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Design and Manufacture of Non-Contact Moving Load for Experimental Analysis of Beams

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***Abstract*—**Dynamic tests are an important step of the design of engineering structures, because the accuracy of predictions of theoretical–numerical procedures can be assessed. In experimental test of moving loads that is one of the major research topics, the load is modeled as a simple moving mass or a small vehicle. This paper deals with the applicability of Non-contact Moving Load (NML) for vibration analysis. For this purpose, an experimental set-up is designed to generate the different types of NML including constant and harmonic. The proposed method relies on pressurized air which is useful, especially when dealing with fragile or sensitive structures. To demonstrate the performance of this system, the set-up is employedfor a modal analysis of a beam and detecting crack of the beam.The obtained results indicate that the experimental set-up for NML can be an attractive alternative to the moving load problems.

***Keywords*—**Experimental analysis, Moving load,Non-contact excitation.

I. Introduction

THEneed for a better understanding of the dynamic behaviors of systems indicates the importance of the use of robust and reliable methods to determine the dynamic properties. The response of systems to dynamic load can be obtained through several theoretical and numerical approaches. Some of these approachesare involved in certain simplifications in the calculations. Also, some aspects of the system behavior cannot be predicted in totality and they are only clear through dynamic tests. Thus, experimental procedures play a fundamental rolein complementing thetheoretical–numerical procedures. Therefore, dynamic tests for the description and understanding of the dynamic behavior of a system should be carried out.

For measuring structural dynamics, several excitation techniques such as shaker or an impact hammer are widely used. Shaker attachment to the structure changes the structure's dynamics during the modal test. The application of the manual hammer is a user-dependent method [1]. In addition, excessive force created by an impact hammer may cause damage in delicate structures and deformation or mechanical failure in plastic. Also, in some applications especially in biological or medical devices, direct contact can cause contamination [2]. For determining the natural frequencies and mode shapes of beams, dynamic transverse moving loads can also be employed. Moving loads is one of the major research topics in the civil and structural engineering field and plays a significant role in the design of bridges, pavements and structures. In such matters, various parameters such as speed and type of load are important. The empirical studies of structures under moving loads are addressed in several publications such as [3]-[5]. In the experimental set-up ofcited works and similar articles, the load is modeled as a small vehicle or mass (sprung or unsprung). However, the load model that needs to be in contact with the structure may alter the dynamics of the structure and affect the accuracy of measurements.

Over time, cracks may appear in structural and mechanical components, and thus the detection of crack-like defects is an important problem. These cracks can change the dynamic properties. During the past decades, numerous research works have been carried out on cracked structures, and various crack identification techniques have been developed.Crack detection in cantilever beams was studied analytically and experimentallyby Nahvi and Jabbari [6]. The method is based on measured frequencies and mode shapes of the beam. A new approach for damage detection in beam-like structures with small cracks, without baseline modal parameters was provided by Zhong and Oyadiji [7].An experimental verification of the method in crack detection was also done in this work. Some of the other works on this subject are cited in [8]-[10]. In experimental tests performed in all the above mentioned articles, a cracked beam is excited by a hammer or shaker.The identification of cracks in beamssubjected to a concentrated moving load is a problem that should be considered due to its practical applications.Knowing thedynamic response of a crackedbeam can help engineers in the aspects of diagnosis, maintenance and retrofitting of the affected structures.Few research works, especially the experimental ones, exist on the influence of the crack on the response of beams under a moving load. Parhi&Behera [11] utilized an analytical method along with the experimental verification to investigate the vibrational behavior of a cracked beam with a moving mass. A theoretical and experimental study of the response of a damaged Euler–Bernoulli beam traversed by a moving mass presented by Bilello&Bergman [12].

The utilization of experimental noncontact excitation is useful, especially when dealing with fragile or sensitive structures [2]. There are different types of non-contacting excitation such as magnetic, acoustic and laser [13], [14]. Pneumatic excitation using an impinging air jet which was

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applied by S. Vanlanduit et al. [1] and R. Farshidi et al. [2] is one of the techniques of non-contact excitation that can also be used. In these articles, impulse force was generated and modal analysis of a cantilever beam was carried out.

The main aim of the present work is to show the applicability of Non-contact Moving Load (NML) for vibration analysis. Actually, this work is an extension of two previousworks [1], [2],and it considerably enhances the application of them.An experimental test rig was set up to generate the constant and harmonic NML by using pressurized air. The set-up is tested on several benchmark problems: a modal analysis of a beam and a detection of a crack. First, the modal frequencies of the beam were obtained experimentally. In this work, theFFT experimental method is used and the results are compared favorably with non-contact impact load. Another experimental study is carried out to show the ability of the set-up in the detection of cracks. In this study, a cracked beam is excited by NML and the signal is recorded by an accelerometer attached to the beam. There are many types of damage detection methods. One of the well-known types of wavelet transforms called Continuous Wavelet Transform (CWT) is used in this work.The obtained results in different cases indicate that the experimental set-up for NML can be an attractive alternative to the moving load problems.Compared to other moving load generation techniques, NML is simple to use, more accurate, and itneeds less operator involvement; so, errors can be minimized. The application of this method forthe identification of various damaged and undamaged structures needs more elaborate analysis, which can be pursued in future works.

II. Basic Theory and Formulation

A. Beam Equation and Boundary Conditions

Consider a thin and uniform beam of isotropic material. The dimensions have been shown in Fig. 1 in which *l*, *b* and *h* are length, width and thickness respectively. The load *P* moves at speed *c*, from left to right. The small displacement theory of thin beams is based on the Euler-Bernoulli's differential equation. Based on that, the governing equation of the problem for constant cross-section and constant mass per unit length ρ is as follows [15]:

$$EI\frac{\partial^4 v(x,t)}{\partial x^4}+\rho\frac{\partial^2 v(x,t)}{\partial t^2}+C\frac{\partial v(x,t)}{\partial t}=\delta(x-ct)P(t) \quad (1)$$

In this equation, v is the components of displacements in y direction at point x and time t. E, I, C and δ are, elastic modulus, second moment of inertia of the beam cross-section, viscous proportional damping and the Dirac delta function respectively. Boundary conditions on the beam could be defined as [15]:

x = cons.
Free (F) $\partial^2 v/\partial x^2 = \partial^3 v/\partial x^3 = 0$ (2)
Clamped (C) $v = \partial v/\partial x = 0$

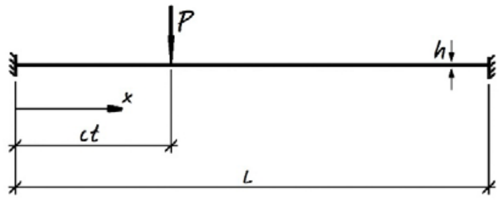

Fig. 1 Geometry of the beam

B. Cracked Beam

The detection of damages in different systems such as machining equipments, railroad rails, and bridges, where there is a concentrated load in motion, is highly important [16]. There are many methods for the detection of cracks. Some of these methods are based on the changes in natural frequencies, mode shapes and deflections. One of the powerful tools for the detection of cracks is the wavelet transform theory, which is used extensively today.

Wavelet Theory and Continuous Wavelet Transform (CWT)

The wavelet transform method is one of the signal analysis methods, with certain advantages over the other techniques of signal analysis. The most important advantage of this approach is its ability to display the local analysis of a signal (i.e., the ability to zoom in at any time or position interval). Since the existence of cracks, creates discontinuities in the responses of a structure in the defective zones, this characteristic is particularly important for the detection of cracks in structures [17].

The wavelets have a base function of ψ, which can be expressed in terms of time or position x. A set of base functions $\psi_{a,b}$ which is generated by dilation (stretch or compression) and translation (in space) of the ψ by a andb respectively is defined as follows [18]:

$$\psi_{a,b}(x)=\frac{1}{\sqrt{a}}\psi\left(\frac{x-b}{a}\right) \quad (3)$$

Wavelet transformation can be in the form of discrete or continuous, which relates function $\psi_{a,b}$to signal$f(x)$. The continuous wavelet transform of signal $f(x)$ is defined as [7]:

$$C(a,b)=\frac{1}{\sqrt{a}}\int_{-\infty}^{+\infty}f(x)\,\psi^*\left(\frac{x-b}{a}\right)dx=\int_{-\infty}^{+\infty}f(x)\,\psi_{a,b}dx \quad (4)$$

whereψ^* is the complex conjugate ofψ. Signal $f(x)$ can be reconstructed by the inverse of the continuous wavelet transform, which is expressed as follows [18]:

$$f(x)=\frac{1}{K_\psi}\int_{a=-\infty}^{+\infty}\int_{b=-\infty}^{+\infty}C(a,b)\psi_{a,b}db\frac{1}{a^2}da \quad (5)$$

In this equation, the value of constant K_ψ depends on the type of the wavelet.

III. Design and Manufacture of Non-Contact Moving Load

A. Characteristics of Pneumatic Excitation

In this section, the system employed to produce a constant and harmonic non-contact load by means of air pressure is introduced. The knowledge of using pressurized air has long played an important role in various agricultural, auto manufacturing, air transport and textile industries. For example, pressurized air has been used in vehicle door operation systems, transport systems, pneumatically driven systems, etc. Because of its cleanness, economical cost and efficiency of pneumatic devices, they are of great importance. The subject of non-contact impact excitation by means of pressurized air has been studied in [1], [2]. The compressor to produce the pressurized air, the nozzle and the air flow controller are the major sections of an air excitation system. To control the air flow, a regulator or a servo solenoid valve can be used. The advantage of the servo solenoid vale over the regulator is that it can be turned on and off more quickly. Solenoid valves have been investigated in previous articles [1], [2]. However, due to having a more adequate price and generating a more desired output, the regulator is studied in the present work.

In using non-contact methods, the correct calculation of the excitation force is important. The force generated by this system depends on different parameters such as pressure, nozzle distance, nozzle shape, etc. The amplitude of the applied force is determined as follows [19]:

$$F = \dot{m} C_m \tag{6}$$

where $\dot{m}$ is the mass flow rate, and C_m is the average velocity. By assuming the conservation of mass, the average velocity in terms of $\dot{m}$ is calculated through the following equation [2]:

$$V_{avg} = \frac{4\dot{m}}{\pi \rho_0 D_s^2} \tag{7}$$

In the above relation, ρ_0 is the ambient air density and D_s is the target diameter, which is obtained by the following equation[2]:

$$D_s = D(1 + 2.L_g.tan\alpha) \tag{8}$$

where L_g denotes the gap between the nozzle and the target, and α is the dispersion angle. To obtain force, $\dot{m}$ is required and it is related to pressure, area, input and outputmass of the convergent nozzle as mentioned in [20]. So $\dot{m}$ can be defined as follows:

$$\dot{m} = a_1 \cdot \frac{p_0}{T_0^{0.5}} \left[\frac{k}{R}\right]^{0.5} \cdot \left[\frac{m_1}{\left[1+\left(\frac{k-1}{2}\right)\cdot m_1^2\right]^{\left(\frac{\frac{k+1}{2}}{k-1}\right)}}\right] \tag{9}$$

where T_0 and P_0 are the stagnation pressure and temperature, m_1 is the incoming Mach number and k = 1.4 and R = 287.

Constant and Harmonic Load

For a constant load excitation, an open-loop control program written in the MATLAB software can be used to control the regulator's output force. To obtain a more desired output in the generation of harmonic load, a closed-loop control program along with filtering has been employed in order to eliminate the excess noises and frequencies. In the PID controller used, the feedback is taken from the pressure sensor installed on the back of the nozzle, and the sinusoidal wave (i.e., harmonic excitation) can be observed. The desired input and the pressure sensor output for the harmonic load produced with a frequency of $20/2\pi\ rad/s$ can be seen in Fig. 2. Using a load cell, the output harmonic force generated by the nozzle is shown in Fig. 3. This output force is calibrated by the load cell, based on weight, and its minimum and maximum values are 1.3 and 2.45gr, respectively.

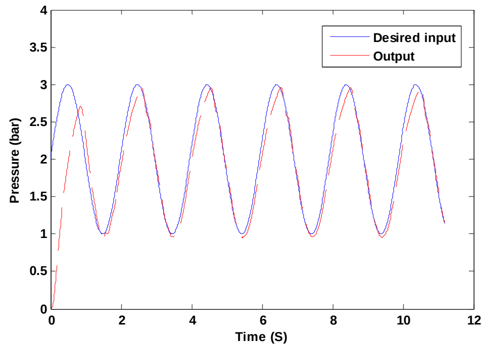

Fig. 2 The desired input and the pressure sensor output for the harmonic load

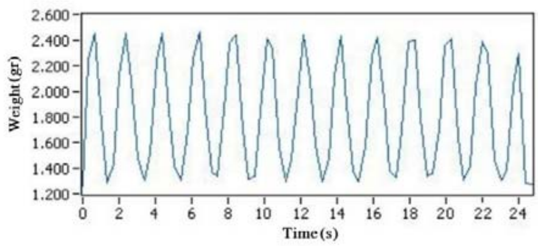

Fig. 3 The output harmonic force

In the next step, another control program is prepared, to which an input force is given as the desired parameter and then by getting a feedback from the load cell and controlling it by the PID controller, the output is corrected. This way, we will be able to produce different arbitrary forces. For example, the produced harmonic force can be observed in Fig. 4. According to the figure, a desired force with amplitude of 0-2gr and frequency of $60/2\pi\ rad/s$ has been given as input data. The phase difference observed between the desired and output force can be due to different reasons, including the damping of the device, the filter used in the load cell and the use of the controller. Fig. 5 shows the range of the pressure applied to produce the mentioned harmonic load.

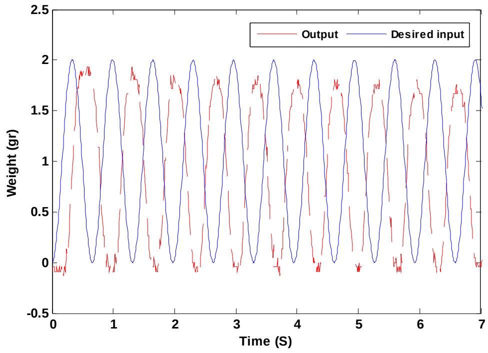

Fig. 4 The desired input and output force for the harmonic load

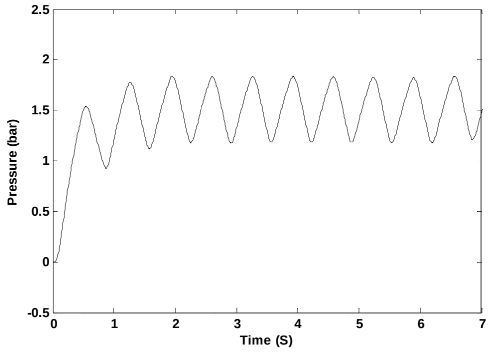

Fig. 5 The range of pressure applied to produce the harmonic load

B. Mechanism of Motion

To make the introduced pneumatic system capable of producing moving loads, a mechanism has been designed whose most important parts are the guide rods, block, belt, pulley and the motor. The nozzle and sensor introduced in the preceding section have been installed on a slider block made of polyamide, which is light and easy to fabricate. For moving the slider, an electric motor has been used. Among the different methods of transmitting the movement from the motor to the slider block, the belt and pulley mechanism has been adopted, for its effectiveness and applicability at high speeds [21]. The designing of the belt and pulley are carried out based on the motor specifications, which can be calculated by means of the equations available in [21]. The slider block is installed on two steel guide rods and moved by the belt, and considering the used motor, it can move at any speed. The significant parameter that affects the movement and should be scrutinized is the friction between the guide rods and the slider. The schematic of the apparatus and the movement mechanism is shown in Fig. 6.

C. Experimental Set-up

Based on the items explained in the previous sections, the moving part of the device can be designed and fabricated at any size and dimension. In order to perform the laboratory tests, a setup was prepared, which can be seen in Fig. 7, and the properties of related components are listed in Table I. The length of the considered guide rods is 39.5cm, and the motor can produce a maximum speed of 333 Hz through the relevant driver.

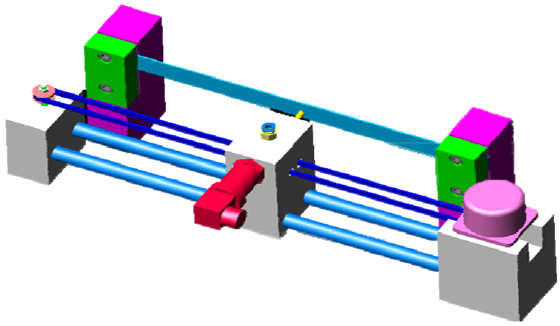

Fig. 6 The schematic of experimental set-up of non-contact moving load

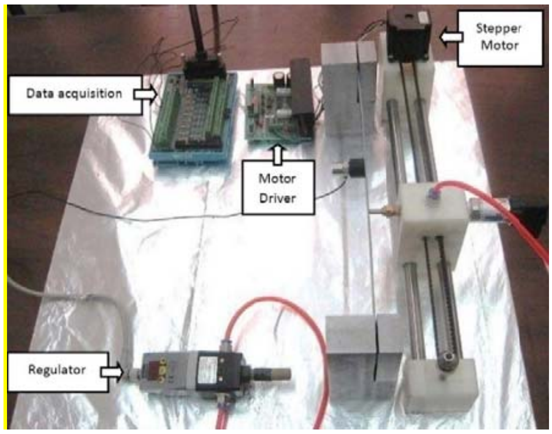

Fig. 7 (a) Experimental set-up

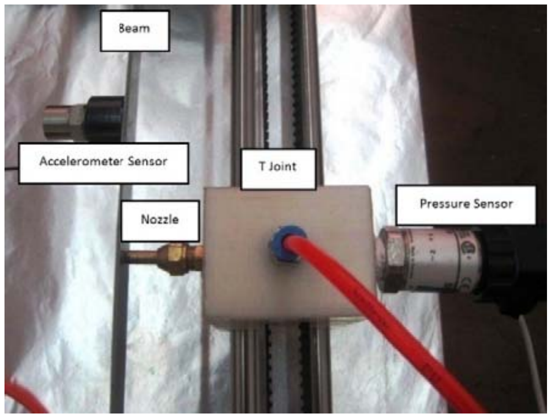

Fig. 7 (b) Close-up of the thin beam, nozzle and sensors

TABLE I
PROPERTIES OF RELATED COMPONENTS

Components	Type
Pressure Sensor	WIKA
Regulator	Parker (P3HPA12AD2VD1A)
Motor driver	V 4.3
Accelerometer	B & K, 4366
Power amplifier	B & K, 2635
Data acquisition	Symphonie 01db

IV. Experimental Results and Discussions

To validate the experimental setup devised to produce the non-contact moving load, two case studies applied on a beam have been considered.

A. Beam Experiment

In this section, the natural frequencies of a beam made of stainless steel 420 with dimensions of 385*20*1.5 mm^3, on which a constant moving load is applied through a pressure of 5 bars at a speed of 14.22 cm/s, have been calculated. To compare the frequencies obtained by the moving load, the considered beam has also been excited by impact load 2ms with a pressure of 4 bars. The vibration signal generated has been sensed via sensor and then amplified by power amplifier. The amplified signal is converted to digital numeric values by a data acquisition device. The numeric values are then manipulated by a computer and the natural frequencies are computed via the FFT.

The calculation of the first five natural frequencies for a cantilever beam is performed using NML, as shown in Fig. 8. The obtained result through non-contact impact excitation is depicted in Fig. 9. Comparison between natural frequencies by NML and impact results is reported in Table II. As can be seen, the maximum deviation is about 5.7%.

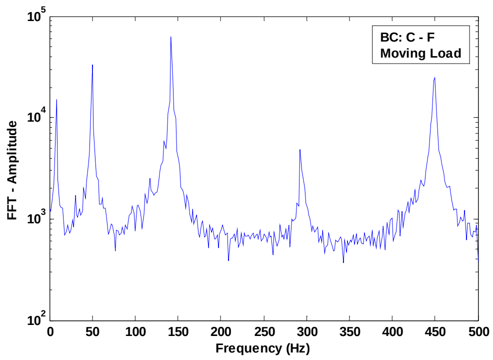

Fig. 8 The first five natural frequencies of the beam

TABLE II
Natural Frequencies of the Beam Experiments with Non-Contact Impact and Moving Load – B.C: C – F

Mode number	freq-impact load	freq-moving load	dev-in%
1	8.361	8.361	0%
2	50.17	50.17	0%
3	143.8	142.1	-1.18%
4	275.9	292.6	5.7%
5	448.2	449.8	0.335%

B. Experimental Test of the Proposed Set-up for Crack Detection

In this section, damage in a cracked beam is detected by exciting the beam with a constant moving load. A stainless steel 420 fixed-fixed beam with dimensions of 375*20*1.5 mm^3 was used, and the accelerometer sensor is positioned in the middle of it. The load was kept constant at 5 bars and the speed was 6.4 cm/s. A damage detection method based on the CWT is applied to analyze in a cracked beam. Crack location can be detected by peaks in the CWT coefficient of data using Gaussian4 Wavelet.

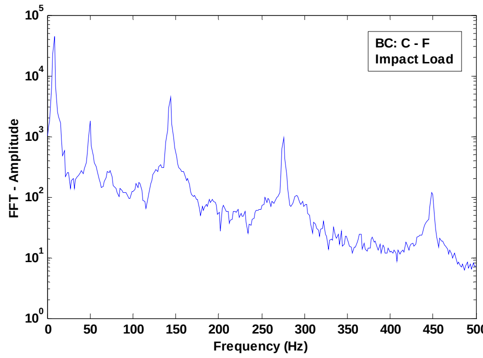

Fig. 9 The first five natural frequencies of the beam

A damage was created at 11.2cm from the left support of the beam. Fig.10 shows result of CWT coefficient of the displacement. One peak can be clearly seen that is the exact location of the crack.

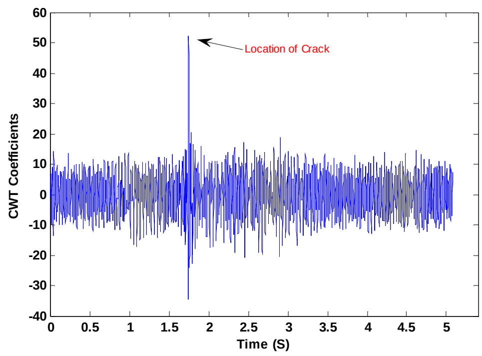

Fig. 10 CWT coefficient of response of beam – single crack

V. Concluding Remarks and Recommendations

In this study, Non-contact Moving Load (NML) using pressurized air is successfully applied to obtain the dynamic characteristic of beam and detection of a crack. It is shown that NML is a very powerful tool to excite a structure and it can be an attractive alternative to the moving load problems. For the dynamic analysis, frequency, one of the important quantities, was calculated using FFT experimental method and the results were compared to non-contact impact load. Crack detection in a beam subjected to moving load using Continuous Wavelet Transform (CWT) is conducted in which the moving load is modeled as NML instead of moving a small vehicle or mass. According to the result of CWT and peak, the exact location of the crack is detected. There is an obvious necessity to develop simple and accurate methods. It can be inferred that in comparison to other methods the NML has several advantages, for example it is inexpensive, controlled and automated so that operator differences can be avoided.

Further studies on the subject of NMLs are important from different aspects, and the following recommendations can be presented in this regard:

1) Obtaining a variety of responses based on the type of system and performing the necessary analysis.
2) Accommodating the model with the practical bridge-vehicle systems; for example, using beams with different materials and shapes (curved, skew).
3) Using other experimental models such as plates and shells and performing tests on biological tissues.
4) Increasing the degrees of freedom of the designed system to enable its movement in different directions.

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