IMPEDANCE-BASED STRUCTURAL HEALTH MONITORING WEB SYSTEM FOR TESTS IN GROUND

Moura Junior,José dos Reis Vieira, mourajr@mourajr.com
Tsuruta, Karina Mayumi, kmtsuruta@mecanica.ufu.br
Palomino, Lizeth Vargas, lvpalomino@mecanica.ufu.br
Steffen Junior, Valder, vsteffen@mecanica.ufu.br
Rade, Domingos Alves Rade, domingos@ufu.br
Federal University of Uberlandia, School of Mechanical Engineering,Av. João Naves de Ávila, 2121.

Inman, Daniel J, dinman@vt.edu
Center for Intelligent Material Systems and Structures, Virginia Polytechnic Institute and State University, Blacksburg, Virginia.

Abstract. *This contribution aims at developing a structural monitoring remote system based on electro-mechanical impedance methods of SHM (Structural Health Monitoring). This method uses piezoelectric patches to excite structures locally, becoming it capable to identify incipient damage. In this case, the monitoring is performed through the web since it was developed to enable simultaneous supervision of many structures localized in many different places, such as in industrial and academic research centers. The collected data are previously analyzed and stored in databases, which can be enriched along several years, and further, studied by using the Data Mining Techniques. This study can be useful for aircraft ground testing, such as fatigue and life cycle tests, enabling a powerful system to store, manage and exchange information. Finally, the system proposed can be modified to include other methodologies, or, alternatively, to make it more sophisticated, i.e., to develop the complete system based on Oriented Object Programming.*

Keywords*: Oriented Object Programming; Electromechanical Impedance Method; Structural Health Monitoring.*

1. INTRODUCTION

This work presents an electro-mechanical impedance-based method by remote monitoring. The goal is to monitor cases of incipient damage and store these cases consistently into a database. The signals are automatically and continuously processed and alert of deviations of behavior are issued by the responsible users for the system to making checks presence. This study intends to improve the capabilities of remote monitoring for the purpose of remote supervision of structures through a process of SHM (Structural Health Monitoring), based on the variation of the signals of electro-mechanical impedance.

2. IMPEDANCE-BASED HEALTH MONITORING

The electro-mechanical impedance-based method of structural health monitoring utilizes sensors/actuators, consisting of small patches of PZT (Lead Zirconate Titanate), usually smaller than 25x25x0.1 mm^3. They are used to measure directly the local dynamic response.

Piezoceramic transducers act directly producing an electric charge when subjected to mechanical efforts. Conversely, a mechanical deformation is caused when an electric field is applied.

To obtain the electro-mechanical impedance signature of the structure, the technique based on the impedance uses the two effects of piezoelectric materials simultaneously, i.e., the direct and indirect effects. When the alternating electric field acts in the PZT patch bonded on the structure, the whole structure with the PZT patch vibrates together. If the exciting frequency is too high, the dynamic response of the structure reflects only in a small region, near to the sensor/actuator. From the dynamic response of the structure, the PZT patch strains generating an electric field. Then, the PZT patch acts as an actuator and sensor of the local deformation. When any type of damage or crack appears in the structure, the dynamic response of the structure is changed locally and it can be sensed through the electrical response of the PZT patch. So, the impedance measured can be classified according to two different types: i) a mechanical impedance due to mechanical system that can be described as the ratio between the power harmonic applied to this system and the speed through which it moves at the same point (Raju, 1997); ii) the electrical impedance which is described as the opposition that a circuit or component provides the alternating current (AC) or the division of the circuit alternate voltage input by the circuit alternate current output. As the electric impedance is a complex quantity, it is divided into two parts: resistance and reactance. The resistance in AC circuits is the same as the counterpart of continuous current and is expressed as an ohmic positive. The reactance can be inductive, or ohmic non-negative, or capacitive, ohmic non-positive (Gibilisco, 2002).

The PZT patches use a very low potential difference (lower than 1 V), generating a high frequency of excitation in certain points of the structure (Moura Jr and Steffen Jr, 2004, 2006). According to Raju (1997), the value

of 1 V shows good results for the identification of structural changes as compared to lower values. The value of 1 V is the maximum value that may be assigned by the equipment that was adopted in the study.

The figure 1 shows a one-dimensional (1D) electro-mechanical model of the impedance-based structural health monitoring system. It is considered that an axial PZT actuator/sensor is placed in one end of the system, while the other end is fixed. Liang et al (1994) demonstrated that admittance *Y(ω)* of the PZT patch actuator is a combined function of the electrical impedance $Z_a(\omega)$ and the mechanical impedance of the structure *Z(ω)*, as shown in Equation 1.

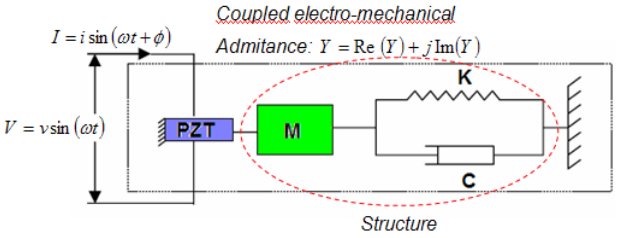

Figure 1: One-dimensional model used to represent a PZT patch-driven dynamic structural system.

$$Y(\omega) = \frac{I}{V} = i\,\omega\,a\left(\bar{\varepsilon}_{33}^{T} - \frac{Z(\omega)}{Z(\omega)+Z_a(\omega)} d_{3x}^{2}\,\hat{Y}_{xx}^{E}\right) \tag{1}$$

where, Y is the electrical admittance (inverse of the impedance), V is the input voltage applied to the PZT pach; I is the output current measured; a is the geometric constant of the PZT, Z_a and Z are the PZT material's and the structure's mechanical impedances, respectively, $\hat{Y}_{xx}^{E}$ is the complex Young's modulus of the PZT with zero electric field, d_{3x} is the piezoelectric coupling constant in the arbitrary *x* direction at zero stress, ε_{33}^{T} is the dielectric constant at zero stress and δ is the dielectric loss tangent of the PZT.

Assuming that the mechanical properties of the PZT patch does not vary over the time, equation 1 shows that the electric impedance of the PZT is directly related to the mechanical impedance of the structure. Then, the signals of the electrical impedance of the PZT patch can be used for structural integrity monitoring of the system. The impedance-based technique consists basically in obtaining frequency response function (FRFs) of the structure and the subsequent evaluation of the modification of these signals. Ideally, the modifications found in the FRFs indicate a structural change, and therefore some kind of damage (Raju, 1997).

The charts of the responses of impedance provide qualitative information about the integrity of the structure, while the quantitative information is usually provided through a scalar. This scalar value is described as the "root mean square deviation" as defined by Sun et al. (1995) by equation 2.

$$M = \sum_{i=1}^{n} \sqrt{\frac{\left[\mathrm{Re}(Z_{i,1}) - \mathrm{Re}(Z_{i,2})\right]^2}{\left[\mathrm{Re}(Z_{i,1})\right]^2}} \tag{2}$$

where M is the damage metric, $Z_{i,1}$ is the impedance of the PZT measured at healthy conditions and $Z_{i,2}$ is the impedance for the comparison with the baseline measurement at the frequency interval *i*.

3. WI-FI CONNECTIONS AND APPLICATIONS FOR INTERNET

An important issue that is considered in this work is the use of technology for data transmission through wireless connections. Two technologies are quite used nowadays: Wi-Fi and Bluetooth (Davis and Mansfield, 2002).

Wi-fi is a specification for wireless networks as promulgated by the IEEE Standards Association (Davis and Mansfield, 2002). The IEEE utilizes numbers to designate patterns instead of names. Inside the scheme of IEEE, the number 802 is used to designate networks in local and metropolitan areas (LANs and WANs). To specify wireless LAN networks, it utilizes 802.11 and 802.11b to the version that works in the spectrum of 2.4 GHz at high speeds (over 11Mbps).

Otherwise, the Wi-Fi utilizes more specialized equipments and is able to cover a distance as large as a few hundred of meters. On the other hand, the Bluetooth technology is limited to a maximum range of 100 meters. Besides, this technology has a lower data transfer capacity (Miller, 2001) as compared with the Wi-Fi.

Another tool used in this work is related to the data communication using Internet. The use of Internet (World Wide Web) is done by computers using the protocol Hyper Text Transfer Protocol (HTTP) (Tansley, 2002). This

method allows the interpretation of hypertext documents, or HTML pages, in a method based on client-server architecture. Summing up, using HTTP, the sequence of the following steps is (Tansley, 2002):
1. The client through a browser opens a connection to a web server;
2. Through a submission the client makes a request;
3. The client is answered by the server;
4. The connection is undone.

Through the web browser, the user accesses the address by a uniform resource locator, (URL), which can be any name of the type www.teste.com.br/meusprogs/prog1.cgi, where this URL is composed as follows: protocol, domain name, way to the appeal, name of the resource and lastly, if any, information of consultation.

Some languages have been designed specifically for programming in the environment of the Internet. One of the most popular ones is the PHP (Tansley, 2002). Unlike the other languages, such as C and Java, PHP is used exclusively for the Internet. The code, or PHP program, is hosted in the internet server. Thus, the user performs a call, which is processed into the server, and then this information is sent back to the client's web browser (Tansley, 2002).

Internet pages can be designed to be either static or dynamic. Static pages are documents that are not changed, while dynamic pages are restructured in accordance with the requests of the customers, i.e., they interact with the user. The pages made in PHP code are capable of generating dynamic pages, working at the same time with the concepts of classes (Object-Oriented Programming) and databases. It is important to remember that all actions are performed on the server machine, thereby protecting the code of the application, unlike applications such as Java applets (client's side execution). Every time a web browser tries to run a script or PHP embedded in an HTML document, the PHP code is analyzed by the module in the server and then runs. This process can be better understood from figure 2.

A great advantage of the PHP language is that it is an open source project, and can be used for both private and commercial applications; also, it is independent of the platform on which it is installed. It is able to work in both the main environments, Linux and Windows.

Furthermore, a system that needs to manipulate data, such as the PHP language, requires storing information. The basic way would be the use of the ASCII files with data information. However, in a case of a large volume of manipulating operations and data types, it is more convenient to use a DBMS (Database Management System). The DBMS thus can be seen as a program capable of storing and managing large amount of information. More than this, to consider the program as a DBMS system, it is necessary that the program is able to manage information between tables, such as foreign keys and primary keys. A table is a basic unit capable of storing information on a specific group of variables, fields or properties of an object. Each line or body of a table is called a register. The controls between the tables, representing their associations, are designated as primary and foreign keys.

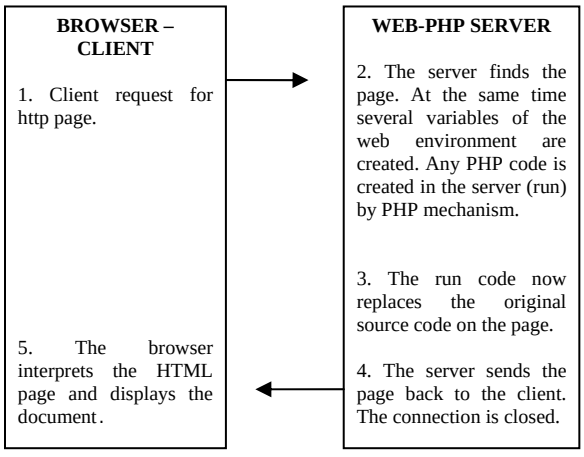

Figure 2: Client-server model with PHP (Tansley, 2002)

The most used DBMS in the Internet, turned to small applications, is probably the MySQL. The MySQL has the advantages of being small, robust (widely tested on different approaches) and freeware. A scheme is illustrated in Figure 3 to show the use of MySQL associated with the PHP scripts.

Figure 3: Relationships between client's browser and the database (Tansley, 2002).

To show the simplicity of the PHP scripts and its connection to databases a simple example is reproduced below, in which a connection is held in the database "Test", followed by a query on the same basis, as shown in the Figure 4.

In the code presented by Figure 4, a connection to the MySQL database is provided through the username (*usuario*) and password (*senha*). The database is asked to use the base named "test". Inside the base “test”, a table named "minhatabela” is to be found. This table exhibits two columns, namely, "nome" (means name, in Portuguese) and "profissao" (means job). Finally, the script connects to the base and lists all records contained in the fields of the table, printing each one in a separate line by generating a file that returns to the client in the HTML format. Remembering, for the client, the only information that can be seen is the HTML document showing the lines of the consult to the database. If the client chooses to view the source code of the document, the script is not presented, showing only HTML codes.

```
<HTML>
<BODY>
<?php
$conexao= mysql_connect(“localhost”,”usuario”,”senha“);
if(!$conexao)
{ echo “There is no connection to the MySQL” ;
  exit;}
$DB = mysql_select_db(“Teste”,$conexao);
if(!$DB)
{ echo “You cannot select the database” ;
  exit;}
$SQL = “SELECT * FROM minhatabela”;
$mysql_resultado = mysql_query($SQL,$conexao);
$nro_linhas = mysql_num_rows($mysql_resultado);
if($nro_linhas == 0)
{ echo “I’m sorry. There is no information”; }
else {
while($linha = mysql_fetch_array($mysql_resultado))
  {$nome = $linha[“nome”];
   $profissao = $linha[“profissao”];
   echo “$nome : $profissao <BR>”; }
mysql_close($conexao);  ?>
</BODY>
</HTML>
```

Figure 4: Source code of databasetest.php

4. DEVELOPMENT OF THE REMOTE SYSTEM FOR SHM

For the development of an electro-mechanical impedance-based remote monitoring system, several technologies are used together aiming at its feasibility and functionality. A general view of the process can be seen in figure 5 (Felice Neto *et all.*, 2007 and Moura Jr, 2008) .

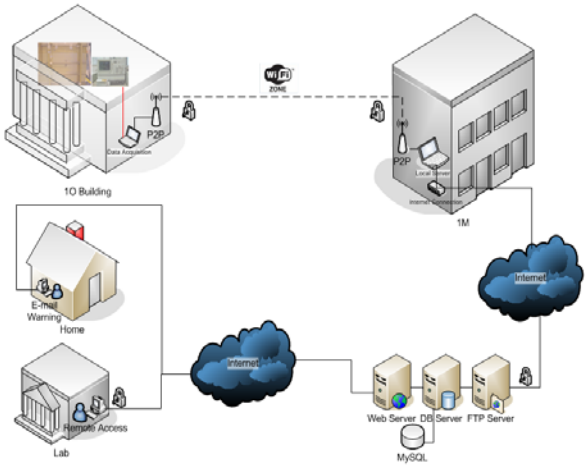

Figure 5: Remote monitoring system.

First, the process is started at the 1O Building at the campus of the Federal University of Uberlândia. There is an impedance analyzer that measures in the lab the signatures of a given component or structure. By the use of an interface GPIB (IEEE 488) a laptop takes the control of the signature acquisition. A part of the source code in C language used

for data acquisition is shown in Figure 6.

```
#include <windows.h>
#include <ni488.h>
#include <stdio.h>
int Device = 0
int BoardIndex = 0;

void main()
{
  int   PrimaryAddress = 17;
  int   SecondaryAddress = 0;
  char  Buffer[8000];
  FILE *datafile1, *datafile2;
...
  ibwrt(Device, "A?", 5);
  ibrd(Device, Buffer, 8000);
  Buffer[ibcntl] = '\0';
  datafile1 = fopen ("Z:\CANAL_A.dat","w");
  fprintf (datafile1,"%s\n",Buffer);
  fclose (datafile1);
  ibonl(Device, 0);
          ...
}
```

Figure 6: Source code of the data acquisition

As observed in Figure 6 the file is stored in Z:\CANAL_A.dat. This process of writing the data is different because such directory is shared by the local laptop at the 1M Building. The communication between the laptops is made peer-to-peer, by wi-fi, through the IEEE 802.11g protocol. It is important to say that in this peer-to-peer access, a cipher key is asked for the validation of the user.

In the local laptop server (1M Building) an Apache server with PHP scripts is configured. Such server allows the direct communication with the remote server (by the PHP scripts) through the internet (FTP protocol). In terms of security, another cipher key is asked by the remote server for authentication of the automatic user of the local server. The local server only copies the file “CANAL_A.dat” to the remote server.

In the remote server the following specific servers are configured: FTP, PHP, and Web Apache (with PHP scripts). A MySQL database server with a base named SHM is also configured. In this remote server there are some PHP scripts. One of them is responsible for opening the file “CANAL_A.dat”, which was saved as explained above, to calculate the damage metric by using the equation (2), and to update the database SHM in the MySQL server. Then, if the value is higher than expected, it sends an e-mail to the person in charge warning about the situation. A given script is dedicated simply for registering new users. The last script presents the current condition of the structure.

All this process of data acquisition, file transfers, and refreshing of the database is repeated each 10 minutes. This period of time can be set up depending on the type of damage expected, by just changing the interval between the operations into the PHP codes.

Figure 7 shows the SQL script to create one of the tables of the SHM database, called “usuario”.

```
CREATE TABLE `Usuario` (
  `Idusuario` INT UNSIGNED NOT NULL AUTO_INCREMENT PRIMARY KEY COMMENT 'identificador-chave primaria',
  `Nomeusuario` VARCHAR( 40 ) NOT NULL COMMENT 'nome do usuario',
  `Instituicaousuario` VARCHAR( 40 ) NOT NULL DEFAULT 'FEMEC-UFU' COMMENT 'nome da instituicao de origem',
  `Funcaousuario` VARCHAR( 15 ) NOT NULL DEFAULT 'estudante' COMMENT 'funcao do usuario',
  `Enderecousuario` VARCHAR( 40 ) NOT NULL DEFAULT 'Campus Sta Monica-1M-Uberlandia-MG-Brasil' COMMENT 'endereco do usuario',
  `Emailusuario` VARCHAR( 30 ) NOT NULL COMMENT 'email do usuario',
  `Datacadastrousuario` DATE NOT NULL COMMENT 'data do cadastro do usuario'
) ENGINE = MYISAM COMMENT = 'Tabela sobre os informacoes dos usuarios';
```

Figure 7: SQL script to create the table “usuario”.

The screenshots of the impedance-based SHM remote system are shown in figures 8 – 11. In figure 8 the login’s screen is shown, which makes the validation of the user. The figure 9 shows a screenshot that allows to the user choosing between register new users and monitoring structures.

Figure 10 shows the screenshot of the register’s screen of new users. In figure 11 the screenshot of the monitoring page is presented. Further, some changes could be made for organizing the data in graphics (or a friendly interface). The fields shown in the table represent the monitoring of a hypothetical structure.

Figure 8: Screenshot of the login page of the remote system.

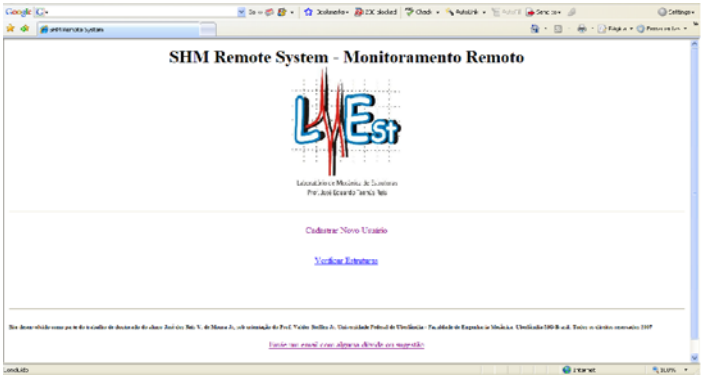

Figure 9: Screenshot of the choices page.

Figure 10: Screenshot of the registering page.

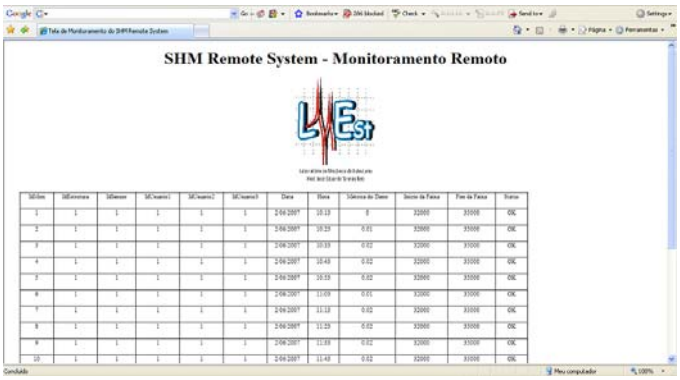

Figure 11: Screenshot of the monitoring page.

5. CONCLUSIONS

As observed in this paper, it is possible to understand the essential resources for the development of a remote monitoring system. Many types of monitoring can be considered, like temperature, motion, electricity sensors, etc. The type of monitoring used in this work is electro-mechanical impedance-based, a type of technique that in last few years has seen major advances regarding the identification of incipient damage, mainly in the aerospace field. However, for the development of the remote monitoring system, some concepts of computer science, such as internet programming languages and databases are essential for the establishment of a robust and flexible system (for accommodating possible technological changes, as necessary).

6. REFERENCES

Davis, H. and Mansfield, R., 2002, "The Wi-Fi Experience: Everyone's Guide to 802.11B Wireless Networking". USA. Que Press.

Felice Neto, F.R., Gruppioni, H.C.P., Tsuruta, K.M., Moura Jr, J.R.V., Steffen Jr, V., 2007, "Impedance-based Structural health monitoring Remote system". XIV Congresso Nacional de Estudantes de Engenharia Mecânica - CREEM 2007, Uberlandia, MG, Brazil.

Gibilisco, S., 2002, "Manual de eletrônica e de telecomunicações", Reichmann e Afonso Editores, Brasil.

Liang, C., Sun, F.P., and Rogers, C.A., 1994, "Coupled Eletromechanical Analysis of Adaptive Material Systems – Determination of the Actuator Power Consumption and System Energy Transfer ", Journal of Intelligent Material Systems and Structures , Vol. 5, 12 – 20.

Miller, M., 2001, "Descobrindo Bluetooth". Rio de Janeiro, RJ, Brasil. Editora Campus.

Moura Jr, J. R. V. and Steffen Jr, V., 2004, "Impedance based Health Monitoring: Frequency Band Evaluation", XXII IMAC, Dearborn, MI – USA.

Moura Jr, J. R. V. ; Steffen Jr, V., 2006, "Impedance-Based Health Monitoring for Aeronautic Structures using Statistical Meta-modeling". Journal of Intelligent Material Systems and Structures, v. 17, p. 1023-1036.

Moura Jr, J.R.V., 2008, "A Contribution to Structural Health Monitoring Systems Applied to Aeronautic and Space Structures". PhD. Thesis, Universidade Federal de Uberlândia, Uberlandia, MG, Brazil.

Raju, V., 1997, "Implementing Impedance-Based Health Monitoring". Master thesis. Virginia Polytechnic Institute and State University. Blacksburg – USA.

Sun, F. P., Chaudhry, Z., Liang, C., and Rogers, C.A., 1995, "Truss Structure Integrity Indentification Using PZT Sensor-Actuador", Journal of Intelligent Material Systems and Structures, Vol. 6, 134-139.

Tansley, D., 2002, "Como Criar Web Pages Rápidas e Eficientes Usando PHP e MySQL". Rio de Janeiro, RJ, Brasil. Editora Ciência Moderna.

7. ACKNOWLEDGMENTS

The first author is thankful to CAPES for her PhD scholarship. The authors acknowledge the support of FAPEMIG/CNPq.

8. RESPONSIBILITY NOTICE

The authors are the only responsible for the printed material included in this paper.