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ADAPTATION OF AN INDUSTRIAL APPLICATION FOR AN INSTRUCTIONAL LABORATORY IN MECHANICAL VIBRATIONS

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ABSTRACT

Extensive theoretical treatment is given to damping as the process of energy dissipation during mechanical vibration. The challenge in the classroom is to adequately convey this concept and extend it by teaching students practical applications in engineering analysis and design. Students are motivated by real-world problems; applying these types of problems with strong instructional classroom content significantly enhances the learning environment.

This paper proposes the adaptation of an actual research project to a simple, yet innovative, mechanical vibrations laboratory. The adapted project involves an ongoing effort at the Los Alamos National Laboratory to investigate damping factors of various alloys used in military tank munitions. The kinetic-energy penetrators used in these tank rounds are cylindrical in shape and are a major class of weapons designed to defeat heavy armor. Unwanted transverse oscillations of these penetrators degrade the accuracy of the rounds and may lead to glancing blows off the target.

The process of measuring damping in long rod penetrators lends itself to a number of key teaching points for engineering students in a vibrations course. Experimental work can easily reinforce a variety of methods to measure damping including the logarithmic decrement method, the bandwidth method using half power points, or measurements taken from a real axis plot of the transfer function. The simple shape of the penetrators allows for the comparison of experimental calculations and theoretical predictions in finding the natural frequencies. Differences based on a variety of end conditions and constraints may also be explored. The lab is particularly well-suited to modal analysis and gives the students a better understanding of mode shapes and associated concepts. Adapted research projects such as this can prove to be highly successful in emphasising the relevance and applicability of the introductory concepts of mechanical vibrations to real engineering problems.

INTRODUCTION

Engineering students learn best those concepts which they can relate to practical applications. Carried one step further, cadets at the United States Military Academy (USMA) learn best those things which they can relate directly to their chosen profession. This premise serves as the motivation in looking for ways to adapt industrial applications to instructional laboratories. The purpose of this paper is to describe one proposed innovative approach for an undergraduate vibrations course. Specifically, a research project is described which can be adapted for use as several possible lab exercises and demonstrations.

THE RESEARCH PROJECT

Kinetic-energy penetrators are a type of military tank munition used to defeat armor. These high-velocity, solid cylindrically-shaped projectiles are made of various dense, hard alloys to achieve maximum penetration characteristics. Typically, they are fin-stabilized and surrounded by a sabot which is discarded once the tank round leaves the gun tube. A schematic is shown in figure 1.

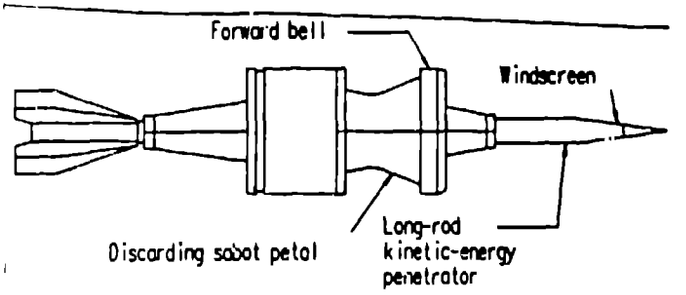

Figure 1. Kinetic-Energy Penetrator Round.

Gun-launched kinetic-energy penetrators need a sufficiently high length-to-diameter ratio to penetrate modern armor steel configurations. They experience a severe environment upon launch. Lateral loads are imparted on the rounds due to imperfections in the gun tube and tube droop. Once the rounds leave the tube, the long-rod penetrators are subjected to further excitations during sabot discard and flight. These lateral loads cause transverse oscillation of the penetrators.

The transverse vibrations of these rods affect the accuracy of the rounds and are very undesirable. Even slight bending may lead to yaw during flight and glancing blows off the target. The author has been involved in research at the Los Alamos National Laboratory to attain damping levels of various composite alloys used in manufacturing these rounds. The aim is to develop rounds that not only exhibit superior penetration characteristics but also have a sufficiently high level of damping to quickly reduce unwanted transverse vibrations.

LABORATORY EXERCISES

Overview

The project described above obviously has important military applications. In conducting the research, however, it was realized how easily it could be adapted to laboratory exercises and classroom demonstrations. This fact presented an excellent opportunity since the Department of Civil & Mechanical Engineering at USMA is acquiring a Bruel and Kjaer Model 2034 Signal Analyzer with accessories as part of a laboratory upgrade and modernization program. In addition, a microcomputer hardware package along with PC Modal Analysis software is being purchased. In anticipation of the arrival of this new signal analysis equipment, laboratory exercises, as described in this paper, are being planned and will be integrated into the course of instruction.

erimental Method and Equipment

The test specimens used in the research project were actual netrator rods not yet machined into final shape. The dimensions re close to those of the final munitions, approximately one inch diameter and thirty inches in length. Test specimens with simple lindrical shapes could be easily fabricated for typical educational se.

The actual flight of the long rod penetrators to the target is constrained. Hence, testing the rods with free-free end conditions uld be most appropriate but difficult to replicate in a lab. To and approach these end conditions, the rods in the actual search project were suspended from one end using various means cluding aircraft control cable and filament line. A similar setup n be used in an instructional lab. The learning point for students to minimize the constraints on transverse vibrations of the rods, reby best duplicating the actual flight of the penetrators.

Data analysis for the research was done with an Applied gnal Analysis Package (ASAP) on a Masscomp computer system. SAP was developed by Applied Technology Associates, Inc. of huquerque, New Mexico. Data was collected with light weight deveo Model 2250A accelerometers and PCB Model 208 force nsducers on the input. For transient tests, 120,000 digitized data ints were collected at a rate of 6,000 to 8,000 samples per second. ls accounted for a total data stream of about 15 to 20 seconds d allowed for frequency analysis up to at least 1,500 Hertz. For aker (forced motion) tests, 300,000 data points were sampled at a e of 6,000 to 8,000 points per second and averaged at 32,768 nt intervals. Analysis in an instructional lab could be accomshed with any type of data acquisition package coupled with a iety of signal analysis systems. The laboratory configuration is ondary to the experience the student gains in applying classroom ory to measuring actual parameters of a mechanical system.

Three separate methods to experimentally determine the nping of the penetrators are described in the following sections.

Logarithmic Decrement Method: The logarithmic decrement thod is a primary means of measuring system damping using the nsient response of an underdamped system. Plotting the time ay of the exponentially decaying oscillations, the logarithmic rement, δ, is defined as

$$\delta = \frac{1}{n} \ln \left(\frac{x_0}{x_n}\right) \tag{1}$$

re x_0 and x_n are the amplitudes of the zeroth and nth cycles, pectively. By taking a ratio of successive cycles, a relationship be developed between the logarithmic decrement and the damp- factor of the system, ζ.[1]

$$\zeta = \frac{\delta}{\sqrt{(2\pi)^2 + \delta^2}} \tag{2}$$

method of excitation of the specimens for the instructional lab uld be using a transient impact hammer test with an accelerom- mounted on the suspended rod. A typical plot of the time ay response is shown in figure 2.

As a logical extension of the lab, students can plot the freency spectrum of the rod to determine the natural frequencies of first several modes. The time decay curve from the impact ham- test would contain a mixture of modes for the continuous rod. choosing cutoff frequencies from the spectrum, the time decay can be low-and high-pass filtered to determine the damping ciated which each of the first several modes.

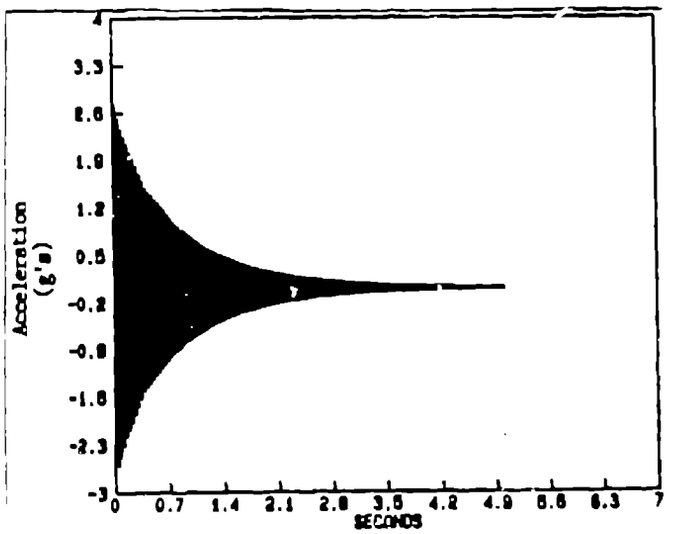

Figure 2. Typical Time Decay of Penetrator Oscillations.

Further educational benefit is derived by having students calculate the percentage of oscillation decay which occurs during the time of flight. The velocity of the rounds are typically about 1 to 2 kilometers per second. Target engagements usually occur at ranges between 1.5 and 4 kilometers. Hence, a two second flight time is a good starting value. Students predict the percentage of decay after experimentally determining the log decrement and calculating the number of cycles the round experiences during flight.

$$\delta = \frac{1}{n} \ln \left(\frac{x_0}{x_n}\right) \tag{3}$$

$$\% \text{ reduction} = (1-a)\ 100\% \tag{4}$$

Results from the actual research found damping to be primarily a material property and apparently independent of frequency. For most materials, the majority of the oscillations of the higher modes (>90%) had decayed after two seconds.

Bandwidth Method: A forced response of the penetrators using either an impact hammer input or a vibration shaker with a random signal input allows experimental determination of damping using the bandwidth method. Students use a plot of the transfer function in the frequency domain to determine the natural frequency and half-power points for each of the first several modes of the penetrators (See figure 3).[3]

$$\zeta = \frac{1}{2}\left(\frac{\omega_2 - \omega_1}{\omega_n}\right) \tag{5}$$

where ω_n, ω_1, and ω_2, are the natural and half-power frequencies for each of the resonant peaks of the transfer function plot.

This experiment allows the students to apply a second method of determining the equivalent viscous damping factor for a vibrating system.

Real Axis Transfer Function Plot: A third method of experimentally measuring the damping can be demonstrated by plotting only the real part of the transfer function in the frequency domain.[3]

$$\text{Transfer Function} = \frac{\text{Output}}{\text{Input}} = \frac{1}{(1-r^2) + i\,(2\zeta r)} \tag{6}$$

$$\text{Real Part of Transfer Function} = \frac{1 - r^2}{(1-r^2)^2 + (2\zeta r)^2} \tag{7}$$

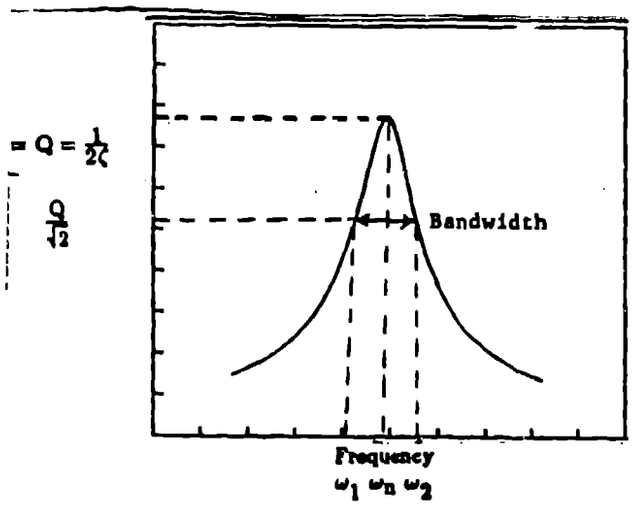

Figure 3. Bandwidth Method

retically, one may now take the derivative of the real part of ransfer function with respect to the frequency ratio, r, and set al to zero. The result is two extreme values of r, one mum and one minimum, for each resonant peak.

$$r = \sqrt{1 + 2\zeta} \qquad\qquad r = \sqrt{1 - 2\zeta} \tag{8}$$

ising that r is simply the ratio of the frequencies at each of extremes, ω_B and ω_A, with respect to the natural frequency,

$$\frac{\omega_A}{\omega_n} = \sqrt{1 - 2\zeta} \qquad\qquad \frac{\omega_B}{\omega_n} = \sqrt{1 + 2\zeta} \tag{9}$$

natural frequency, ω_n, can be eliminated from both expressions llow one to relate ω_A and ω_B to the damping factor.

$$\zeta = \frac{1}{2}\,\frac{\left(\frac{\omega_B}{\omega_A}\right)^2 - 1}{\left(\frac{\omega_B}{\omega_A}\right)^2 + 1} \tag{10}$$

Other Extensions of the Lab: Once the equivalent damping or has been calculated using each of the three methods described ve, a comparison can be made along with a discussion of the itations of each method. In the actual research project, the ults from the different tests were fairly consistent.

The simple cylindrical shape of the penetrator rods or ivalent lab specimens allows for a closed form solution of the ural frequencies.[5]

$$\omega_i = \frac{\lambda_i^2}{l^2}\sqrt{\frac{EI}{\rho A}}$$

$$\text{where } \lambda_i = 4.73,\ 7.853,\ 10.996, \text{ etc.} \tag{11}$$

ese can then easily be compared to the experimental values taken m the plot of the frequency spectrum, and any discrepancies can explained (the effect of damping, nonlinearities, boundary condi- ns, etc.).

The theoretical mode shapes may also be solved exactly. By ploying any number of modal analysis software packages, these o may be compared to the experimental results. By visualizing the mode shapes, students better understand the significance of their mathematical calculations.

CONCLUSION

Computers and modern vibration analysis equipment have changed the way we teach engineers. We owe it to our students to introduce them to this equipment during their undergraduate education. The challenge is to do so in a manner which adequately conveys concepts from the classroom to practical applications. All too often our engineering students get wrapped up in the instrumentation and technical nature of laboratory equipment and hence fail to adequately relate the theoretical basis of their classroom experience to real-world problem solving. Beyond that, there is a tendency in labs to only learn how to measure damping, as opposed to also learning why damping is important and what are the effects of damping.

The description of the instructional laboratory in this paper is an attempt by the author to offer one way of bridging this gap. The ability to relate the topics the student is learning to a current research project emphasizes the importance of the material and significantly enhances learning. The students are exposed to both analytical and experimental techniques of vibrations testing at a level which is consistent with an undergraduate vibrations course.

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