C. R. Mecanique 341 (2013) 687–696

Contents lists available at ScienceDirect

Comptes Rendus Mecanique

www.sciencedirect.com

A tool for controlling accelerometers. Secondary calibration data

Fernando Juliani [a,*], Everaldo de Barros [a], Mauro Hugo Mathias [b]

[a] *Institute of Aeronautics and Space, Integration and Tests Division, Praça Marechal Eduardo Gomes, 50, 12228-904, São José dos Campos, SP, Brazil*

[b] *Universidade Estadual Paulista "Júlio de Mesquita Filho", Campus de Guaratinguetá, Avenida Doutor Ariberto Pereira da Cunha, 333, 12516-410, Guaratinguetá, SP, Brazil*

ARTICLE INFO

Article history:
Received 9 January 2013
Accepted 28 September 2013
Available online 22 October 2013

Keywords:
Accelerometer
Secondary calibration
Vibration testing
Database

ABSTRACT

Vibration monitoring requires acceleration transducers capable of providing data with high precision. Accelerometers are the most frequently used vibration transducers. Their calibration plays an important role in measuring vibrations and is a key component in ensuring the integrity of the vibration measurement. For managing secondary calibration data of accelerometers, a database computer system was implemented. The implementation of this software has been an important step forward in providing a wide range of analysis and display tools. This paper reviews the main concepts involving accelerometer secondary calibration and describes the tool developed and the methods used in its development.

1. Introduction

In Dynamics, many analyses are designed to study the effects of vibration in mechanical systems. In the aerospace field, one of the purposes of the vibration study is just to minimize it through the adequacy of the designed and developed structure to the harsh environment in which it will be installed. Tests related to vibration comprise a life cycle stage of these vibratory systems and generally involve response analysis of a large number of piezoelectric accelerometers which monitor the movements of the structure excited and determine the corresponding input–output relationship.

Since the accelerometer is one of the main components of the measuring system employed in the mechanical vibration tests, its periodic calibration is advisable for two reasons: (i) during the tests, the accelerometers can be subjected to harsh treatments that may result in an appreciable change in their operational characteristics; (ii) measurement traceability to national standards and adherence to either contractual or legal conditions are required by the customers requesting the tests.

Among several accelerometer calibration methods, there is the primary calibration, performed by National Metrology Institutes (NMIs), and the secondary calibration, which involves obtaining the transducer sensitivity to both the fixed frequency of calibration and to the changing frequencies in the operating frequency range. In this case, the traceability is ensured by a reference standard accelerometer positioned between the exciter and the accelerometer to be calibrated. This method is typically used by laboratories located at research institutes, companies and factories that perform calibration in order to meet internal demand and to fulfill requests from external clients.

The Accelerometer Calibration Central Laboratory located at Institute of Aeronautics and Space (IAE) – a research center of the Brazilian Air Force, is responsible for calibrating and managing a large number of accelerometers, and therefore must

* Corresponding author at: Instituto de Aeronáutica e Espaço, Praça Marechal Eduardo Gomes 50, 12228-904, São José dos Campos, Brazil.
E-mail addresses: fernandofj@iae.cta.br, frdjuliani@gmail.com (F. Juliani).

1631-0721/$ – see front matter
http://dx.doi.org/10.1016/j.crme.2013.09.007

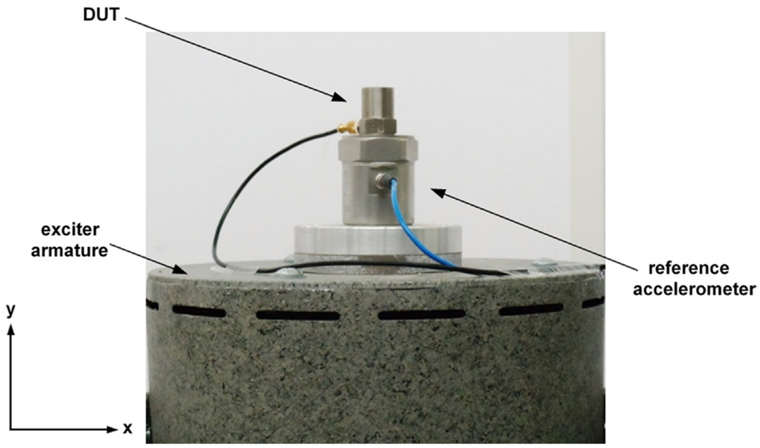


Fig. 1. DUT mounted on reference accelerometer.

manage data from their calibration and use. Thus, the records regarding each calibration must contain the appropriate information to facilitate the identification of factors influencing the uncertainty. There must be traceability from both activities involving piezoelectric accelerometers: secondary calibration and vibration monitoring. Thus, it has become imperative to develop a database application which would help in managing data related to calibration process and at the same time, fill the informational gap between these activities.

According to ISO/IEC 17025 [1], data control is an important topic regarding testing and calibration methods and validation of these methods. However, traceability data involving simultaneously calibration and testing activities is not common. Often, the institution which performs the calibration is not the same as the one where the tests are carried out, which makes it unreasonable to maintain a transducer operation history. The proposed study addresses a specific case, in which both calibration and vibration testing activities are performed by the same institution, justifying the maintenance of transducer data in both activities.

2. Fundamental concepts

The accelerometers used in vibration monitoring are often subjected to high-intensity forces which can result in a substantial change of their characteristics or even their permanent damage. And because they have a small size and are often manipulated, accelerometers may still be defective even when not used (e.g. when exposed to falls). For this reason, accelerometer calibration is conducted to check the sensitivity. It is an important operation that must precede testing activities and structural vibration monitoring in order to ensure accuracy and reliability of the results generated by the chain of instruments used in measurements. One of the key criteria for the selection of a piezoelectric accelerometer is its sensitivity, defined as the ratio between the developed charge and the acceleration that caused the charge flow.

There are also other reasons for the transducer calibration besides establishing a relationship between physical quantity and definite degree of accuracy [2]:

• Based on laws, contracts or regulations, customers who request the test may require evidence to prove the accuracy of the transducer;

• In cases where the accelerometer is used either in a particular setup or in an undocumented and unknown environment, it is necessary to calibrate it for this condition. However, the accelerometer calibration chart covers most applications;

• A control system is an important part of the calibration process, especially in measurement systems composed of many instruments. Mistakes in calculating the sensitivity of the system can be avoided with simple calibration verification.

The accelerometer calibration is a process in which a known input is generated for an instrument and its response is recorded to establish an input–output relationship that makes it possible to determine the sensitivity and the linearity within a frequency range. In general terms, the calibration is achieved by applying a harmonic motion along the sensitive axis that is generated by an electrodynamic exciter. There are various methods of calibrating accelerometers, being the following the most common:

• Absolute methods (include the primary accelerometer calibration): the movement amplitude is measured through either laser interferometry or reciprocity techniques. This calibration method is applied by NMIs that are accredited for calibration of reference standards. In Brazil, the primary calibration is conducted by the National Institute of Metrology, Quality and Technology (INMETRO). The primary accelerometer calibration is not discussed in this paper.

• Comparison method (encompasses the secondary accelerometer calibration process): in this method the accelerometer to be calibrated, named as the Device Under Test (DUT), is mounted over a standard reference accelerometer and both are mounted over the electrodynamic exciter armature in a configuration referred to as calibration by comparison or "back to back" [3,4], as illustrated in Fig. 1.

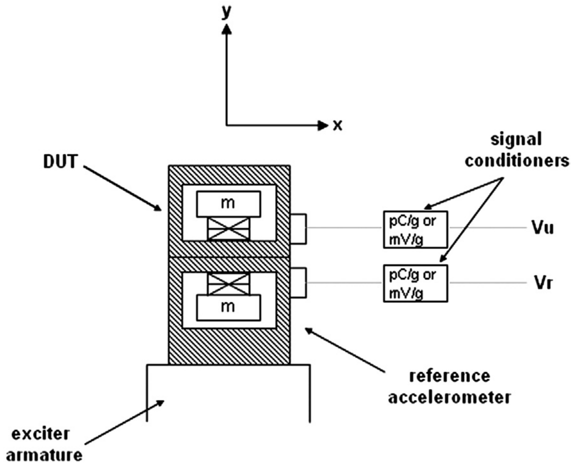


Fig. 2. Back to back calibration method [4].

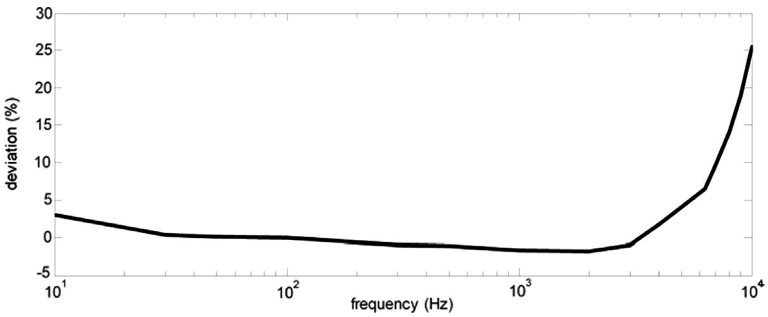


Fig. 3. Typical frequency response.

The secondary accelerometer calibration is limited to the amplitude and frequency range used in reference standard accelerometer calibration [3]. The DUT, with unknown sensitivity denoted as S_u, is mounted on a reference standard accelerometer with S_r sensitivity. When the assembly is subjected to a sinusoidal excitation with fixed frequency in the y direction, the V_u and V_r accelerometer outputs are measured and because $S_u = V_u/y$ and $S_r = V_r/y$, the S_u sensitivity is obtained from the expression

$$S_u = S_r \frac{V_u}{V_r}$$

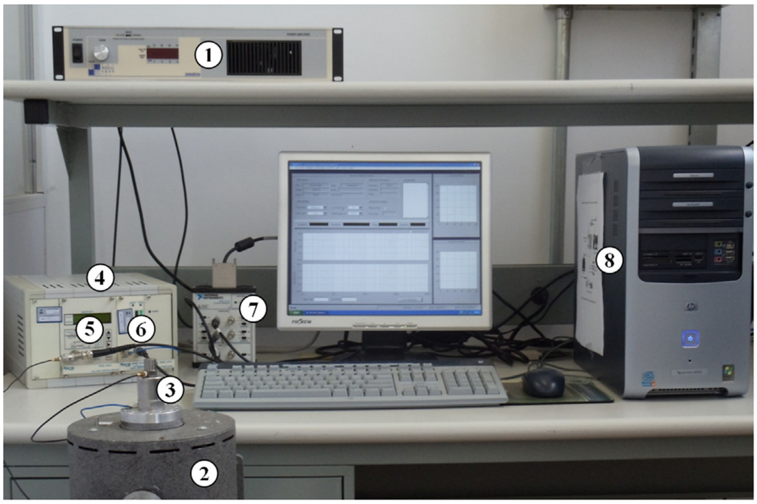
Thus, when both transducers are subjected to a vibratory movement introduced by the exciter, the ratio of the respective output voltage will be proportional to their sensitivities and, as the reference standard accelerometer sensitivity is already known, the DUT sensitivity can be accurately determined. The schematic diagram of the back to back calibration method is illustrated in Fig. 2.

Additionally, an accelerometer secondary calibration should provide the sensitivity value and the respective frequency response, thus indicating not only the sensitivity value measured for a fixed calibration frequency but also the deviation from reference sensitivity along the accelerometer operational frequency range, as illustrated in Fig. 3.

According to recommendations of ISO 16063-21 [5], the best results in terms of accuracy are usually achieved when the two accelerometers are rigidly fixed in the "back to back" configuration with their sensitivity axes being parallel to the direction of motion. Indeed, inaccuracies can be produced due to: an imperfect alignment of the accelerometer sensitivity axis regarding the desired measurement axis; stiffness of the coupling; temperature variations or because of the effect of accelerometer cable vibration. In this calibration method the reference standard accelerometer calibrated by an NMI and the signal conditioner become a single unit, ensuring the calibration traceability [4].

3. The calibration performed at Accelerometer Calibration Central Laboratory

The piezoelectric accelerometers secondary calibration performed at Accelerometer Calibration Central Laboratory is held with The Modal Shop (TMS) 9155C system for calibrations in the frequency range of 5 Hz to 10 kHz and amplitude of up to 10 g. The system consists of an exciter, a power amplifier, a reference standard accelerometer, a chassis containing



1. Power amplifier
2. Exciter
3. Reference accelerometer
4. Chassis
5. Signal conditioner #1
6. Signal conditioner #2
7. Connection accessory
8. Control system

Fig. 4. Accelerometers secondary calibration system components.

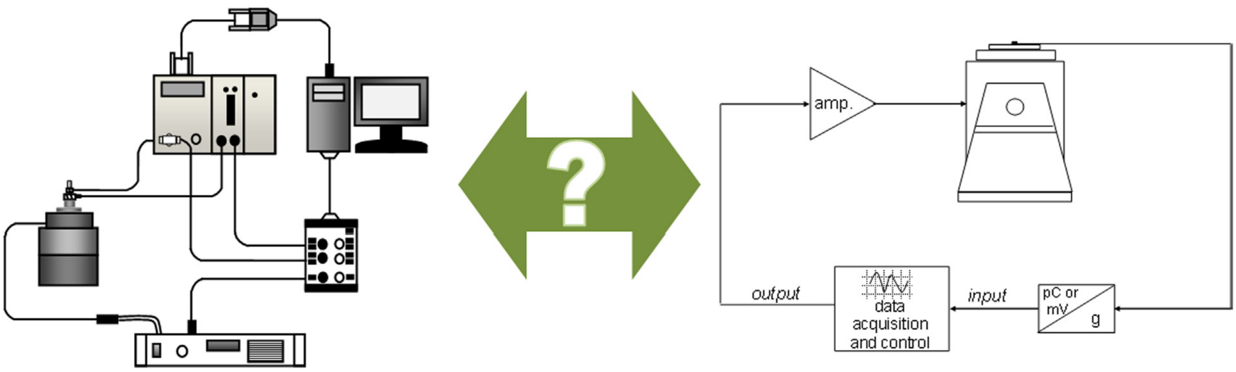


Fig. 5. Lack of connection between secondary calibration (on left) and testing (on right) activities.

two signal conditioners, a connection accessory and a microcomputer with both data acquisition control board and control software installed. These components are illustrated in Fig. 4.

3.1. Deficiencies in the calibration process at Accelerometer Calibration Central Laboratory

Although 9155C software manages both data acquisition and accelerometer calibration, and has relevant features such as certificate issuance in accordance with ISO/IEC 17025, it does not meet some needs that are remarkable especially when services are provided to IAE Test Division. In this case it is essential that there be a link between the calibration process and the tests to be performed. It is necessary to manage not only the calibration data itself, but also some information of test activities and vibrations monitoring that are intrinsic to laboratory activities. The shortcomings detected are:

- Lack of data traceability of the calibration process and the use of the accelerometer for either vibration monitoring or testing, as illustrated in Fig. 5. The connection between the processes does not exist, and makes it difficult to manage future calibrations, since the use of the accelerometer on a vibration testing or monitoring shortens the amount of time that must exist between calibrations. According to recommendations set out in internal procedures, the accelerometers must be calibrated periodically in the maximum period of one year;
- Need to manage the sensitivity values obtained during the calibration processes of the same accelerometer, enabling an assessment of the variability of these values;
- Lack of management of the accelerometer use for vibration testing and monitoring that allows obtaining a history and information about its applicability;
- Lack of management of storage physical location of accelerometers, which reduce significantly the time to locate it for using.

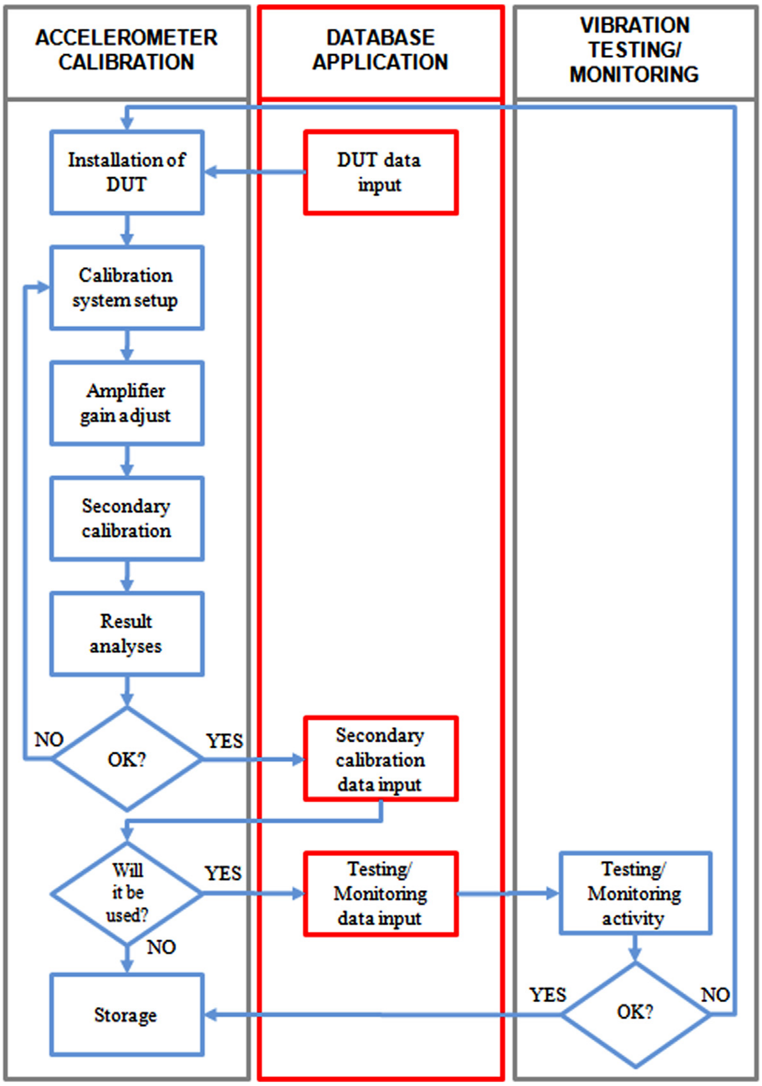


Fig. 6. Processes flow with emphasis on the systematic deployment proposal.

- Need to control data signal conditioners that are used with accelerometers. Information about their characteristics is not stored by 9155C system, and availability of physical location data also helps to make agile the vibration testing preparation process.
- Although the signal conditioner calibration is not object of this paper, data related to it are also important for global traceability of the calibration system. During a vibration testing, inconsistent results may be obtained and this sometimes occurs due to the use of signal conditioners which are not calibrated. Therefore, the calibration data management of these components is essential.

3.2. Proposed solution for managing accelerometers

Having the difficulties been outlined, it was decided to develop a database application that could be modeled according to the characteristics of the Accelerometer Calibration Central Laboratory, and at the same time, one that would meet what is recommended by ISO/IEC 17025, mainly in terms of data management.

The proposed solution consists basically in deploying an application database that fills the informational gap between accelerometer calibration and testing activities, and provides the laboratory staff managing hundreds of accelerometers. Fig. 6 illustrates the calibration and testing workflow with the implementation of the proposed application.

The existence of a computational tool is essential to provide relevant data regarding accelerometer, calibrations and tests in which accelerometers are involved. This repository of information allows traceability and greater control of laboratory operators on the physical integrity of the transducer, reflecting subsequently in the data transmitted during the test. Afterwards, this stored information is correlated, providing data management of both accelerometer calibration and its use in tests.

Regarding the application development process, the fact of that being designed and implemented under the laboratory allowed it to be shaped according to local needs at very low cost. Although there are commercially available software packages providing similar solutions (e.g., Calilab, MyLIMS and SE Calibration), these programs are generally inflexible and expensive, especially when either functionality increments or modifications of existing modules are needed. The representation of scientific data is highly dynamic and constantly requires structural changes in the structure of the database [6]. Therefore, the cost of repeated updates needed in a dynamic environment becomes prohibitive.

Surveys conducted on publications dealing with the development and use of proprietary systems for managing monitoring data in fields like Acoustics [7], Hydrology [8] and Chemistry [9] confirm the effectiveness of developing a system database owner. Regarding calibration data management, an integrated data focused on primary calibration laboratories is proposed [10]. However, recent scientific studies addressing specifically the management of secondary calibration data through a developed database application were not found.

The existence of a Data Communication Network (DCN) infrastructure that supports the client–server architecture – considerate the most appropriate for this purpose, is a facilitating element to the development of software applications at IAE. For the client–server model to be implemented, a DCN must have some requirements [11]: a set of server computers that provide services to other subsystems (such as print services, file management and databases), a set of customers who request the services offered by servers (running a program on multiple clients simultaneously), and a computer network that enables customers to access these services. Since the software application is connected to Relational Database Management System (RDBMS), it processes both request information from users and updated information in the database.

4. Development methodology

In this paper the methods adopted in meaningful activities that comprise the stages of software design and implementation will be described: data modeling, data access and interface design.

4.1. Data modeling

The development of a logical and appropriate structure database is essential for software application to work consistently. The database modeling was performed by following the basic concepts of the relational model, using the relational database, relational operations and both entity integrity and referential integrity rules. The relational database consists of a set of tables and relationships among them [12]. These relationships are defined by a set of rules, such as the uniqueness of both the tables and the records.

The entity integrity rule, in turn, relates to rejection of null values in the identifier field of each data table, while the referential integrity rule is intended to satisfy constraints on the use of primary keys and foreign keys, which represent the relationships between tables.

The modeled database was defined by eighteen data tables in a $1:n$ (one to many) relation. In relationships in which referential integrity is enforced, consistency was established in the database, thus avoiding the possibility of both accidentally deleting operations and altering data. If the user has permission to delete and attempts to delete a record from a table that is related to another record in another table, the database will provide an error message, preventing the action. The relationships between the main database tables are schematically illustrated in Fig. 7.

4.2. Data access

In terms of database security it was necessary to introduce some restrictions on information access related to accelerometer calibration. The access is allowed to a certain number of users so that possible error effects in either data entry or data updating can be minimized.

Since the RDBMS is a software layer between the physical database (where the data is stored) and the users of database application [12], it manages user requests for accessing database records as well as provides features regarding design of databases and tables to the Database Administrator (DBA). SQL Server is an RDBMS developed by Microsoft [13] and it is currently used by IAE. Features that involve database security aspects such as authentication, authorization policies and transaction control are not managed by the developed database application, but by the integration between the RDBMS installed on the server database and the directory service configured on the domain controller.

Active Directory (AD) is the directory service included in the Windows Server, which is the operating system currently used. The core unit of logical structure in AD is the *domain*. It can store millions of sets of attributes named objects that represent computer network resources. Network administrators must be able to manage the use of these objects. A *domain controller* is a computer running Windows Server that stores a replica of the domain directory and manages all aspects of domain user interaction, such as locating AD objects and validating user *logon* (authentication) attempts.

At this point, the integration between the RDBMS SQL Server and the Directory Services AD relieves the application database operator from performing a new authentication to obtain access to the tool. The authentication service is performed by the domain controller that requires to the user (through either Windows XP or Windows 7 operating system

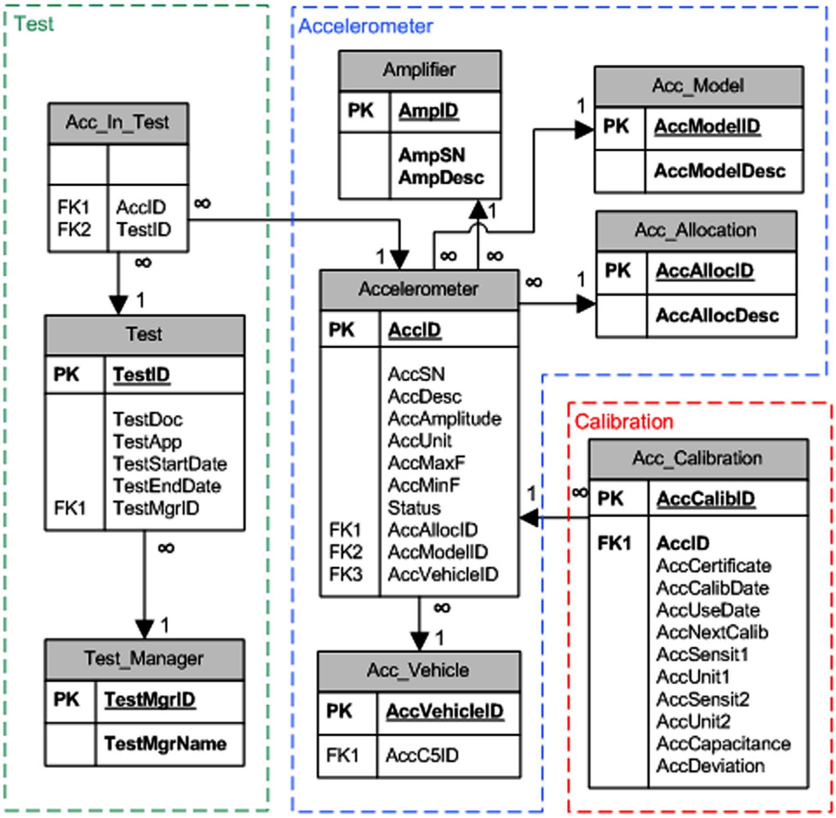


Fig. 7. Database schema with main tables, fields and primary keys.

access) a valid domain account to access the database. Fig. 8 illustrates schematically the application access process flow provided by integration between the RDBMS installed on the server database and the directory service configured on the domain controller.

Permissions related to data that the user can both view and manipulate are defined by the DBA. There are three possible states for user permission [13]: *granted* (or positive), *denied* (or negative) and *none*. A user database can only perform the activities that it was provided with. In this case, there is a corresponding entry in the *sysprotects* RDBMS system table. A negative entry on the same table prevents users from running activities. In the latter case (none), the user does not have explicit privileges but can perform an activity if his role has the appropriate permission.

4.3. Interface design

The application interface was developed using the seventh version of the Borland Delphi visual programming language. It belongs to the Rapid Application Development (RAD) tool group [14] and the advantages of this software were the easing of setting up a visual and event-driven tool and the ability to accelerate the software development process (codification, screen design and database connecting). While a programmer is working in the form designer, Delphi is generating a code behind the scenes for the components that are manipulated on the forms. The application development requires more than building a good interface, and the goal of RAD tools is just to simplify the interface creation to allow the developer to focus more on the analysis, design and system coding.

The control options available to application users include the secondary calibration data and accelerometer management, available in three tabs named *Accelerometers*, *Search* and *Tests*. These tabs include secondary calibration data from the accelerometer, its descriptive data, information about storage physical location in the laboratory, the location on the vibratory structure that will be subjected to testing or vibration monitoring, calibration data of respective signal conditioner and use management of accelerometers in tests.

The tab used for the accelerometer registration provides information about the calibration plan concerning accelerometer and corresponding signal conditioner (if applicable). This information involves uniquely identification, description, serial number, type and location. The registration of the accelerometer calibration process is complemented by the *Accelerometer calibration data* frame which in sequence includes the calibration *Certificate number*, the *Calibration* date, the date when the accelerometer was used after calibration (*Utilization*), the *Sensitivity* value for a fixed frequency in units of pC/g or mV/g, a *Capacitance* value in units of pF, the maximum *Deviation* of the reference sensitivity curve and the *Sensitivity* value for a

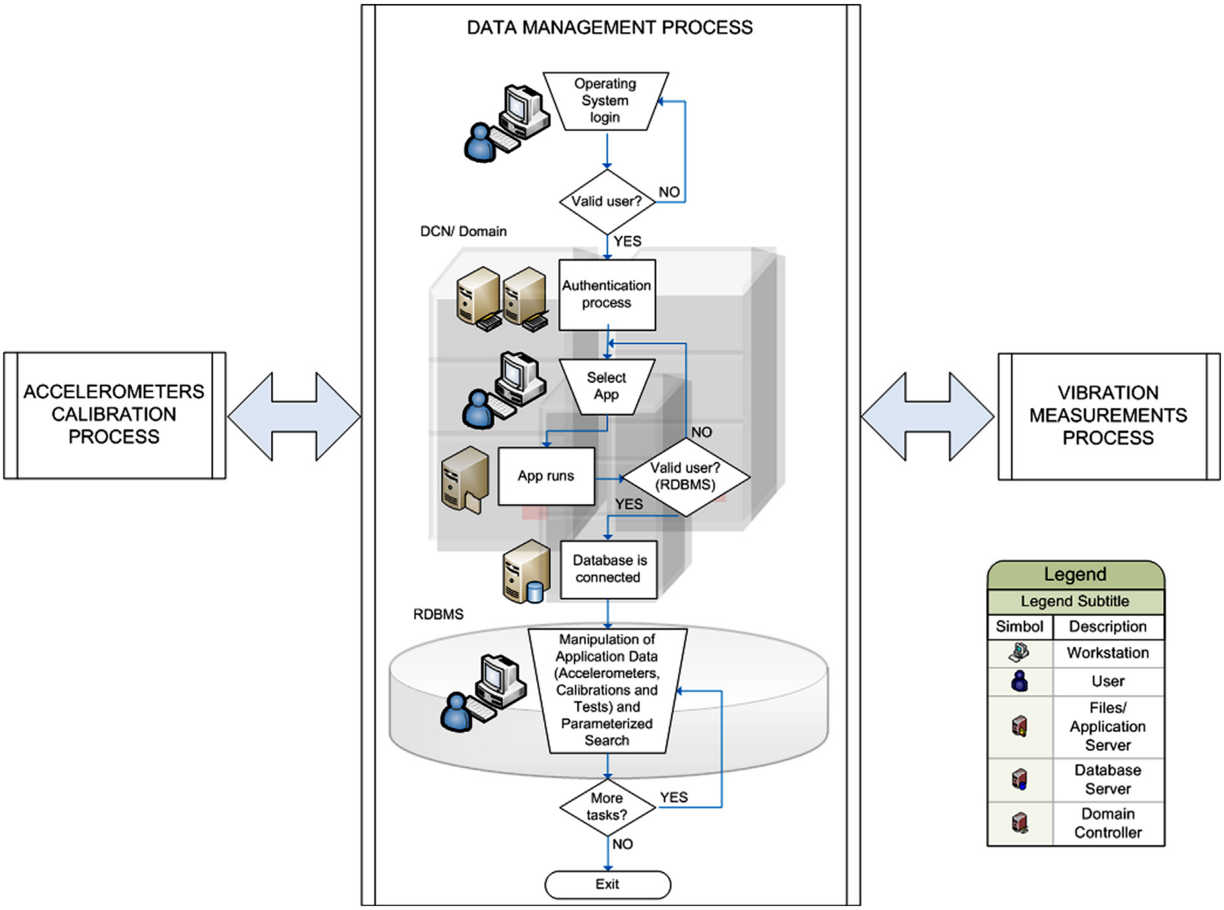


Fig. 8. Data access flow provided by integration between RDBMS and AD.

fixed frequency in units of pC/ms^2 or mV/ms^2. The list of calibrations performed with the transducer is registered in this frame, which also includes *Next calibration* date for a calibration period of twelve months after the date of accelerometer use and the *Sensitivity variation* related to the last calibration performed.

When accelerometers stored at the laboratory are required for testing, some documentary information, such as test description, the requester's name and identification of accelerometers used, are recorded in the database. Thus, it is established a link between the data from the accelerometer calibration and the testing. Based on this management, the laboratory staff will have subsidies to both administer and program related activities. The tabs used for the accelerometer and testing registration are illustrated in Fig. 9.

5. Results

The results of this research are presented through some ISO/IEC 17025 requirements met by the implementation of the developed database application, which can contribute to the development of a consistent quality management system at the Accelerometer Calibration Central Laboratory. The ISO/IEC 17025 specifies the general requirements for the competence to carry out tests or calibrations using standard methods, non-standard methods and methods developed by the laboratory. It is applicable to all organizations performing tests or calibrations, regardless of the number of people or the scope of test activities and calibration.

5.1. Control of records

The developed application database uniquely identifies the records inserted, allowing access at any time by authorized users through a friendly interface that provides clarity on information availability. Records can also be printed in the form of reports by authorized operators. Both the application and the database are hosted on DCN servers' computers that support high demand of processing and data storage. These computers are housed in a conditioned and restricted access room.

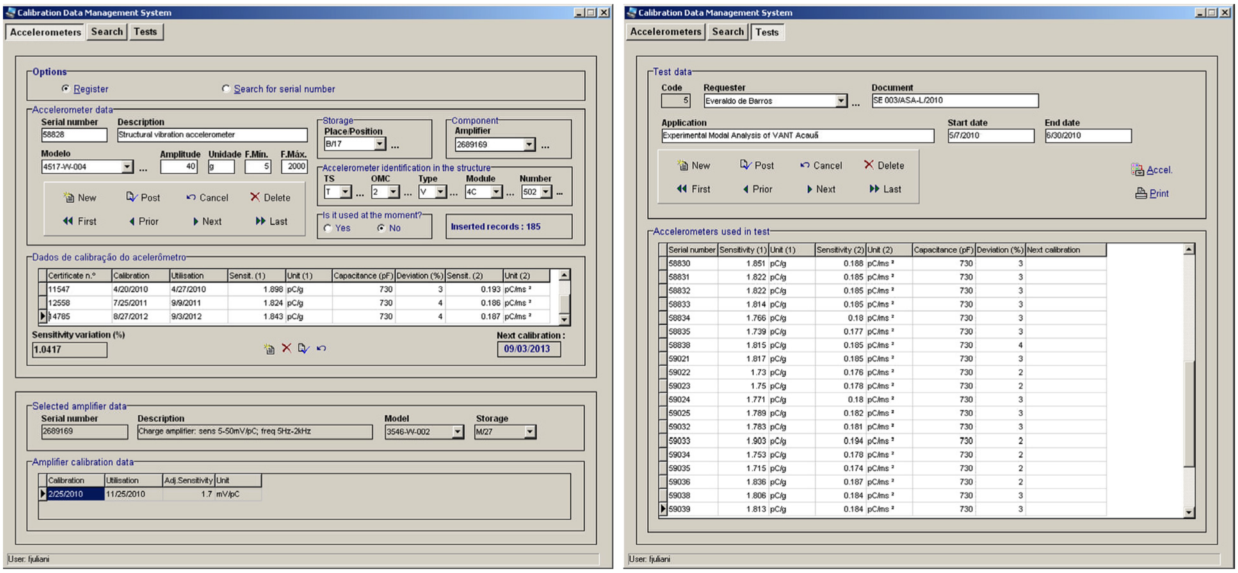


Fig. 9. The graphical user interface for accelerometers data management, displaying the accelerometers tab (on the left) and the tests tab (on the right).

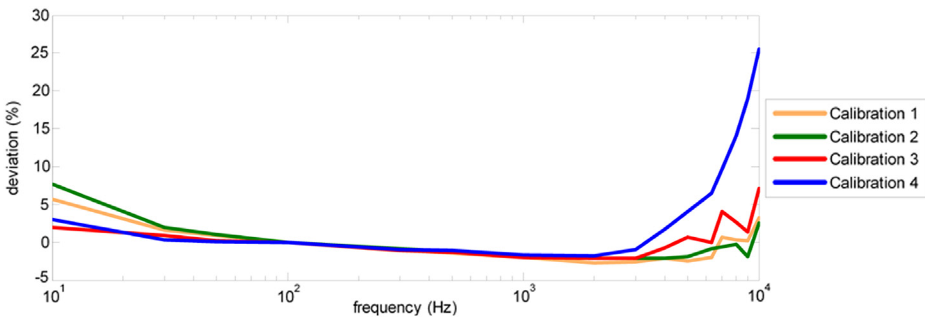


Fig. 10. (Color online.) Measurement traceability of secondary calibration performed in a piezoelectric accelerometer.

5.2. Equipment

The application database tables were modeled to allow the operator to enter information concerning the transducer characteristics. This information include a unique identifier generated by the system, an accelerometer serial number, the model description, the item storage physical location in the laboratory, the item location on the vibratory structure to be tested (when necessary), all calibration data and the date of next calibration. Accelerometers of the laboratory have the serial number printed on its structure and data such as date of both last calibration and next calibration are printed on the label of the case where it is physically stored. This information is stored electronically on the accelerometers database management system.

5.3. Measurement traceability

The accelerometer and correspondent signal conditioner used in testing and vibration monitoring are calibrated before entering service as well as the other items that make up the calibration system. The accelerometer database stores information related to the calibration of both accelerometers and signal conditioners, thus allowing their measurement. Fig. 10 illustrates the response traceability of secondary calibration performed in a piezoelectric accelerometer.

5.4. Reporting the results

The calibration data manager system enables the printing of the accelerometer's synthesized information, or detailed results for each accelerometer calibration or more, according to the criterion adopted by the user. The same applies to the data signal conditioners used with the accelerometers. Initially the calibration data of interest to the user can be visualized, subsequently being offered the option of printing it on paper. The printed report has relevant information like serial numbers and its accelerometer signal conditioner, besides description, sensitivity, units of measurement and dates of both calibration and use in test. Thus, the calibration data of both the accelerometers and signal conditioners can be traced.

6. Conclusion

This paper presented a systematic that, through a developed database application helps operators of the Accelerometer Calibration Central Laboratory in data management of hundreds of transducers.

With the implementation of this database application, laboratory operators have access not only to the recent activities of calibration and testing, but also to the descriptions of previous years' activities. This information is stored in electronic format through database tables managed by the RDBMS and can be accessed through data report. The large number of calibrations recorded enables statistical treatment of data, allowing laboratory operators to accomplish sensitivity variance analysis between calibrations.

The database application meets the needs of operators regarding the storage, identification and organization of data. In addition, the DCN infrastructure guarantees information confidentiality, providing it is accessed only by authorized operators, with their access accounts and passwords. Since the data management system is a complex of hardware and software components under a DCN infrastructure, processes regarding storing, processing and distribution of information tend to be run smoothly by users, even with a large number of simultaneous accesses to application.

The development of this database application was stimulated by the quest for automation of the laboratory processes, aiming at agility in the Accelerometer Calibration Central Laboratory activities. It was found that the information management related to both calibration of accelerometers and their employment in tests and vibration monitoring is required for starting a Quality Assurance System implementation and getting subsequent laboratory accreditation by INMETRO.

The management of activities by the laboratory through a database allows, with the passage of time and the consequent downgrading of the hardware and software used in laboratory activities, the application to be replaced by a new solution without great difficulty, being the tool developed or acquired, through the simple migration of existing data stored from the old system to the new system installed.

Finally, it was found that the proposed solution, by means of appropriate computational adjustments, may be useful for the management of various transducers such as pressure transducers, force transducers and microphones, which are utilized in different types of monitoring and testing.

References

[1] ISO/IEC 17025:2005, General requirements for the competence of testing and calibration laboratories, International Organization for Standardization, Switzerland, 2005.
[2] M. Serridge, T.R. Licht, Piezoelectric Accelerometer and Vibration Preamplifier Handbook, K. Larsen & Son A/ S, Glostrup, 1987.
[3] G. Buzdugan, E. Mihailescu, M. Rades, Vibration Measuring, Martinus Nijhoff Publishers, Bucharest, Romania, 1986.
[4] K.G. McConnell, P.S. Varoto, Vibration Testing: Theory and Practice, John Wiley & Sons, New York, USA, 2008.
[5] ISO 16063-21:2003, Methods for the calibration of vibration and shock transducers – Part 21: Vibration calibration by comparison to a reference transducer, International Organization for Standardization, Switzerland, 2003.
[6] T. Critchlow, Data foundry: information management for scientific data, IEEE Trans. Inf. Technol. Biomed. 4 (2000) 52–57.
[7] J.Z. Sikorska, P.J. Kelly, J. Pan, Development of an AE data management and analysis system, Mech. Syst. Signal Process. 20 (8) (2005) 2321–2339.
[8] C.J. Carleton, R.A. Dahlgren, K.W. Tate, A relational database for the monitoring and analysis of watershed hydrologic functions: II. Data manipulation and retrieval programs, Comput. Geosci. 31 (4) (2005) 403–413.
[9] H. Kjeldsen, J. Olsen, J. Heinemeier, An integrated data-analysis and database system form AMS ^{14}C, Nucl. Instrum. Methods Phys. Res. B 268 (7–8) (2010) 980–984.
[10] V. Batagelj, J. Bojkovski, J. Drnovsek, Software integration in national measurement-standards laboratories, Sci. Meas. Technol. 2 (2008) 100–106.
[11] I. Sommerville, Software Engineering, Pearson Addison-Wesley, Boston, MA, USA, 2007.
[12] C.J. Date, An Introducting to Database Systems, seventh edition, Pearson Addison-Wesley, Boston, MA, USA, 2003.
[13] D. Petkovic, SQL Server 2000 – A Beginner's Guide, Osborne McGraw-Hill, Berkeley, CA, USA, 2000.
[14] S. Teixeira, X. Pacheco, Delphi 6 Developer's Guide, Sams Publishing, USA, 2002.