Proceedings of
2001 ASME International Mechanical Engineering Congress and Exposition
November 11–16, 2001, New York, NY

SEE LABS RUN: A DESIGN-ORIENTED LABORATORY FOR TEACHING DYNAMIC SYSTEMS

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ABSTRACT

Design engineers must have an intuitive understanding of the behavior of dynamic systems. Teaching the mathematical tools for analyzing and designing dynamic systems presents the challenge of maintaining the connection to the physical world. This paper describes a novel sequence of undergraduate laboratory experiments that illustrates basic concepts in dynamic system analysis and motivates their use as design tools. The approach taken connects the laboratory sessions with a *design goal* for a dynamic mechanical device that the students can see, touch, re-design and modify. The device used is called the "Dashpod," a simple, pneumatically-actuated, self-stabilizing, dynamic hopping machine. Through coordinated laboratory sessions and lectures, students used classroom concepts to improve the machine's hopping motion. This paper describes the purpose and design of the Dashpod, presents examples of how it was integrated into laboratory exercises and shows results of student evaluations.

1. INTRODUCTION

The design of any mechanical system requires a basic intuitive understanding of its dynamic behavior. Mechanical engineers must be familiar with fundamental concepts such as time constants, stability and resonance in order to fully realize their designs. However, teaching the mathematical principles used to analyze and design dynamic systems presents the challenge of connecting the theory to physical reality. At first encounter, descriptions of homogeneous solutions, complex eigenvalues and Bode plots can seem overly abstract to students. Moreover, these mathematical concepts must be well motivated and taught as *design tools*, along with their potential and limitations, rather than as intangible equations and formulas.

Teaching aids such as in-class demonstrations, computer simulations [Lee et al., 1998; Bonert, 1989]] and well-crafted problem sets help bridge this gap between theory and physical reality. Laboratory exercises further present the opportunity for students to get first-hand interactive experience with the concepts explained in the classroom, but we argue that laboratory sessions must go beyond simple demonstrations of

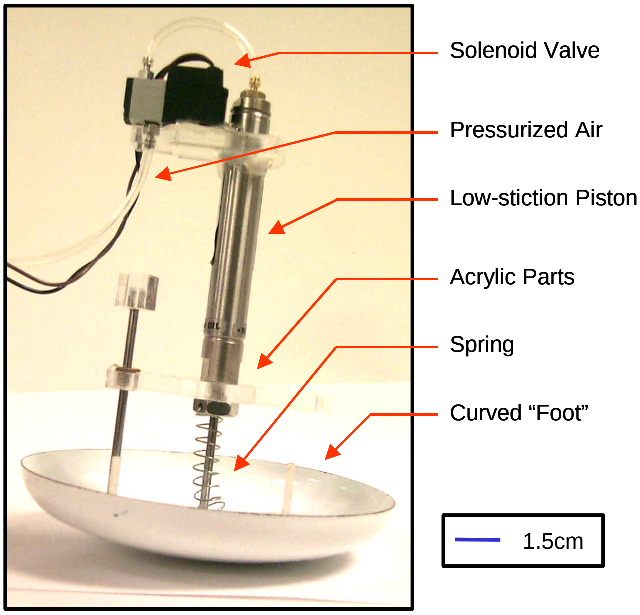

Figure 1. The Dashpod: a simple, dynamic hopping machine for undergraduate dynamic system laboratories.

these concepts [see also Everett, 1997].

For example, Richard et al. [2000] introduced the "Haptic Paddle," a single-axis force-feedback joystick for undergraduate dynamic system laboratories. The Haptic Paddle was used not only for force-feedback simulations of dynamic phenomena, but also as a mechanical system with which class concepts such as inertia and motor equations were demonstrated. Students assembled the joystick from a kit and used class concepts to create a predictive model of the device's dynamic behavior. This idea of centering the theme of a series of laboratories around a physical, dynamic mechanical device that the students can assemble, touch, "play" with, re-design and modify results in increased student enthusiasm [Ghorbel, 1999; Lyons et al., 1998; Clark and Hake, 1997].

In this paper, we go a step further to suggest that an effective laboratory experience challenges the students with a design goal for the central mechanical device. Once the students are faced with a clear design goal, the role of the laboratories is to present the tools that might be used to analyze, model and design the device in order to meet the goal. The laboratory sessions guide students through the process of figuring out which tools to use and how to use them appropriately. Thus, while class concepts are being demonstrated, their use as design tools is also motivated and made relevant.

In the laboratories presented here, junior- and senior-level students in a mechanical engineering Dynamic Systems course at Stanford University were challenged to improve the performance of the "Dashpod" (Dynamics And Systems Hopping Pod): a simple, pneumatically-actuated, self-stabilizing dynamic hopping machine (see Figure 1). In the laboratory sessions, the students first used simple modeling concepts learned in class to characterize the Dashpod's dynamic behavior and to start making predictions about the factors that affect the machine's hopping performance. Students then evaluated the limitations of these models and used appropriately more complex models as they were explained in class. Thus, in addition to understanding the physical relevance of the mathematical concepts given in lectures, students learned basic dynamic design methodology.

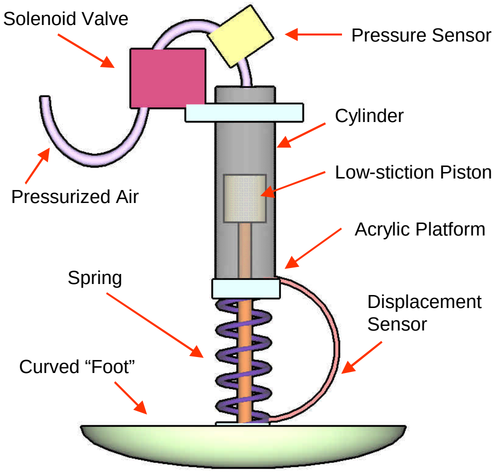

Figure 2. Dashpod diagram. The Dashpod's main components are a solenoid valve, a pneumatic cylinder and piston, a spring and a wide curved foot.

The following section describes the Dashpod, its components and the design goal as it was presented to the students. Next, we describe the laboratory sessions and how they were coordinated with the class syllabus. Finally, we discuss future improvements based upon end-of-quarter student evaluations.

2. THE DASHPOD HOPPING MACHINE

The framework discussed above for undergraduate dynamic systems laboratories challenges the educator to find a compelling mechanical device whose components and objectives enhance the desired course material. The Dashpod hopping machine is a simple mechanical system that integrates well with the pedagogical goals of an undergraduate dynamics laboratory. It is inspired by robotics and biomechanics research on legged locomotion [Wei et al., 2000; Blickhan and Full, 1993; Raibert, 1986; Cham et al. 2000]. As shown in Figure 2, the basic configuration of the Dashpod consists of a low-stiction pneumatic piston attached to a wide dish or curved "foot" on which it stands. A spring connects the foot to the pneumatic cylinder and platform along the piston shaft and a solenoid valve regulates air into the cylinder's upper chamber. Depending on the laboratory goals, a pressure sensor can be attached to measure the cylinder's air pressure and a displacement sensor can be used to measure the relative distance between the platform and foot. The Appendix contains descriptions and costs of the commercial parts used.

The machine can be made to hop vertically by supplying the

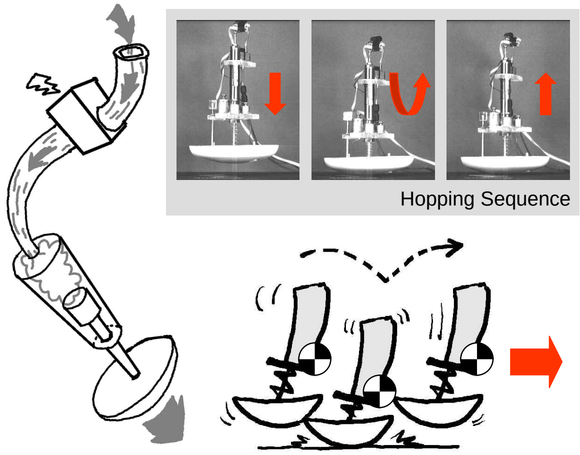

Figure 3. Dashpod hopping diagram. The solenoid valve allows pressurized air to fill the pneumatic cylinder, causing the Dashpod to push against the ground. If the valve is activated periodically, the hopping motion is also periodic. An off-axis center of mass will cause the Dashpod to hop in a certain direction.

valve with pressurized air (approximately 20 psi) and applying current to it, causing the valve to open. This fills the cylinder's upper chamber with pressurized air, thereby pushing the Dashpod's platform up. At some point, the Dashpod's foot loses contact with the ground, and the machine travels ballistically through the air before landing again. If the valve is turned off at this point, the platform will compress the spring when it lands, storing energy that can be used for the next hop. If the valve is activated at a certain frequency, the hopping motion is periodic with a certain hopping height, as shown in Figure 3. If the center of mass of the Dashpod is placed off-set from the piston axis, then the machine "leans" to one side. Thus, when the valve is activated, the machine hops in a specific direction with a certain horizontal velocity.

In essence, the Dashpod is a resonant mass-spring-damper system, one of the key mechanical systems in dynamic analysis. However, as described in the following sections, understanding the basic mechanisms that affect the hopping performance of the Dashpod provides many good opportunities for analysis of other simple dynamic models besides the spring-mass-damper. In addition, the Dashpod is a good vehicle for teaching basic dynamic design methodology. Like most real-life systems, the Dashpod's hopping motion is actually a non-linear, multi-variable phenomenon that is the subject of current research [Ringrose, 2000; Koditschek and Buehler, 1990]. However, the application of simple, fundamental models to a novel dynamic system before resorting to complex, multivariable models is a good approach to dynamic design. Such a methodology would be difficult to teach using only demonstrations.

Students were challenged to improve the forward hopping motion of the Dashpod in a competitive setting between lab teams of two or three students. At the end of the laboratory sequence, students raced the Dashpods under configurations or re-designs as suggested by their analysis, assuming that increasing the machine's vertical hopping also improved forward hopping.

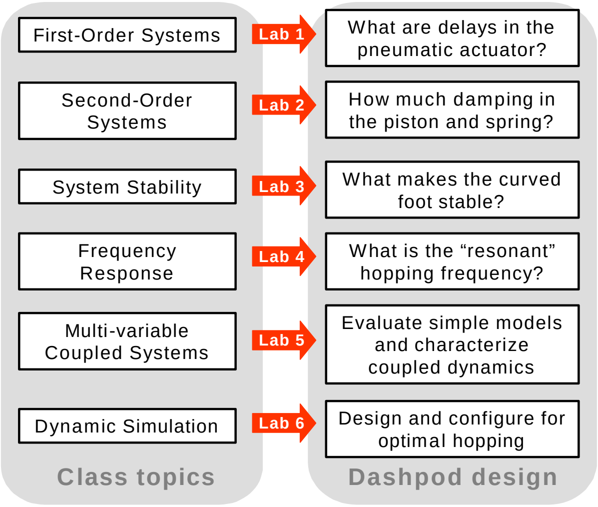

Figure 4. Syllabus topics and their corresponding labs for the Dashpod.

3. LABORATORY DESCRIPTIONS

Each laboratory session was focused on a clear question about a component of the Dashpod as it pertained to the final design goal. Given this question, students were guided through the use of the modeling tool given in class that was applicable in each case. For example, analysis of first-order, second-order systems and their time response were first used to characterize the Dashpod's basic mechanisms in order to understand the factors that influence hopping. Subsequent labs focused on more complex models, culminating in a non-linear dynamic simulation. Figure 4 shows the syllabus topics covered in lecture and the corresponding laboratory design question. The following sections describe each of the laboratories in more detail.

3.1. Lab 1: First Order Systems and Actuator Delays

The first of the Dashpod's subcomponents that the students characterized was the pneumatic actuator. Since actuator delays will determine how effectively the machine will hop, students were asked: "What design parameters affect the speed of the actuator?" For example, one important design decision is whether to mount the air valve on the machine or off-board. In this lab, students used an electronic pressure transducer to record the time history of the pressure inside the cylinder after the valve is activated. They compared this time history to a simulation of a first-order model of the pneumatic system composed of an air supply, the valve, the tubing and the cylinder chamber as shown in Figure 5a along with its differential equation.

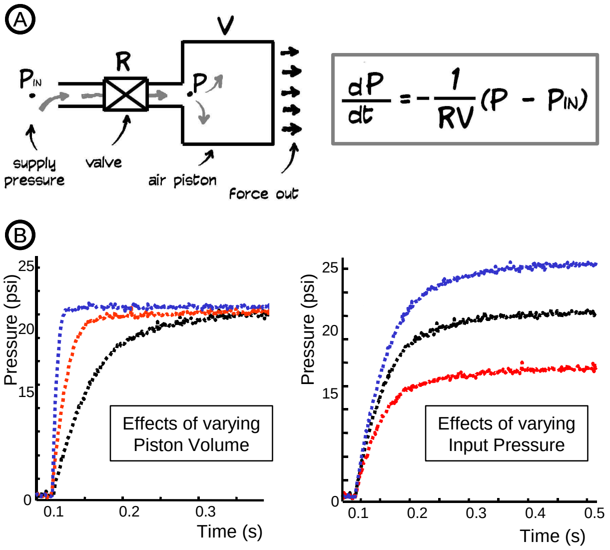

Figure 5. First-order Systems. This lab illustrated the design impact of changing system parameters in the Dashpod's pneumatic actuator.

The students' task was to estimate the "time constant" (the time it takes for the pressure to reach 63% of its steady-state value) for a trial run and record this value for different design parameters. Sample plots are shown in Figure 5b. The students first evaluated the linearity of the system by comparing the time constant for different input pressures, P_{in}. They found that it was constant within reasonable bounds, as predicted by the linear model. The students then varied the volume of the cylinder chamber by holding the piston at different positions and recorded the time constant. This gave them an estimate of the range of actual delays, since this volume will be constantly changing during actual operation. Finally, students varied the length of tubing between the valve and the actuator and found that shorter tubing resulted in smaller time constants. Both these last phenomena were compared to the model's prediction of the time constant being a inverse function of R, the flow resistance of the valve and tubing (related to tubing length), and V, a measure of the "capacitance" of the cylinder volume.

In this session, students obtained an intuitive sense of the time constant as a quantity inherent in a linear system and not dependent on the magnitude of the input. They observed what physical parameters affect it and how it impacts design decisions.

3.2. Lab 2: Second Order Systems and Damping

The second laboratory session focused on the Dashpod's fundamental mechanism: the interaction between the system's mass, spring and damping. Students were asked to fix the curved foot to the ground and consider the moving mass-spring-damper system, as shown in Figure 6a. The task was to identify the parameters in the second-order linear model for the mass' displacement, M, B and K, and compare a simulation of this model with actual data. Given only this instruction and the means to record the time history of the displacement through a displacement sensor, students had to figure out how to estimate the parameters.

Measuring the mass of the moving system provided a good exercise since students had to discern which parts of the Dashpod would be considered under the model and which parts were considered fixed to the ground. Estimating the spring constant provided a hands-on experience with the force-displacement relationship of a spring and a sense of how linear it actually is. To estimate a value for B, the damping constant, students recorded the time history of the mass' motion to an initial displacement, as shown in Figure 6b. Using the formula given in class for the maximum overshoot, they estimated the damping ratio for the given configuration and then calculated a value for B. Finally, a simulation of the model using the estimated parameters was compared with the actual data.

This session provided students with hands-on experience of class concepts such as a second-order underdamped response, overshoot and the damping ratio. It also familiarized students with the process of identifying and evaluating parameters for a model that can be used for future re-designs.

3.3. Lab 3: Stable and Unstable Systems

A certain range of values for the curvature of the foot makes the Dashpod self-stabilizing while standing upright. For example, when perturbed to one side, the Dashpod rocks back and forth, eventually returning to its upright position. In this lab, students analyzed why this happens and how it can affect the

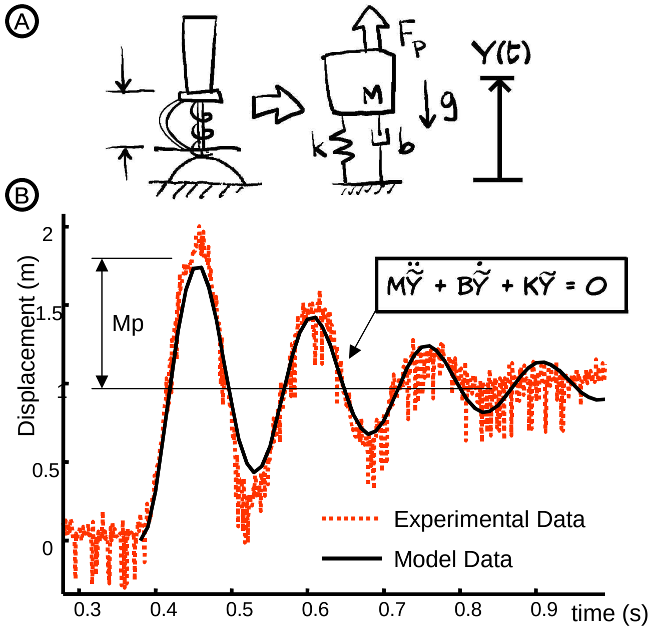

Figure 6. Second Order Systems. Students identified the model parameters *M*, *B* and *K*.

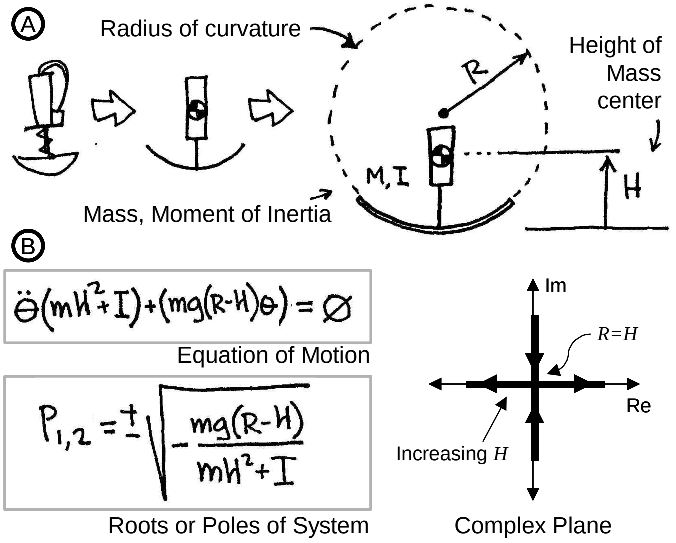

Figure 7. Stable and Unstable Systems. Students varied the height H of the center of mass and observed how the stability of the system changed.

hopping performance in the final design. To do this, the system was modeled as a planar rigid body with mass *M* and moment of Inertia *I* that is connected to a foot of constant radius *R* that rolls on the ground (shown in Figure 7a). Obtaining the linearized differential equation for this system constitutes a good demonstration of using energy-based methods such as Lagrange's for generating equations of motion. For this laboratory, however, students were directly given the equations due to time constraints.

Again, students were only given the tasks of estimating the parameters used in the model and evaluating the model's effectiveness. How to estimate the radius of curvature of the foot, the moment of inertia, mass and center-of-mass location was an open-ended question. This forced students to really think about the concept of inertia and how they would measure it. Most students used the bi-filar pendulum method [Steidel, 1989] to estimate the Dashpod's moment of inertia, while others hung the Dashpod from one end like a pendulum and measured the swing period. To evaluate the model, students compared the actual period of oscillation of the Dashpod's rocking motion with the period predicted by the model and the parameters they estimated.

The session's main pedagogical impact was in varying the height *H*, of the center-of-mass, and observing the behavior. As predicted by the model, increasing this value *moves* the "poles" or "roots" of the system's differential equation in the complex plane, as shown in Figure 7b. As *H* is increased, these "roots" move from the imaginary axis to the origin and finally to the real axis. Students saw the connection between the location of these poles and the rocking behavior. As they moved the center of mass higher in the Dashpod, the poles moved along the imaginary axis and the period of the rocking oscillations decreased. When the value of *H* approaches *R*, the center-of-mass is such that the poles are near the origin, making the Dashpod approximately neutrally stable such that it remains near the angle it is initially placed at. If $H > R$, one of the roots is real and the Dashpod falls over unstably, as predicted by the model. Thus, students got an intuitive sense for the meaning of stability and its connection to the roots, or poles, of the system.

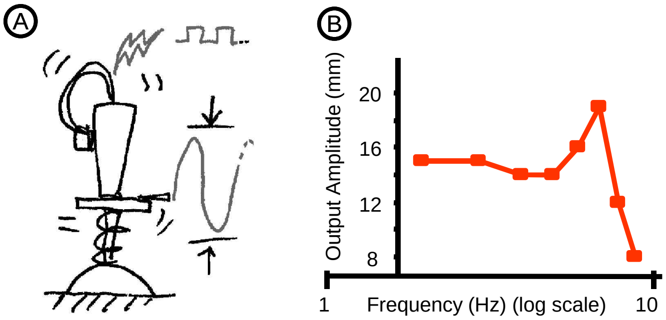

Figure 8. Frequency Response. Students evaluated the second-order model by comparing the resonance of the actual system with the model prediction.

This understanding is important to the design goal as will be seen in Lab 5.

3.4. Lab 4: Resonance and Frequency Response

In this laboratory session, students were asked to characterize the Dashpod's response to activating the air valve over a range of frequencies. Their task was to determine whether the best frequency for hopping was well predicted by the resonant frequency of the second-order model they identified in Lab 2. To determine this, students first fixed the Dashpod's foot to the ground and experimentally found the resonant frequency by measuring and recording the amplitude of oscillation of the sprung mass as the frequency of valve activation was varied (see Figure 8). This reinforced understanding of the concept of a system's frequency response given in class. They then compared this experimental frequency response to the one predicted by the linear model. Finally, they released the Dashpod's foot and observed the machine's hopping as a function of frequency. They found that the best hopping frequency was slightly lower (~5Hz) than the resonant frequency of the sprung mass (~7Hz). Therefore, students concluded that although the oscillations of the sprung mass could be used as a rough design model for hopping behavior, a more complex model was clearly needed.

3.5. Lab 5: Coupled Dynamics

As class lectures covered multi-variable and higher order systems and analysis tools, students were now ready to address an important assumption made in previous labs. The individual Dashpod components analyzed in previous labs were treated

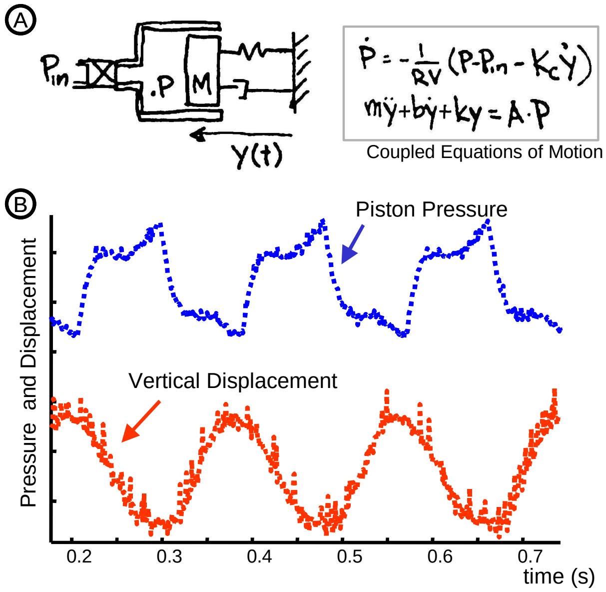

Figure 9. Coupled Dynamics. In this session, students determined that the simple systems modeled in previous sessions are actually significantly coupled, as seen in (B). They then evaluated a more complex model, seen in

separately, neglecting coupling effects between them. Motivated by the need for a more accurate model to use as a design tool, students first evaluated the coupling effects between the pneumatic actuator and the mass-spring-damper system. They obtained a qualitative sense of this coupling by simultaneously measuring the displacement of the sprung mass and the pressure inside the cylinder while the valve was activated at a certain frequency. A sample plot is shown in Figure 9b, which shows that the pressure does not behave like the plots in Figure 5, and instead seems influenced by the displacement of the platform and piston. A more accurate model was proposed to the students, as shown in Figure 9a, in which the rate of change of the pressure is linearly influenced by the velocity of the sprung mass. Students used a simulation of this multivariable model to iteratively find a value of the coupling gain *Kc* which matched the observed behavior.

The other coupled dynamics that the students considered were the influences by the moving sprung mass on the Dashpod's rocking motion. Students observed that if the sprung mass was excited at a certain frequency, large rocking motions were also indirectly induced. Students found that this frequency was near the natural frequency of the rocking model used in Lab 3. Thus, they learned that the presence of dynamic coupling must be considered when designing different components of a system.

3.6. Lab 6: State-space and Dynamic Simulation

The previous laboratory sessions gave the students an intuitive sense of the basic mechanisms that can be designed to improve the Dashpod's hopping motion. From Lab 1, student estimates of the pneumatic actuator's time constants put an upper limit on the frequency for effective hopping at 25Hz. Students saw in Lab 2 that the mass-spring-damper system is relatively underdamped, so that it would be advantageous to excite the system near its resonant frequency, as confirmed in Lab 4. In Lab 3, students showed that the machine could balance itself if the center-of-mass was appropriately placed. However, Lab 5 indicated to them that the center-of-mass must be designed such that the natural frequency of the rocking motion is not near the chosen hopping frequency. Otherwise, extreme rocking motion can be induced that could tip the machine over.

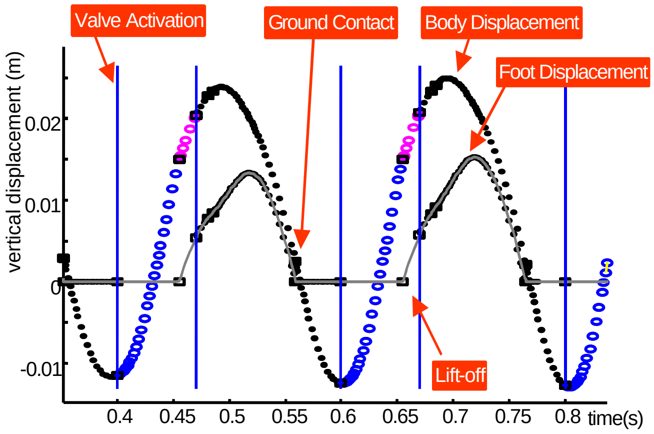

Figure 10. Dynamic Simulation. Guided by the intuitive understanding gained from previous sessions, the students used a dynamic simulation that modeled the machine's intermittent dynamics to optimize hopping.

These guidelines represent a basic intuitive understanding of the dynamics of a mechanical system that designers must have about their designs. Such an understanding has come from a dynamic design methodology that emphasizes the application of simple models to a novel system before resorting to complex ones. Guided by this understanding, students in the final laboratory session used a more complex dynamic simulation of the Dashpod's vertical motion to obtain numerical values for some of the design parameters. This simulation was partially implemented using Matlab to model the non-linear intermittent dynamics of an airborne and a ground-contact phase. Students were asked to complete the simulation by providing the differential equations in state-space form of the Dashpod during ground contact. This gave the students a sense of the structure that most numerical integrators use to solve differential equations. Using the numerical values of the parameters found in previous sessions, the students used the simulation to maximize the hopping height while varying valve activation frequency and mass (see Figure 10).

Finally, the sequence of laboratories culminated in each group of two or three students applying their observations to the actual Dashpod and competing against other groups to see who could make their machine hop forward the fastest. Speed was measured by placing the Dashpods on a treadmill and adjusting the treadmill speed until it matched the machine's. Here students quickly found that their optimal settings for maximal hopping height were not necessarily the best for forward hopping speed. This fact was unforseen by the authors, but provided an interesting lesson in the meaning of optimization. Despite this discovery, the competition still continued and students had to quickly readjust their parameters to optimize for speed. The various speed records were recorded, and the winners were announced in class and given Dashpod trophies.

4. RESULTS AND DISCUSSION

Despite many of the difficulties in implementing the labs for the first time, student response was very enthusiastic. For many students, analyzing and playing with an actual hopping machine was a novel experience that they found fun and engaging. Of course, it is difficult to objectively quantify the teaching benefits of the laboratory sessions, especially in a real-time educational setting. However, as a means to assess the students' experience with the lab sessions, we conducted an end-of-quarter survey. Figure 11 shows the tabulated results of the survey which asked students their opinion on the individual lab sessions and how the overall experience improved their learning.

These results are encouraging and show that students felt that the laboratory experience positively improved their learning. Comments provided in the survey showed that some students would have liked to have seen more examples of dynamic systems besides the Dashpod, while others would have liked to have analyzed it in more depth.

5. CONCLUSIONS AND FUTURE WORK

It is clear that design engineers must have a thorough and intuitive understanding of mechanical dynamic behavior. While interactive demonstrations help illustrate the mathematical concepts used in dynamic analysis, we argue that these concepts must also be motivated as design tools.

An effective framework for a laboratory experience that achieves this focuses the individual sessions on a compelling mechanical device that the students can physically interact with. Students are challenged to achieve a *design goal* for this device, while the sessions' role is to teach the mathematical *tools* that can be used to meet this goal. Giving them only the tools allows the students to figure out for themselves how to apply the tools to the given problem, which is a valuable learning experience. In addition, guiding the students through the process of modeling and designing a mechanical device gives the educator the opportunity to teach basic dynamic design methodology, which would not be possible using only demonstrations.

This framework was implemented using the Dashpod hopping machine, a simple and fun mechanical device. Student response was enthusiastic and indicated improvement on learning class material. Analyzing the mechanisms that affect the Dashpod's hopping motion proved to be a good vehicle to illustrate and motivate basic dynamic design concepts and methodology.

Future work would address several issues to enhance the laboratory's effectiveness. For example, limited resources can impede a satisfactory implementation. The number of computers needed with data acquisition capabilities and the cost of the parts needed currently make it difficult give students enough laboratory time and to give each group their own personalized device. These time constraints limited the amount of work that could be expected from the students. A fuller implementation could ask students to derive more of the equations and Matlab scripts that were given to them in the implementation described in this paper.

Individual Lab Ratings (1=yuck, 3=okay, 5=awesome)				
LAB	Title	Mean Rating	Max. Rating	Min. Rating
1	Actuator Delays	3.68	5	2
2	Damping	3.73	5	3
3	Stable/Unstable Systems	3.57	5	2
4	Resonant Frequency	4	5	3
5	Coupled Dynamics	3.68	5	3
6	Dynamic Simulation	4.27	5	3

Overall Lab Rating (1=confused me more, 3=Okay, 5=Brought it home!)			
How well did labs improve what I learned in class?	3.9	5	3

Figure 11. Averaged Student Evaluation Results (25 questionnaires collected in a class of 55 students).

Another possibility for improvement would be to increase the size of the Dashpod from hand-sized to perhaps shoebox-sized. This would "slow down" many of the dynamic phenomena, allowing students to more directly observe them, and would also make the machines more robust and easier to assemble.

Since this was the first time that the Dashpod was used, we did not have exact answers to many of the questions that were posed to the students. In almost all cases, we did not know how well the models proposed would describe the Dashpod's actual behavior. This provided the students with a unique sense of taking part in a novel exploration, which we believe reinforced the design tools and methodology. We encourage educators implementing this framework for laboratories to continually change or modify the laboratory's mechanical device or design goal in order to maintain this sense of discovery.

ACKNOWLEDGEMENTS

The authors would like to thank the Autumn 2000 students of ME 161 at Stanford University for their support, patience and enthusiasm. In addition, we thank Dr. Paul Mitiguy, Susan Lee and the members of the Dexterous Manipulation Laboratory. This work is supported by the Design Division of the Mechanical Engineering Department and by the Office of Naval Research under N00014-98-1-0669.

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APPENDIX: MATERIALS AND COST

The parts used to build the basic Dashpod are shown in the following table:

Part	Manufacturer/ Retailer	Approx. Cost
Low-stiction air cylinders (part E9D2.0N)	Airpot Corp., Norwalk CT	$40
Miniature Solenoid Valve, (part H010E1)	Humphrey Valves/ Bay Pneumatics, Palo Alto, CA	$25
Curved Foot (common light fixture)	Angelo Lighting Co./ Lighting supply store	$3
Acrylic Parts (laser cut)	Plastics Supplier	$8
Common spring	Hardware store	$2
Tubing and fittings	Bay Pneumatics, Palo Alto CA	$1

The sensors used to measure displacement and pressure are shown in the table below. The displacement sensor used was a “bend” sensor, and proved to be difficult to work with. Other possible sensors that could be used include a linear encoder or an LVDT.

Part	Manufacturer	Approx. Cost
Pressure sensor (589G)	Nova Sensor, Fremont CA	$30
Bend Sensor	Abrams Gentile Entertainment	$10

The Dashpod was interfaced to a computer using a Computer Boards data acquisition card, which recorded the sensor data and activated the valves.