NON-CONTACT EXCITATION SYSTEM TO HIGHLIGHT THE VIBRATION MODES OF BEAMS

Rusalin Lucian Paun, *Universitatea Babes-Bolyai, Cluj-Napoca, ROMANIA*
Gilbert-Rainer Gillich, *Universitatea Babes-Bolyai, Cluj-Napoca, ROMANIA*
Cristinel Popescu, *Universitatea Constantin Brâncuși, Târgu-Jiu, ROMANIA*
Daniela Burtea, *Universitatea Babes-Bolyai, Cluj-Napoca, ROMANIA*

ABSTRACT: This paper introduces device dedicated to the excitation of beam-like structures for damage detection issues. The vibration-based damage detection system consists of two subsystems, one used for actuation and the second for acquiring and processing the measured signal. The actuation is produced by an electromagnetic force induced by an induction coil controlled by a driver. The force can get a sinusoidal or a swept-sine evolution in the frequency range 1 to 1600 Hz. By controlling the individual vibration modes, we ensure a good signal-to-noise ratio, and, therefore, an accurate frequency estimation. The test procedure is presented in detail in this paper. It is verified by applying it to a cantilever beam with a constant cross-section in the absence and the presence of a small added mass. The small frequency changes are precisely identified.

KEY WORDS: vibration mode, non-contact excitation, induction coil, ferromagnetic materials.

1. INTRODUCTION

Vibration-based damage detection is a modern, economical, nondestructive, and global method. The method is based on detecting changes in the vibration behavior of beams. For instance, the changes of the natural frequencies that occur due to defects can be used. In [1] are described in detail vibration-based methods available up to 1996. Updates of this information is given [2], while newer approaches are made available in [3]. Because the modal parameter changes are small even if severe defects affect the structure, these methods require precise estimation of the occurred changes [4].

Ambient factors are used to excite the structure [5] or the excitation can be generated in a controlled manner by an operator [6]. Several methods are mentioned in the literature to produce controlled mechanical oscillations to study possible defects in metallic beams or plates: with sound waves produced by loudspeakers [7], with piezoelectric elements [8], or with induction coils [9].

Our team has developed a modern and robust vibration-based method to detect structural damage [10-12], and has contrived some algorithms to increase the readability of the natural frequencies [13-15]. However, the frequency estimation still needs a controlled excitation system.

In this paper, we introduce a system that uses an induction coil as the exciter element. It permits inducing mechanical oscillations with controlled frequency and amplitude, in order to obtain different modes of vibration of the beams. We succeed to estimate the natural frequencies of beams with high accuracy and to quantify small frequency changes occurred due to an additional mass.

2. DESIGN OF THE ACTUATION / ACQUISITION SYSTEM

The system proposed in this paper consists of two subsystems: the electromagnetic excitation subsystem and the signal acquisition and processing subsystem. The block diagram is presented in Figure 1. The requirements of the excitation subsystem are as following: adjustable frequency, controlled time length, precise positioning.

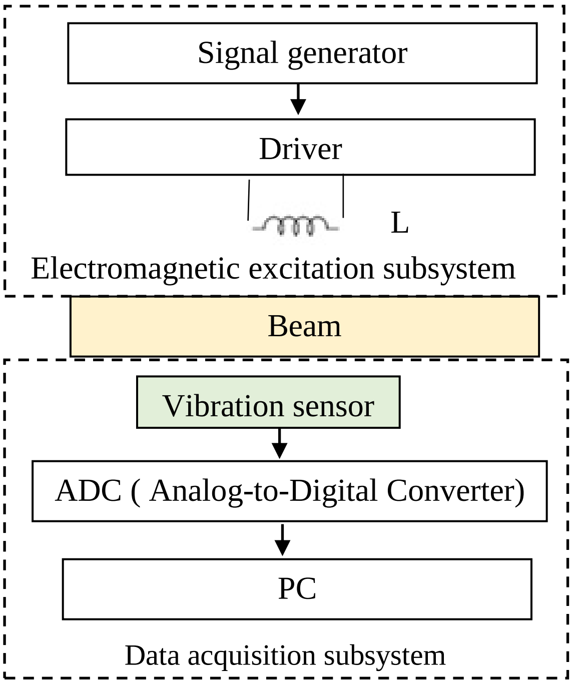

Figure 1. Actuation / acquisition system's functional block diagram

The acquisition subsystem should be able to acquire and estimate the frequencies of short-time signals, in a frequency range 1-1600 Hz and accelerations up to 100 m/s^2.

2.1. The excitation subsystem

The electromagnetic excitation subsystem consists of signal generator unit, it actually is an Arduino Uno R3 development board, coil's driver unit, which is mainly based on a DIT150N03 MOS-FET transistor, and a coil. Whole the subsystem supplies from the same 5 Vdc power supply, which has to ensure at least 1.5 A current.

Arduino Uno R3 was coded to allow the configuration of the signal parameters and afterwards to perform the signal generation based on the set configuration.

Driver unit has been designed to achieve fast coil switching at more than 1 A current. Therefore, the MOS-FET transistor was choused at low drain-to-source voltage and very low drain-to-source resistance at saturation / complete open. Due to the low voltage, the transistor allows very low input, output and transient capacitance.

The coil is made of enameled Cu wire with a diameter of 0.8 mm. The inner diameter of the coil is 30 mm, the outer diameter is 100 mm, and the number of turns is 300. The width of the coil is 10 mm. This shape was adopted to optimize the magnetic flux in the immediate vicinity of the coil and to obtain a maximum excitation of the beam. An average current through the coil is adopted as 1 A. The basis relationship used to calculate the force is:

$$F = \frac{\mu_0 A (NI)^2}{2g} \quad (1)$$

where F - electromagnetic force;
μ_0 - magnetic vacuum permeability;
A - cross section area of the coil;
N - the number of turns of the coil;
I - average current of the coil;
g - distance from the end of the coil, on the middle axis.

The excitation subsystem can generate frequencies in normal mode or in sweep mode. Frequencies can be adjusted in the ranges specified in the Table 1. In addition to the generation mode and the frequency range, it can be adjusted the time period in which the excitation signal of the beam is generated and the time between two excitation signal train (normal or swept modes). Because of the variable frequency, the impedance of the coil is increasing with the frequency value. Thus, a variable duty cycle is provided, its value increasing also with the frequency value in steps as presented in the below table. In Table 1 the frequency resolution decreasing with the frequency value is also specified.

Table 1. Frequency resolution and duty cycle of electromagnetic excitation subsystem

Range [Hz]	1-50	50-500	500-700	700-1000	1000-1200	1200-1400	1400-1600
Frequency resolution [Hz]	0.1	0.5	1	2	3	4	5
Duty cycle [%]	7.5	15	30	40	42	45	48

The signal generation time can be set between 0.5…30 s. For signals with a frequency range between 1 Hz and 100 Hz, the generation time can be set between 5 and 30 s, for signals with a frequency range between 100 Hz and 500 Hz can be set for the generation time between 2 s and 30 s and for signals with a frequency range between 500 Hz and 1600 Hz, the generation time can be set between 0.5 s and 30 s. The coil is supplied with square wave voltage, with adjustable duty cycle factor, in order to obtain a constant average current through the coil and, implicitly, a constant electromagnetic force. The frequency range generated is between 1 Hz and 1600 Hz. The duty cycle factor is adjusted according to the range of frequencies generated: below 100 Hz, between 100 Hz and 500 Hz, between 500 and 1500 Hz. A large diameter (approximately 100 mm) circular construction was adopted for the coil to concentrate the magnetic field lines in the center of the coil. The coil is made with sockets at a predetermined number of turns (50, 100,150 and 200).

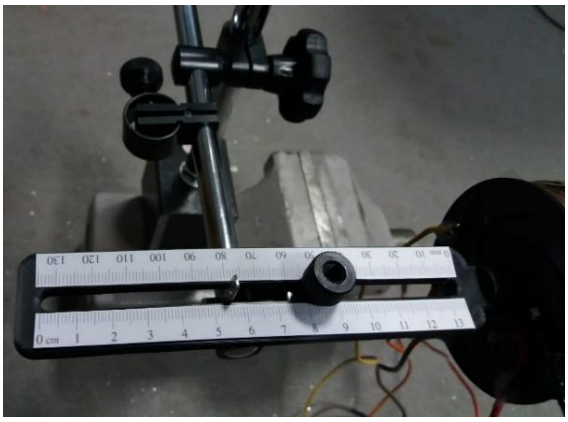
Figure 2. Coil fixed on adjustable mounting bracket

The coil is placed on a support, as shown in Figure 2, which can be moved in a controlled manner along the beam. The distance between the beam and the coil can also be adjusted and registered to ensure the repeatability to the experiments.

The block diagram of electromagnetic excitation subsystem is showed in Figure 3. Communication between Arduino Uno and LCD is realized on the 4 bits data bus. The MOSFET driver is realized with a DIT150N03 N-Channel Power MOSFET transistor. The power supply is 4.5 Vdc source.

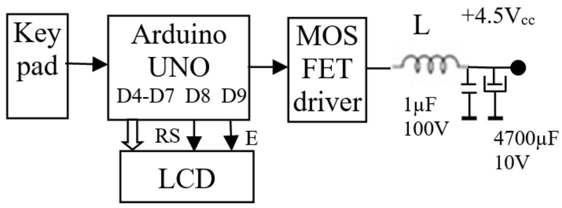

Figure 3. Electromagnetic excitation subsystem block diagram

Figure 4 shows the signal generator in work. The output frequency is set to 1234.21 Hz. The device software allows a rapid setting of frequency value using a keypad.

Figure 4. Signal generator configuration

For an easy setting the signal generator parameter, a subroutine has been created that allows the modification of each digit of which a numerical value is composed.

For this, from the left button on the keyboard of the Arduino Uno module choose the number you want to change (units, tens, hundreds, thousands), then with the openwork of the Up - Down buttons change the value to how much you want. To change the decimal digits (tenths, hundredths) use the button to the right of the Up-Down buttons. The automatic value change period is 0.3 seconds.

2.2. The signal acquisition and processing subsystem

PC performs data acquisition, processing and analysis using the LabView software platform. The acquired data are taken over using a special communication protocol between the ADC module and LabView. For data acquisition it is necessary to select the appropriate ADC module, choosing the method of the acquired data and the range of the values. ADC converts the analog values of the electrical signal into numerical values on a certain number of bits, fixed or prescriptive number, depending on the nature of the ADC used. The mono-axial accelerometer converts the mechanical acceleration into stress values continuous, proportionate and distributed over three circuits. Each circuit corresponds to an axis.

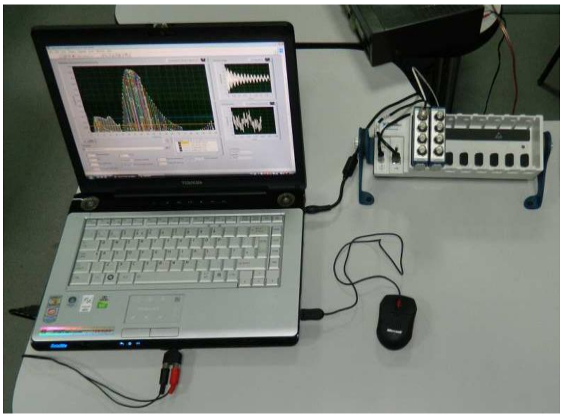

Figure 5. Overview of the acquisition / processing and analysis subsystem

Figure 5 shows the overview of the acquisition and processing subsystem composed by a laptop, the NI cDAQ-9172 compact chassis with a NI 9234 four-channel dynamic signal acquisition module. The Kistler 8772A10 accelerometer is connected to laptop via the chassis and the signal acquisition module.

The virtual instrument (VI) developed in LabView processes the signal by an advanced frequency estimation algorithm [15]. The signal in the time and frequency domains is stored on the laptop for future analysis.

2.3. The system functioning

The coil is fixed on a magnetic mounting bracket that allows controlled movement. This is necessary because the position of the coil must be changed depending on the excitation mode to be analyzed. The optimization of the beam excitation is obtained by placing the coil at an antinode of the targeted vibration mode, as shown in Figure 6 for the vibration mode two. In this figure we illustrate the beam *1* and the fixing system represented by a vise *2*. The limit position of the second mode shape is exemplified with dotted line. The accelerometer *3* is placed at the free end of the beam to obtain significant acceleration. It is connected via the ADC *4* to a laptop *5*. The coil *6* is placed in front of an antinode, in order to transfer an important amount of energy to the beam. Simple and repeatable positioning is ensured by using the fixing system *7* that has a magnetic base and distance markers. The signal generator *8* and the driver *9* used to control the electromagnetic excitation forces are supplied from a power supply.

The system was tested for a cantilever beam with the length L = 1 m, width W = 50 mm and thickness T = 5 mm. The beam is made of steel, with the estimated values of the Young's modulus E = $2*10^{11}$ N, Poisson ratio ν = 0.3 and mass density ρ = 7850 kg/m^3.

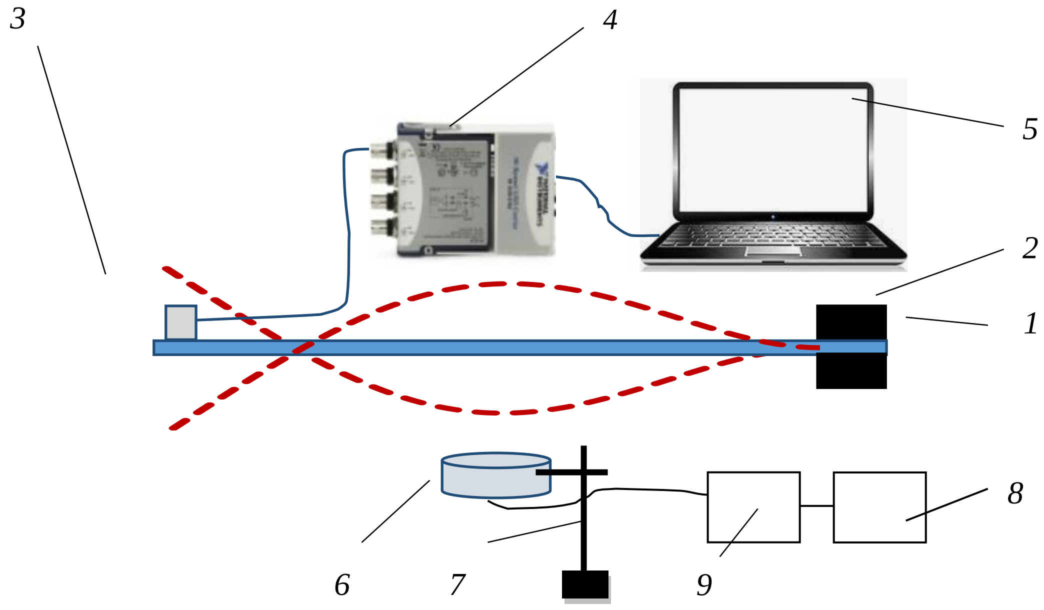

Figure 6. Overview of the testing scenario

3. RESULTS AND DISCUSSION

The measurements are made for the beam with constant cross-section and after a T-shaped crack is manufactured at *x/L* = 0.21. The damage depth is 2.5 mm and from the tip of the transverse extent the crack propagates in the longitudinal direction with 15 mm. The excitation is performed with a variable force that has the frequency close to the resonance for the transverse vibration modes. After the maximum amplitude is achieved, the beam vibrates free and the signal is acquired. The frequency is estimated using the PyFEST application developed by the authors, which is comprehensively described in [16]. The blue points are for the healthy beam, the orange points for the damaged beam.

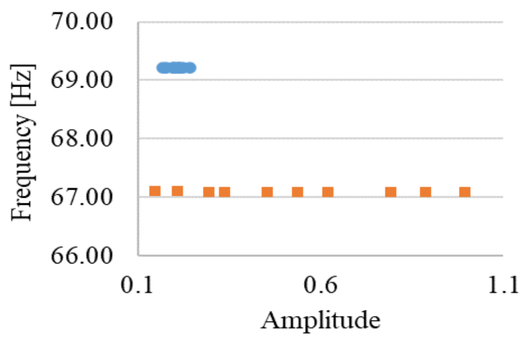

Figure 7. Frequency-amplitude values for mode 3

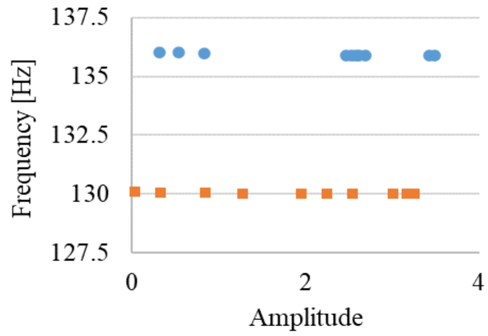

Figure 8. Frequency-amplitude values for mode 4

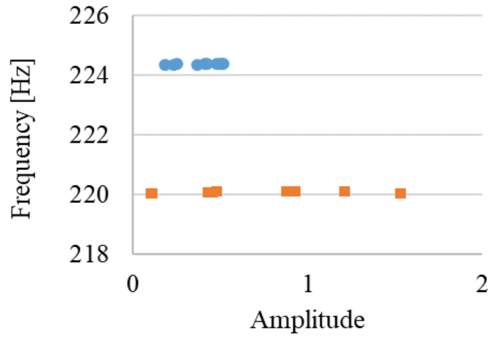

Figure 9. Frequency-amplitude values for mode 5

One can observe in Figures 7 to 9 that the frequencies are distributed on a linear and horizontal trendline, both for the healthy and damaged case. This clear results make damage assessing easy and precise.

4. CONCLUSION

The developed actuation system permits transferring energy to the beam in a controlled manner, in order to achieve significant accelerations. This ensures repeatability in estimating the natural frequencies. It was found the frequency does not change with the amplitude of the signal for a larger amplitude range, which means the beam behaves linear. If the frequencies are stable and independent of the amplitude, these are proper for assessing the structural health monitoring.

REFERENCES

[1] Debling S.W., Farar C.R., Prime M.B., Shevitz D.W., Damage identification and health monitoring of structural and mechanical system from changes in their vibration characteristics: a literature review. Report No. LA 13070-MS, Los Alamos National Laboratory, MN, 1996

[2] Sohn H., Farar C.R., Hemez F.M., Shunk D.D., Stinemates D.W., Nadler B.R., A review of structural health monitoring literature: 1996-2001, Los Alamos National Laboratory report, LA 13976-MS 2003

[3] Mesquita E., Antunes P., de Arruda Coelho F.C., Andre P.S., Arede A.J.C.D., Varum H., Global overview on advances in structural health monitoring platforms, Journal of Civil Structural Health Monitoring 6(3), 2016, pp. 461-475.

[4] Ntakpe J.L., Gillich G.R., Mituletu I.C., Praisach Z.I., Gillich N., An Accurate Frequency Estimation Algorithm with Application in Modal Analysis, Romanian Journal of Acoustics and Vibration 13(2), 2016, pp. 98-103.

[5] Au S.-K., Operational Modal Analysis. Modeling, Bayesian Inference, Uncertainty Laws, Springer Nature, Singapore, 2017.

[6] Ewins D.J., Modal Testing: Theory, Practice and Application, Research Studies Press Ltd., Baldock, 2000.

[7] Romanu B.I., Iancu V., Gillich G.R., Determination of the Natural Frequencies of Beams Using Sound Pressure, Romanian Journal of Acoustics and Vibration 10(2), 2013, pp. 93-96.

[8] Liew H.F., Syed I., Rosemizi A.R., Muzamir I. Baharuddin I. Exploring Piezoelectric for Sound Wave as Energy Harvester, Energy harvester, 105, 2017.

[9] Yang J., Wang L., Xu J., Design and Implementation of Vibration Energy Harvester Based on MSMA Cantilever Beam, Transactions on Electrical and Electronic Materials 21, 2020, p. 399–405.

[10] Gillich G.R., Tufoi M., Korka Z.I., Stanciu E., Petrica A., The Relations between Deflection, Stored Energy and Natural Frequencies, with Application in Damage Detection, Romanian Journal of Acoustics and Vibration 13(2), 2016, pp. 87-93.

[11] Tufoi M., Gillich G.R., Praisach Z.I., Ntakpe J.L., Hatiegan C., An Analysis of the Dynamic Behavior of Circular Plates from a Damage Detection Perspective, Romanian Journal of Acoustics and Vibration 11(1), 2014, pp.41-46.

[12] Gillich G.R., Maia N., Mituletu I.C., Tufoi M., Iancu V., Korka Z., A new approach for severity estimation of transversal cracks in multi-layered beams, Latin American Journal of Solids and Structures 13(8), 2016, pp. 1526-1544.

[13] Gillich G.R., Mituletu I.C., Negru I., Tufoi M., Iancu V., Muntean F., A, Method to Enhance Frequency Readability for Early Damage Detection, Journal of vibration engineering & technologies 3(5), 2015, pp. 637-652.

[14] Gillich G.R., Mituletu I.C., Praisach Z.I., Negru I., Tufoi M., Method to Enhance the Frequency Readability for Detecting Incipient Structural Damage, Iranian Journal of Science and Technology, Transactions of Mechanical Engineering 41(3), 2017, pp. 233-242.

[15] Mituletu I.C., Gillich G.R., Maia N.M.N., A method for an accurate estimation of natural frequencies using swept-sine acoustic excitation, Mechanical Systems and Signal Processing 116, 2019, pp. 693-709.

[16] Nedelcu D., Gillich G.R., A structural health monitoring Python code to detect small changes in frequencies, Mechanical Systems and Signal Processing 147, 2021, 107087.