An Experimental Setup for the Introduction of High School and Undergraduate Students to Vibration and Mechatronics Topics

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Abstract. The paper presents an experimental setup suited to a starting introduction of high school and undergraduate students to basic topics in vibrations, data acquisition and signal processing. The setup is portable, based on low-cost gear motor, sensors and control electronics, with 3D printed custom parts, and it has been used in different education contexts. Its specification, realization, features and usage are discussed in the paper.

Keywords: Mechanical Vibrations, Mechatronic Systems, High School and Undergraduate Students; Engineering Education.

1 Introduction

The possibility to experiment and to perceive the behavior of simple dynamic systems and to correlate physical objects and mathematical models by means of hands-on experiences is a key aspect of the complex learning process that is required from engineering students.

At the same time, the availability of a setup to be used to provide high school students with a "touch and feel" experience on relevant engineering topics – mechanical and mechatronics systems, vibrations, signal acquisition and processing – may be very helpful in their orientation process toward the choice of University programs.

This paper presents an example of such a system, which is now used at our University for both previous purposes. The idea of stimulating student curiosity and learning by vibration lab experiences is not new [1-4], and currently there is a growing interest in the use of virtual lab experiences [5-7].

Although virtual lab tools are very convenient from several points of view, in particular cost, flexibility, possibility of usage by unlimited number of students, intrinsic safety, we deem important, especially in introductory lectures, to have students perceive the physics – motion, noise – of vibrations rather than only see computer animations and plots as obtained in simulations. Starting from these considerations and according to the expected audience for the presented experimental setup, the proposed solution is characterized by specific features, as discussed in Section 2. Then, the consequent design is outlined in Section 3. Section 4 presents examples of use and, finally, Section 5

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discusses how to relate experiments to topic discussion for both high school and undergraduate engineering students.

2 Purposes and general design guidelines of the experimental setup

The device has been designed with two main demonstration purposes, tailored to different educational contexts.

One application goal has been the presentation of topics related to mechanical and mechatronics engineering to high school students of the two last years, in Italy, twelfth and thirteenth years of school, in order to show them interesting aspects of engineering problems and stimulate their curiosity to such fields. Regarding this first application, several requirement features have been considered in system design, starting from practical ones, to the final objectives of its usage:

- ease of transportation, complete self-containment, in order to be able to use it directly in high school classes and labs, without the need of specific instruments or setup;
- simple and easy to explain basic functions of the device, presented physical phenomena, and expected results; the audience being capable to get, at least at a descriptive level without the need of complex math tools such as differential equations, an insight of the vibration physics and of the engineering tools used to generate and measure them;
- possibility to connect experiment fruition with student experiences carried out both in learning and personal activities, for example, by associating vibration phenomena measurement and generation with sound (music) generation (speakers) and listening (ears);
- possibility to perceive experiment events both in a physical direct way (vision, noise), and at a more precise, quantitative, instrumental level, in order to be able to relate different aspects and complexities of the device and of the studied phenomena;
- possibility to suggest that engineering is a path to educate people to deal with complex problems, connected to the everyday life, with quantitative methods based on scientific and technological knowledge.

The second aim of the device is an aid for the presentation of topics in mechanical vibrations within courses in mechanical engineering degrees at undergraduate level. To this purpose, the following guidelines have been taken into account in the definition and design of the device:

- similarly to previous case, ease of transportation and setup, for in classroom use;
- system completeness from a mechatronic point of view: thanks to the presence of electric actuation, mechanical transmission, vibrating link, sensor, acquisition system, power electronics the system comprises almost all elements, except an internal control loop (which we plan to include in future developments), of a mechatronic device;
- possibility to correlate physical phenomena to their quantitative measurement and to display them in real time, both in time domain and frequency domain.

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- possibility to associate the experimental setup with the results obtained by limited complexity mathematical models, such as 1 d.o.f. lumped parameters vibrations, so as to discuss also modelling and analysis topics of mechanical vibrations

Beyond previous guidelines, the following general criteria have also been adopted in devising the system:

- use of cheap off-the-shelf components (control and electronics, sensors, electric gearmotor), within the range of 40-50€ each;
- all custom design parts can be built in PLA, with additive manufacturing production by a desktop 3D printer;
- the system can be easily assembled, dismounted, repaired, by using only screwdrivers, wrenches and pliers.

3 Description of the system

3.1 Hardware configuration

The system functional scheme and actual prototype are depicted in Fig. 1, while Fig. 2, complemented by the BOM in Table 1, shows and exploded view of the 3D CAD assembly from which stl files of 3D printed parts have been generated. The key component of the system is a simply supported flexible beam, made by an aluminium beam with size 400(L)×20(W)×1.7(H) mm. The physical excitation to the flexible beam is provided by a slider-crank mechanism driven by a gearmotor (model MFA RE 975D41). The slider body moves alternatively one of the beam supports in the vertical direction with a stroke of 3 mm. Except for the flexible beam, all the structural components have been designed and realized in PLA by 3D printing. The ratio between crank and rod lengths is sufficiently high to guarantee than only the first harmonic of the slider motion is relevant as exciting signal. The gearmotor reduction ratio is 4:1 and at 12V the output shaft has a no load speed of 1750rpm; a slight overload in the input voltage, acceptable for short times, allows the gearmotor to reach 2400rpm, guaranteeing an excitation signal in the range 0-40Hz.
Two MEMS accelerometers (model Adafruit ADXL326) with a ±16g range are placed on the beam, one located on the support driven by the slider (base accelerometer), to read the input motion, the second on the center of the beam (center accelerometer) to measure the elastic oscillations. Three Velcro fasteners are placed on the beam, so that up to three optional lumped masses can be added to the flexible body in order to change system natural frequencies. A proximity sensor (model E2B-S08KN04-WP-B1 2M) is used to measures the gearmotor rotational speed.

The gearmotor is driven by a PWM regulator (model Yunique Italia 13kHz PWM DC regulator), which, in turn, is driven by a 0-5 V analog input.

After some basic conditioning, all analog and digital signals are conveyed to a NI USB 6211 Multifunction I/O Device. Such a device has been used as it was already available, but for purposes and specifications of the present application a much cheaper DAC could be used (e.g. NI USB-6001 Low-Cost DAQ USB Device). The USB 6211 is also used to generate the 0-5 V analog output that control the PWM regulator.

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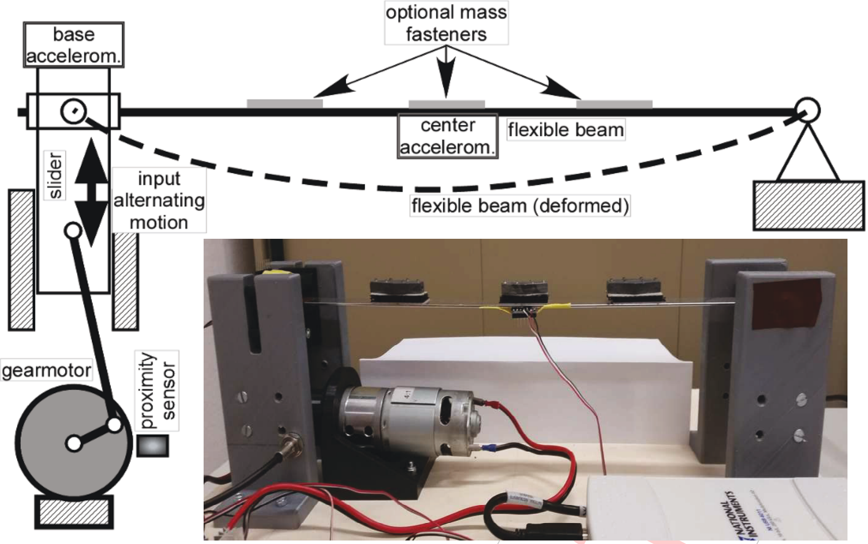

Fig. 1. System conceptual scheme and picture.

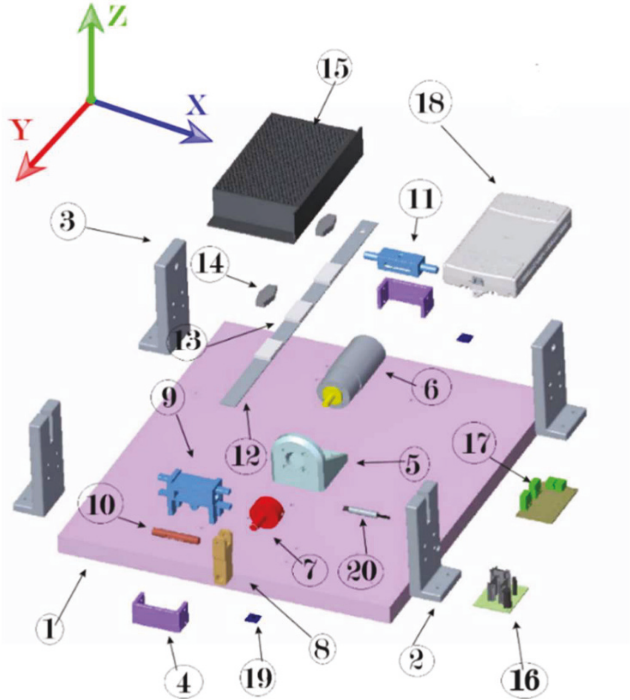

Fig. 2. Exploded view of the system.

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Table 1. Bill of material.

Component	Component
1. base frame	2. shaking joint support (2)
3. fixed joint support (2)	4. reinforcement (2)
5. gearmotor support	6. gearmotor
7. crank	8. rod
9. slider	10. slider-pin joint shaft
11. fixed joint shaft	12. flexible beam
13. optional mass fastener	14. optional mass (2)
15. power supply	16. PWM motor controller
17. accelerometer power supply	18. DAQ device

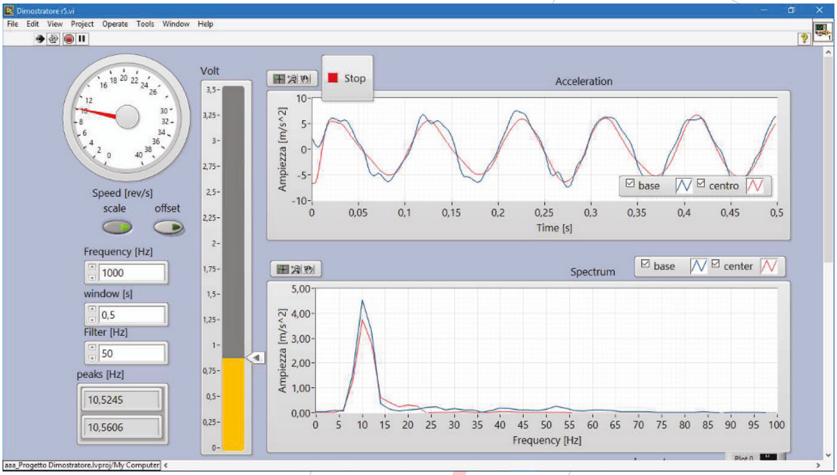

Fig. 3. Front panel of the VI.

3.2 Software configuration

According to the selected hardware configuration, the system software has been developed within the NI LabVIEW environment. The front panel of the LabVIEW virtual instrument (Fig. 3) shows:

- the vertical accelerations registered by base (blue curve) and center (red curve) sensors w.r.t. time (upper right plot);
- the real-time fast Fourier transforms of acceleration signals (lower right plot);
- the gearmotor speed control signal (central vertical slider), i.e. the voltage input to the PWM controller which drives the motor;
- the gearmotor speed measurement (rev/s, upper left clock instrument);
- auxiliary controls: the cutoff frequency of a low-pass filter to eliminate high frequency noise, sampling window length and sampling frequency.

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Moreover, the front panel contains a supplementary plot, shown in Fig. 4, which presents peak values measured by center accelerometer as a function of peak frequency.

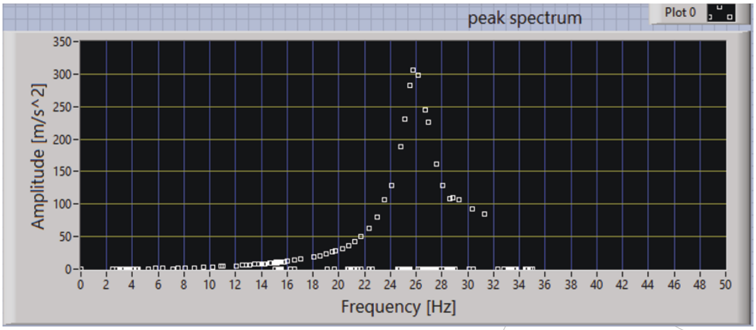

Fig. 4. Front panel of the VI: peak spectrum.

4 Sample result presentation and discussion

The system can be used to show several aspects of mechanical vibrations, data acquisition and filtering and to present acquired vibration data both in time and frequency response plots.

In static conditions, when the input frequency is well below the system first natural frequency, the amplitude of the motion of the center accelerometer is half the amplitude of the base (input) support, as, kinematically, the aluminium beam is a lever with one fixed extreme, the other extreme driven by the slider crank and the midpoint as a measured point. Then, in dynamic conditions, situation changes, also thanks to the low damping and friction in the flexible beam, and the system can be used to demonstrate clearly the physical meaning of the resonance phenomenon. Fig. 5 shows a photo of the beam vibrating at resonance, with a natural frequency around 16 Hz in the case with two added masses; the amplitude of the center motion is an order of magnitude larger than that of the exciting motion of the left support, whose amplitude is 1.5mm . The LabVIEW instrument in Fig. 6-a confirms the physical perception with time and frequency plots of base and center accelerations, in which center acceleration peak values (red curves) are more than tenfold base acceleration values (blue curves) and a careful look to the time plot shows that the phase between the two signals is approximately 90°, thus indicating resonance conditions.

Fig. 6-b and Fig. 6-c show the system behavior at excitation frequencies lower and higher than the natural frequency: input-output signal phases clearly evidence the subcritical (0° phase) and supercritical (180° phase) working conditions.

Finally, Fig. 6-d shows the acceleration of the beam center acquired in case of free motion, generated by displacing and releasing the aluminium beam center with the slider crank mechanism not moving, from which the system (first) natural frequency is obtained. The peak in the FFT plot indicates about 26 Hz, which is the natural frequency of the supported aluminium beam without any optional mass. The decaying ratio in the

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time-acceleration plot could also be used to estimate the damping ratio of the system. The vertical slider in Virtual Instrument control panel (Fig. 3) allows to control the voltage input to the gearmotor so that:

- it is possible to control the working speed of the system, thereby showing its behavior in the different conditions (subcritical, resonance, hypercritical)
- by slowly increasing motor speed to sweep input frequencies and by making use of the capacity of the Virtual Instrument of recording FFT peak values as a function of input speed, the VI is capable of building an experimental frequency response and then plot it as shown in Fig. 4: such a plot is very useful for further topic discussion, especially with University level students.

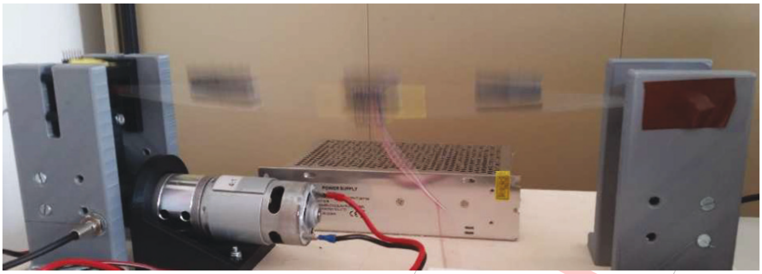

Fig. 5. Forced vibration of flexible beam - input frequency close to resonance frequency.

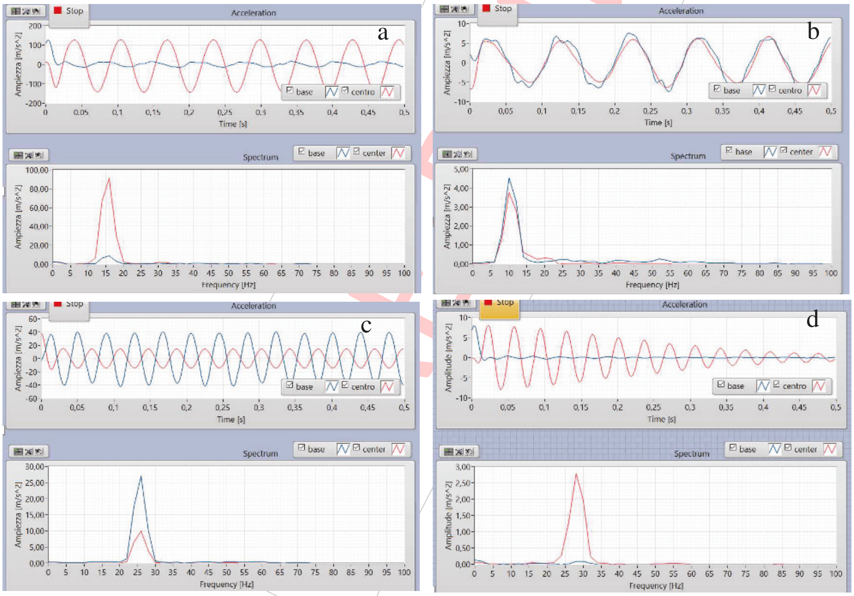

Fig. 6. Examples of working condition outputs: a) forced motion: input frequency close to natural frequency; b) forced motion: input frequency well below the natural frequency; c) forced motion: input frequency over the natural frequency; d) free response (natural frequency determination).

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5 Usage tracks and conclusions

Due to its apparently simple design and way of functioning, complemented by engineering significance of the system functions in term of system dynamics, mechatronic components, data acquisition and real time elaboration, the system can be used in different ways, with different levels of complexity and completeness of presentation of the relevant topics.

In a high school context, the main goal is to provide students with “a feel” of mechanical vibration essential elements (natural frequency, resonance, high frequency signal cutting), along with introducing them to the concepts of measuring and acquiring signals, analog and digital quantities and signal analysis and reporting. In this context, the presentation of the system characteristics and of its use and results can be organized as follows:

- system description:
  - the anatomy of the system is first presented, starting from the beam and by showing its free vibrations, with different mass distributions (additional weights), initially without the LabVIEW acquisition and plots, then evidencing the physical meaning of the natural frequency;
  - then, all other key components of the system can be illustrated and their main features and function discussed, without recurring to mathematical details, but adopting a physical point of view for the explanations, possibly recurring to examples of similar function/components encountered in normal life;
- presentation of the forced motion, discussing qualitatively the relation of input velocity with natural frequency and oscillations amplitude; students are usually rather amazed at seeing the flexible beam vibrating at resonance:
  - at low input speed, the static behavior of the beam as a lever can be easily discussed and comprehended by the students; both time and frequency plots can be described qualitatively, without recurring to precise math definitions
  - once the students are familiar with the system characteristics and functions, the system can be put in resonance conditions, and students can perceive through a sensorial experience (visual, auditive), not easily obtained by “virtual experiences”, the meaning of mechanical resonance and of its potentially dangerous effects;
  - driving the system at input frequencies greater than its (first) natural frequency allows to introduce the idea of frequency response and of output signal amplitude reduction; this is the least intuitive part of the presentation, as students usually do not have preceding experiences of such an effect: the reference to sound generation and hearing experiences, both in humans and animals (ultrasounds) may be helpful in the discussion;
- finally, a more detailed presentation of the plots, the way they are obtained, and more in depth explanation of the concept of frequency response, low and high frequencies, and their dependency on the natural frequency can give the students a better hint on the complexity of actual engineering themes.

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When used in an undergraduate course in Mechanics of machines or introductory Vibrations, for example within a Mechanical Engineering degree, the system can be very helpful to show the strong relation between theory and physical phenomena, so the suggestion is to use the setup as follows:

- first present the introductory theory on mechanical vibrations as usual (one d.o.f. mass-spring-damper dynamic equation, free motion and natural frequency and damping coefficient, forced motion and frequency response, resonance, low and high frequency responses);
- then, take the setup to classroom and:
  - describe it and its components in a way similar to the high-school presentation, but with a much greater attention to engineering and design features and details
  - relevant concepts on the mechatronic features (motor control, accelerometer characteristics), data acquisition (sampling rate, signal filtering) and presentation (time and frequency plots, Fourier analysis) can be discussed with a level of details dependent on the available time and students' background
  - after such presentation, a first set of system runs at low input frequency can be used to get the student acquainted to the "living" features of the system and to begin to correlate abstract concepts presented in theory discussion to perceived physical phenomena
  - drive the system to resonance conditions and discuss its behavior comparing it with analytical results both for undamped and damped systems; similarly go to hypercritical conditions and discuss them
- once the students have experienced the main effects evidenced by the system, a final, more refined discussion about physical, engineering and modelling aspects can be carried out, again, with a level of details dependent on the available time and students' background.

The system has already been used in both contexts with very good appreciation by both high school and engineering students.

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