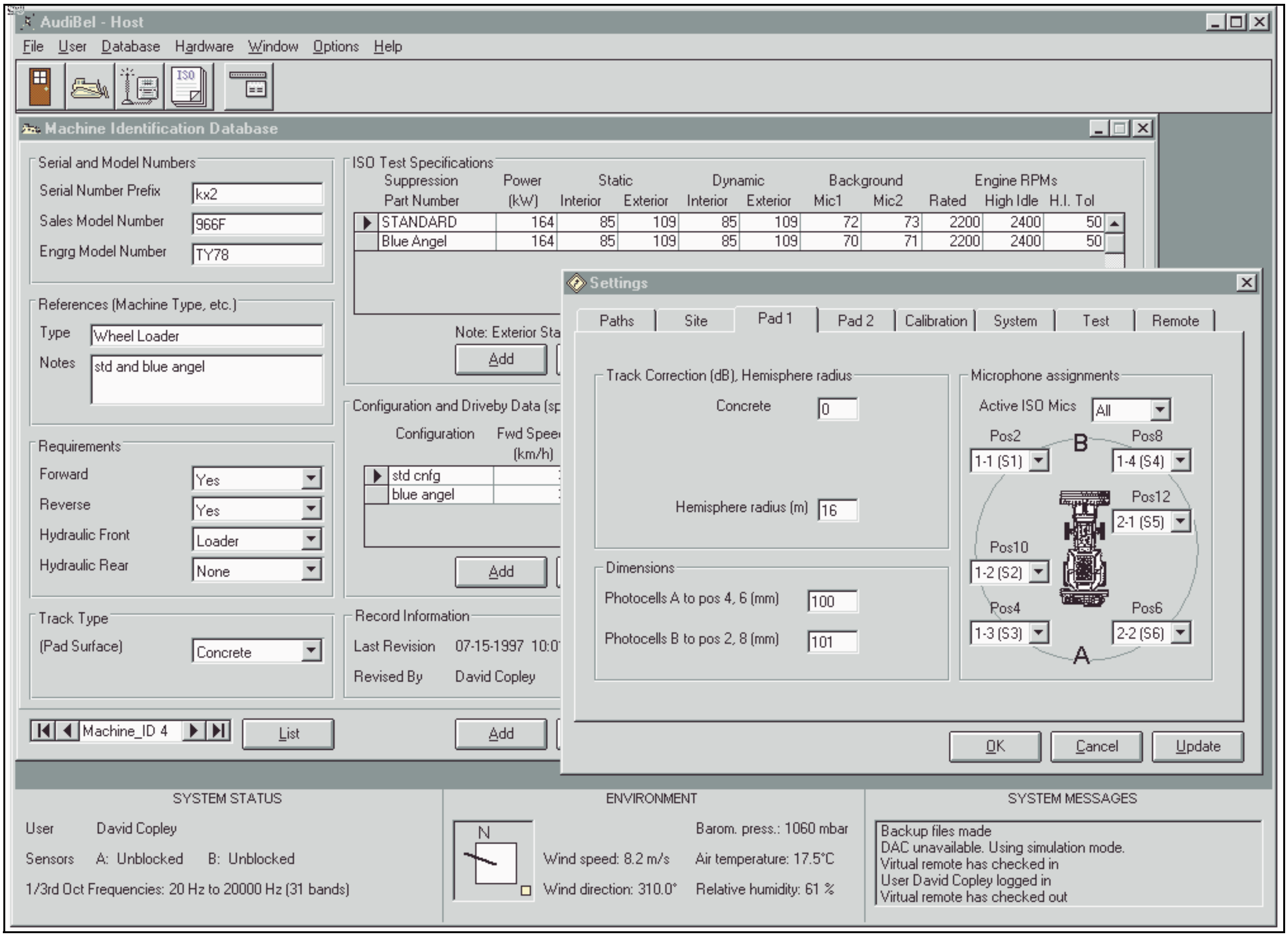
The ambient levels are the levels obtained at each microphone position outside the machine measurement cycle. These levels are reported along with the ISO test results.

The CIC facility is used for remotely monitoring the microphone system for possible faults or damage by checking of the entire microphone signal path.

The Report window allows you to retrieve, view, print, export and save reports. A report contains information pertaining to tests, including machine identification, test conditions, test results and sub-test data.

#) Charge Injection Calibration

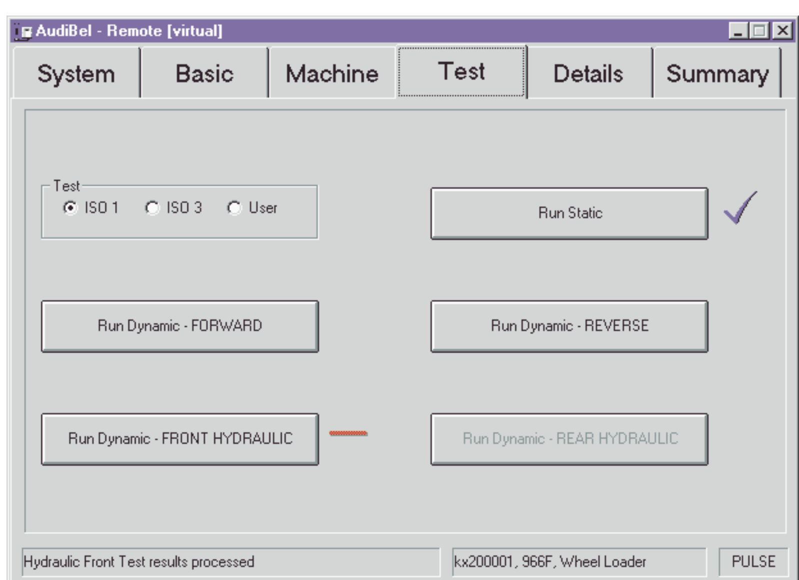
Fig. 4 Audibel-Host Program Screen



Remote Operation

Measurement sessions are controlled by means of the Audibel-Remote software, installed on the Remote PC. This program lets the machine operator run complete tests while in the cabin of the machine. It contains the following Panel Tabs (see Fig. 5): System, Basic, Machine, Test, Details and Summary.

Fig. 5 Test Tab of Audibel-Remote program



The System Panel is used for, e.g., activating PULSE, setting up the sound level meter, and for checking background levels and environmental parameters. Identifying and selecting the machine is done in Machine Panel.

The following tests can be run using the Test Panel:

ISO 1:
There are five possible sub-tests: Static, Forward, Reverse, Front Hydraulic and Rear Hydraulic (see Fig. 5). Depending on the machine and its database information, one or more of the sub-tests will be disabled. For example, a Wheel Loader would not have the Rear Hydraulic cycle. Status markers (a dash or a check mark – see Fig. 5) indicate whether the result of a sub-test is pending or accepted. ISO 1 will run through each selected sub-test once. It is typically used for day-to-day testing of production machines and for development type testing.

ISO 3:
This is similar to ISO 1, except that three test cycles are run per sub-test, as required by standards. Each set of three cycles is examined according to ISO specifications and the arithmetic average of the two highest levels is used as the result (see ISO 6393 and ISO 6395). ISO 3 is typically used for formal certification/homologation tests.

The Details Panel displays sub-test results and related spectra. Results of pending or completed sub-tests can be reviewed at any time (see Fig. 3.

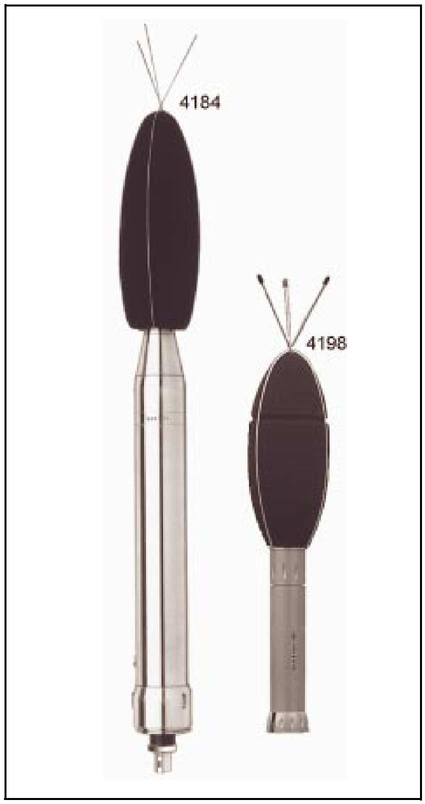
The Summary Panel specifically displays results of completed ISO tests and identifies whether measured values are within limits set for the machine being tested.

System Instrumentation

The Brüel & Kjær PULSE™ Multi-analyzer Type 3560 platform is the central part of the Dynamic Sound Test System. It consists of an 8-channel microphone front-end with generator** and Pulse LabShop Type 7700 Basic Noise and Vibration software used to perform the CPB (L_{eq}) and Overall (LA_{eq}) measurements. Additional PC cards have been added to the PULSE PC (used as host) allowing radio-frequency networking, and measurement of temperature, wind speed, wind direction and machine position. The AudiBel program (developed by Caterpillar Inc.) also resides on the host PC, together with its associated databases for storage of machine and measurement data. As has been described, the AudiBel program controls the entire measurement system, and makes operations easily accessible to non-technical personnel.

**) Used for CIC monitoring

Fig. 6



Eight Brüel & Kjær Weatherproof Microphone Units Type 4184 (see Fig. 6) are recommended for noise measurements on the test pad. Six of them are positioned on a hemispherical measurement surface to measure the sound pressure level of the machine under test. Two are used to measure the background noise. Type 4184 has excellent omnidirectional characteristics and an internal probe tube system makes measurements almost independent of the angle of incidence of sound. Brüel & Kjær has several years of experience with Type 4184, which has proven itself extremely stable in numerous permanent installations.

Alternatively the Brüel & Kjær Outdoor Microphone Unit Type 4198 may be used. It is a less expensive unit designed for semi-permanent outdoor installations. Type 4198 is relatively new, so long-time durability experience has not been gathered yet. This unit is expected to be stable too, but requires more frequent inspection than Type 4184, pending environmental conditions. Use of Type 4198 in the measurement system will require fixed (geometrically determined) corrections to the measured spectra (handled by the AudiBel software). In short, the Type 4184 microphone solution is the install-and-forget-it type solution for high-volume testing, whereas Type 4198 is for the more experienced measurement system user who is able to anticipate and correct potential microphone weaknesses.

Interior cabin noise is measured using the Brüel & Kjær Type 2236 Sound Level Meter. In order to make this measurement automatically, the sound level meter is connected to the remote PC via RS–232. The operator's test cycle commands and the measured cabin noise data are transferred via a radio-frequency network link to the Host PC.

Acoustical Calibration

In order to perform valid sound pressure measurements, an acoustical calibration of the measurement system is needed. Each microphone with preamplifier and cable connecting with the PULSE analyzer front-end needs to be calibrated. Sound Level Calibrator Type 4231 or Pistonphone Type 4228 may be used for this purpose.

The PULSE automatic calibration sequence, called Calibration Master, automates the calibration procedure. A signal detector searches all microphone channels for a valid calibration signal when the Calibration Master is activated. When found, the accurate calibration signal level is measured, and a gain adjustment is set and saved in the measurement project for the particular channel. A light bar (red, amber, green traffic light style) is available. It provides a visible indication of calibration status to the person applying the calibrator to the microphones.

Automatic calibration sequencing thus makes it possible for only one person to perform an accurate calibration covering all the eight site microphones in any order. AudiBel accesses and echoes these PULSE calibration functions such that direct PULSE operator interface is not required.

System Check using CIC

The acoustical calibration procedure must be done on a regular basis to be sure that measurements made with the system are valid.

An interval of several weeks (even months) between acoustical calibrations can be obtained when using CIC monitoring. The patented Charge Injection Calibration technique is a method of remotely verifying the condition of the entire measurement set-up, including the microphone. The CIC method is very sensitive to any change in the microphone's capacitance, which is a reliable indicator of the microphone's condition. In addition, the CIC method will also reveal other sources of errors in the microphone signal chain, such as defective cables and other hardware factors affecting the signal path gain.

The CIC monitoring procedure is as follows:

Immediately after an acoustical calibration, the ratio between the preamplifier output signal and the CIC generator signal for each channel is measured. The ratios are stored as references for future CIC measurements.

Verification of the system can now be performed whenever required (e.g., before starting a new measurement session) by comparing the current measured ratios with the stored reference ratios. For normal temperature and pressure, variations should be less than 0.2 dB.

As CIC measurements are carried out much faster than an acoustical calibration, an important saving in time and expense is achieved as the number of acoustical calibrations during the year can be significantly reduced.

Verification of the calibration state using the CIC technique is handled through the AudiBel software, so there is no need for a trained PULSE operator.

Conclusion

The design goal was to provide a system, which besides fulfilling the requirements for machine data measurement as described in ISO 6393, 6394, 6395, 6396, would also be efficient and easy to operate.

The PULSE/AudiBel system is conceived on the basis of advanced system design. Based on highly user-friendly control software, the system and the machine under test are operated by one person.

Training in using the system is minimal, all control and data entry functions are simple and intuitive due to simple menu layouts and a

Help system. The system provides high productivity, and the cost per machine tested is low due to only one unskilled person being needed, in all. When more than 40 machines per year are tested with the PULSE/AudiBel system, the system rapidly yields a much lower total test cost.

A test report is included with each test. All reports are archived for later retrieval. The system provides data for statistical process control. With a large population of produced machines being tested, an effective feedback can be provided to manufacturing as well as R & D departments.

The long term benefits realized are total documentation and statistics of all measured machines' noise data and an assurance that regulatory bodies can be provided access to data for each individual machine. Besides A-weighted wideband noise data, third-octave data is stored. All data may be retrieved later for subsequent statistical analysis in an optional Access-based statistics package.

The system can be physically calibrated by one person due to an automated calibration procedure. Frequent validation of the entire microphone signal paths can be carried out using the CIC technique. Weather data is measured and included automatically, as is the noise level at the operator position. The inclusion of background noise microphones ensures that measurement data is not unduly influenced by non-machine related sources.

The PULSE/AudiBel will enhance the manufacturing process and contribute to an overall better competitive position in the earth-moving machinery marketplace.

Brüel & Kjær Offers

❍ Complete turnkey Dynamic Sound Test instrumentation systems
❍ Site Planning assistance
❍ Installation of instrumentation system
❍ Training in setting up, calibrating and operating the system

The Dynamic Sound Test System concept is developed jointly by Caterpillar and Brüel & Kjær.

The AudiBel software is developed by Caterpillar, which is responsible for its contents. It is available through Brüel & Kjær.

Brüel & Kjær

WORLD HEADQUARTERS:
DK-2850 Nærum · Denmark · Telephone: +45 45 80 05 00 · Fax: +45 45 80 14 05 · Internet: http://www.bk.dk · e-mail: info@bk.dk
Australia (02) 9450-2066 · Austria 00 43-1-865 74 00 · Belgium 016/44 92 25 · Brazil (011) 246-8166 · Canada: (514) 695-8225 · China 10 68419 625 / 10 6843 7426
Czech Republic 02-67 021100 · Finland (0)9-229 3021 · France (01) 69 90 69 00 · Germany 06103/908-5 · Hong Kong 2548 7486 · Hungary (1) 215 83 05
Italy (02) 57 60 4141 · Japan 03-3779-8671 · Republic of Korea (02) 3473-0605 · Nederland (0)30 6039994 · Norway 66 90 4410 · Poland (0-22) 40 93 92
Portugal (1) 471 14 53 Singapore (65) 275-8816 · Slovak Republic 07 378 9520 · Spain (91) 3681000 · Sweden (08) 711 27 30 · Switzerland 01/940 09 09
Taiwan (02) 713 9303 · United Kingdom and Ireland (0181) 954-2366 · USA 1 800 332 2040
Local representatives and service organisations worldwide

BU 0208–11 97/11